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Research Article

Keywords: integrated crop-livestock systems, resource-use efficiency, energy efficiency, rice-based systems, farming system redesign, agroecological transition, food security, rotational diversity

Posted Date: November 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10951223/v1

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Redesigning subtropical lowland rice systems through crop diversification and livestock integration: trade-offs among energy efficiency, productivity, and economic performance

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Abstract: Sustainable intensification of agrifood systems is essential to reconcile growing global food demand with resource-use efficiency and economic viability. In this context, redesigning production systems through crop diversification and livestock integration can promote greater complementarity in resource use. Rice is a staple food for billions of people, yet in southern Brazil it is predominantly grown as a continuous monoculture under flood irrigation, with high demands for water, fertilizers, and fuel. We hypothesized that diversifying rice-based rotations with upland crops, forages, and cattle grazing would increase resource-use efficiency and economic performance without necessarily increasing absolute energy output. We evaluated five rice-based production systems over eight years (2013-2020), ranging from continuous flood-irrigated rice monoculture to rotations combining rice with soybean, maize, forage crops, perennial pastures, and cattle grazing, quantifying energy inputs and outputs, energy productivity, specific energy, rice-equivalent yield, and economic performance using the full rotation cycle as the analytical unit. This is the first field study to jointly quantify energy efficiency, rice-equivalent yield, and economic performance across diversified rice-based systems over an eight-year period in southern Brazil. Relative to continuous rice monoculture, diversified systems reduced energy input by up to 28%, more than doubled energy productivity (from 0.391 to 0.837 kg per megajoule), and lowered specific energy by 53%. They also increased rice-equivalent yield by 48-54% and net revenue from US$14,499 to as much as US$25,953 per hectare, while the benefit-to-cost ratio rose from 3.3 to 5.2. These findings demonstrate that redesigning crop-livestock rotations, rather than intensifying a single crop, can simultaneously raise resource-use efficiency and economic returns, offering a practical pathway toward more sustainable and food-secure lowland rice production.

Keywords: integrated crop-livestock systems; resource-use efficiency; energy efficiency; rice-based systems; farming system redesign; agroecological transition; food security; rotational diversity

1. Introduction

The transition toward more sustainable and resource-efficient agrifood systems requires more than incremental gains from isolated practices; it calls for changes in how agricultural systems are organized and in the resource flows that underpin their production. Although agricultural intensification has substantially increased productivity, it has also been associated in many contexts with the specialization and simplification of production systems, often accompanied by greater reliance on external inputs and reduced diversity of crops and productive activities (Godfray et al., 2010; Tilman et al., 2011; Struik & Kuyper, 2017; Hufnagel et al., 2020). In this context, sustainable intensification requires strategies that reconcile production, resource-use efficiency, and value generation. Diversification is one such strategy, as it can reorganize the temporal and spatial distribution of crops, pastures, and livestock, thereby altering resource allocation and the composition of products generated (Hufnagel et al., 2020; Carvalho et al., 2021; Reckling et al., 2023).

Subtropical lowland rice systems provide a particularly relevant context for this transformation. Rice (Oryza sativa L.) is fundamental to food security and represents a major component of the agricultural economies of these regions. In Brazil, Rio Grande do Sul is the leading rice-producing state and accounts for approximately 70% of national production. Extensive lowland areas are managed under continuous irrigated rice monoculture, involving recurrent irrigation, fertilization, and mechanization operations and, consequently, high demands for resources and energy (Sousa et al., 2021; Qin et al., 2024; Singh et al., 2025). Although this production model supports high rice yields per unit area, the recurrence of the same crop limits the diversification of products generated from the land over time. Introducing upland crops, forage species, and livestock can modify this pattern by expanding the productive use of land, distributing production among different components, and integrating crop and livestock production flows (Fig. 1) (Theisen et al., 2017; Carlos et al., 2020; Macedo et al., 2021; Mohanty et al., 2024).

However, such changes do not necessarily result in simultaneous improvements across all dimensions of system performance (Macedo et al., 2021; Wang et al., 2026). A lower frequency of irrigated rice may reduce certain input flows, but the introduction of new crops, field operations, and livestock activities may also create additional demands for inputs and energy. Likewise, lower rice production per unit area does not necessarily indicate lower overall productivity when multiple products are considered jointly. These potential trade-offs highlight the need to evaluate alternative production configurations in an integrated manner, simultaneously considering resource use, aggregate productivity, and value generation (Reckling et al., 2023; Wang et al., 2026). Although previous studies have shown that diversification can affect multiple dimensions of agricultural system performance, long-term experimental assessments integrating

these dimensions in diversified lowland rice systems remain scarce (Hufnagel et al., 2020; Reckling et al., 2023; Wang et al., 2026).

Long-term experiments provide a unique opportunity to investigate these relationships because they allow contrasting production configurations to be compared under common environmental conditions and across multiple rotation cycles (Alletto et al., 2022). Nevertheless, the consequences of integrating crops, pastures, and livestock into systems traditionally based on continuous rice cultivation for resource use, energy efficiency, aggregate productivity, and economic performance at the rotation scale remain poorly understood. This knowledge gap is particularly relevant for subtropical lowlands, where diversification of land use can simultaneously modify production intensity, product composition, and the value generated per unit of land area.

In this study, we conceptualize diversification as a strategy for redesigning the production system rather than merely as a change in crop composition. We used an eight-year field experiment conducted in subtropical lowlands in southern Brazil to compare five contrasting production configurations, ranging from continuous irrigated rice cultivation to systems involving rice, soybean, maize, ryegrass, sudangrass, perennial pastures, and livestock production. We jointly evaluated energy inputs and outputs, energy efficiency, aggregate productivity expressed as rice-equivalent yield, and economic performance. We hypothesized that diversification would reorganize resource flows among the different components of the rotation, reducing the recurrence of demands associated with continuous rice cultivation and increasing the efficiency with which invested resources were converted into aggregate production and economic value, without proportional losses in productivity. By comparing these configurations under common experimental conditions over an eight-year period, we sought to determine whether diversification represents not merely a change in the composition of production activities, but a system-redesign strategy capable of reconciling resource-use efficiency, productivity, and value generation.

2. Materials and methods

2.1 Experimental site description and initial conditions

The study was conducted in a long-term experiment (eight years) established at Fazenda Corticeiras, in southern Brazil (31°37′13″ S, 52°35′20″ W; 28 m elevation) (Fig. 2). The soil is classified as an Albaqualf according to Soil Taxonomy (USDA 2014), with a sandy clay loam texture (24% clay, 23% silt, 53% sand) and naturally restricted drainage (Martins et al. 2017). According to the Köppen climate classification, the regional climate is humid subtropical (Cfa), characterized by hot, humid summers, mean annual rainfall of approximately 1,500 mm, and mean annual temperature of 18.3 °C (Wrege et al. 2011).

Historically, between 1960 and 2009 the area was used for annual flood-irrigated rice during summer, remaining fallow in winter. After the 2009 harvest, agricultural activities were discontinued and the area remained fallow between 2010 and 2013. The experiment was established in the 2013 growing season, when agricultural use of the area resumed. Before the study began, the production system consisted of a flood-irrigated rice-winter fallow succession, without planned grazing. Livestock integration became part of the system only after the experiment was established, and was adopted exclusively in the treatments that included animals (Section 2.2).

Before establishment, soil samples (0-0.20 m) indicated 1.8% organic matter, a water pH of 5.5, available P and K of 10 and 76 mg dm^{-3}, 3.5 cmolc dm^{-3} calcium, 2.3 cmolc dm^{-3} magnesium, 0.1 cmolc dm^{-3} aluminum, 13.5 mg dm^{-3} sulfur, cation exchange capacity at pH 7.0 of 10.6 cmolc dm^{-3}, and base saturation of 56%. Based on these results, soil pH was raised to 6.0 by applying 4.5 Mg ha^{-1} of agricultural lime (total relative neutralizing power of 70%), following the recommendations of CQFS-RS/SC (2016).

2.2 Experimental design and rice-based production systems

The experiment was conducted over eight years, comprising two consecutive four-year cycles (2013-2016 and 2017-2020), in a randomized block design with five treatments and three replicates, totaling 15 experimental units with an average area of ~1 ha each. Treatments consisted of five flood-irrigated rice-based production systems, contrasting different levels of crop diversification, rice cropping frequency, tillage, and livestock integration.

The systems evaluated were: S1 - flood-irrigated rice monoculture with winter fallow (rice crop residues and volunteer vegetation), under conventional tillage (harrowing to ~0.20 m after harvest) and without livestock; S2 - flood-irrigated rice in summer followed by grazed ryegrass (*Lolium multiflorum* L.) pasture in winter; S3 - annual rotation between flood-irrigated rice and soybean (*Glycine max* L.) in summer, followed by grazed ryegrass in winter; S4 - a diversified four-year rotation with sudangrass (*Sorghum sudanense*, also grazed in summer), soybean, maize (*Zea mays* L.), and flood-irrigated rice in summer, and grazed ryegrass intercropped with white clover (*Trifolium repens* L.) in winter; S5 - a four-year rotation kept under natural grassland for the first three years and flood-irrigated rice in the fourth, with winter pastures of ryegrass, white clover, and birdsfoot trefoil (*Lotus corniculatus* L.), under continuous grazing except during the rice cropping period. Except for S1, all systems were managed under no-till. The crop and pasture sequence and cultivation parameters for each system are presented in Tables S1 and S2.

2.3 Fertilization, pesticide use, and grazing management

Fertilization followed the recommendations of the Commission of Chemistry and Soil Fertility for the states of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC 2016), according to the nutritional requirements of each crop and system. Nitrogen (N) was applied as urea, P as triple superphosphate, and K as potassium chloride (KCl). The annual N, P, and K rates applied to each crop across systems, expressed on an elemental basis, are presented in Table S3.

Pest, disease, and weed management followed the recommendations of the Southern Brazilian Irrigated Rice Society (SOSBAI 2025), including fertilizer and pesticide application timing. The pesticides applied annually in each system and their respective rates are presented in Table S4.

Grazing in the integrated crop-livestock systems (S2-S5) was managed under continuous stocking with a variable, put-and-take stocking rate, maintaining forage sward height at approximately 0.15 m through the addition or removal of put-and-take animals (Amaral et al. 2013). In winter, grazing was performed with recently weaned steers (~10 months old, 200 kg live weight; a minimum of three animals per experimental unit), generally between June/July and October/November. In the systems with a summer forage phase (S4 and S5), grazing was also carried out in some years using castrated male cattle (~15 months old, 300 kg live weight), under the same sward-height-based management criterion.

2.4 Assessment of the energy efficiency of the production systems

2.4.1 System boundaries and methodological approach

The energy performance of the production systems was assessed following a life-cycle approach, based on the principles established by ISO 14040 and ISO 14044 and adapted to agricultural conditions. The system boundary encompassed the energy flows associated with crop and livestock activities over the eight years of evaluation (2013-2020), from input use to product output. The functional unit adopted was 1 ha of experimental area over the full eight-year period.

Seeds, fertilizers, pesticides, and the fuel used in machinery operations and irrigation were accounted for as energy inputs. Energy outputs corresponded to the cumulative production of rice, soybean, and maize and to animal weight gain converted into beef production. Input and product transport, labor, solar radiation, biological nitrogen fixation, and the energy embodied in machinery and infrastructure were not accounted for. Crop residues and animal excreta were considered internal system flows and were therefore not accounted for as independent energy inputs or outputs.

2.4.2 Inventory of system inputs and outputs

The inventory was built from the experimental records of each system, covering the amounts of inputs and fuel associated with tillage, sowing, fertilization, pesticide application, irrigation, pasture management, animal handling, and harvest. The cumulative amounts of inputs and fuel used in each system are presented in Table S5.

Physical flows were converted into energy values using energy coefficients specific to each input and product, obtained from the literature and presented in Table 1. For pesticides, commercial product amounts were converted into active-ingredient mass based on each product's concentration and then associated with the corresponding energy coefficients. Physical flows were thus expressed in energy units (MJ ha^{-1}) for the calculation of system energy inputs and outputs.

2.4.3 Energy inputs and outputs

2.4.3.1 Total energy input

Total energy input (EI) was determined as the sum of the energy associated with the different inputs and fuels used in each system, according to Equation 1:

$$EI_i = Q_i \,.\, CE_i \qquad \text{equation 1}$$

where:

EI_i: energy consumed by input i (MJ ha^{-1});
Q_i: amount of input i used;
CE_i: energy coefficient of input i (MJ per unit).

EI was obtained as the sum of the energy contributions of all inputs used in the system, according to Equation 2:

$$EI = \sum_{i=1}^{n} EI_i \qquad \text{equation 2}$$

where:

EI = total energy input (MJ ha^{-1})

Diesel consumption for machinery operations was estimated from the average fuel consumption of each operation and its frequency in each system throughout the experimental period. Consumption values of 22.0 L ha^{-1} for rice harvest, 13.8 L ha^{-1} for soybean, and 19.25 L ha^{-1} for maize were considered; 8.8, 8.2, 5.5, and 5.5 L ha^{-1} for sowing rice, soybean, maize, and pastures, respectively; and 3.3 L ha^{-1} per operation for nitrogen fertilizer application. Tillage, performed exclusively in S1, was estimated at 40 L ha^{-1}. For pest and disease management, consumption values of 4.0 L ha^{-1} for winter crops, 8.0 L ha^{-1} for grain crops, and 3.0 L ha^{-1} for succession fields and sudangrass were considered.

Irrigation energy was estimated from the diesel consumption used for water pumping during flood-irrigated rice cultivation. Considering a water demand of 10,000 m^3 ha^{-1}, according to Carracelas et al. (2019), diesel consumption was estimated at 194.44 L ha^{-1} per cropping cycle. Cumulative diesel consumption for irrigation in each system was determined according to the number of flood-irrigated rice cycles carried out during the experimental period.

2.4.3.2 Total energy output

Total energy output (EO) was calculated from the cumulative grain production and animal weight gain obtained in each experimental unit over the eight years. For rice, soybean, and maize, EO was determined by multiplying the cumulative production of each product by its respective calorific value. In the livestock systems, cumulative live weight gain was converted into carcass production using a dressing percentage of 52% (Crusciol et al. 2020) and subsequently into energy based on the calorific value of beef.

Cumulative live weight gain was estimated from average daily gain, the number of animals, and their grazing period in each system. Forage biomass consumed by the animals was considered an internal system flow and was therefore not accounted for as an independent EI or EO; its contribution was represented indirectly through animal weight gain. Thus, in the integrated crop-livestock systems, only animal weight gain was considered as an EO component.

The EO of each component was calculated according to Equation 3:

$$EO_i = P_i \,.\, PC_i \qquad \text{equation 3}$$

where:

EO_i = energy produced by product i (MJ ha^{-1});
P_i = cumulative production of product i during the experimental period (kg ha^{-1});
PC_i = calorific value of product i (MJ kg^{-1}).

EO was determined as the sum of EO across all crop and livestock components, according to Equation 4:

$$EO = \sum_{i=1}^{n} EO_i \quad \text{equation 4}$$

where:

EO = total energy output (MJ ha^{-1})

The calorific values used for rice, soybean, maize, and beef are presented in Table 1.

2.4.3.3 Renewable and non-renewable energy

EI were classified into renewable and non-renewable sources according to the nature of the inputs and operations used in the production systems. Seeds used to establish crops and pastures were classified as a renewable energy source. In S5, during the natural grassland phase, the energy contribution of seeds was considered null, as there was no sowing or external acquisition of propagation material. Conversely, fertilizers, pesticides, fuel used in machinery operations, and fuel used for irrigation were classified as non-renewable energy sources, following the classification adopted by Kakraliya et al. (2022). Energy associated with animal production was not considered an EI, being instead accounted for in system EO through the energy contained in beef production.

Renewable energy (RE) was determined by Equation 5:

$$RE = \sum \text{renewable energy} \quad \text{equation 5}$$

Non-renewable energy (NRE) was determined by Equation 6:

$$NRE = \sum \text{non} - \text{renewable energy} \quad \text{equation 6}$$

The relative shares of RE and NRE were calculated according to Equations 7 and 8, respectively:

$$RE\ (\%) = \frac{RE}{EI} . 100 \quad \text{equation 7}$$

$$NRE\ (\%) = \frac{NRE}{EI} \cdot 100 \qquad \text{equation 8}$$

where:

RE = renewable energy (MJ ha^{-1});
NRE = non-renewable energy (MJ ha^{-1}).

2.4.4 Energy performance indicators

2.4.4.1 Energy Return on Investment (EROI)

The energy efficiency of the systems was assessed through the Energy Return on Investment (EROI), calculated according to Equation 9:

$$EROI = \frac{EO}{EI} \qquad \text{equation 9}$$

where:

EROI = energy return on investment (MJ MJ^{-1}).

2.4.4.2 Net energy

Net energy (NE) represents the energy balance of each production system, calculated as the difference between EO and the energy consumed during the production cycle, according to Equation 10:

$$NE = EO - EI \qquad \text{equation 10}$$

where:

NE = net energy (MJ ha^{-1})

2.4.4.3 Energy productivity

Energy productivity (EP) represents the amount of product obtained per unit of energy consumed during the production process, calculated based on the Rice Equivalent Yield (REY), according to Equation 11:

$$EP = \frac{REY}{EI} \quad \text{equation 11}$$

EP = energy productivity (kg MJ^{-1})
REY = rice-equivalent yield (kg ha^{-1})

2.4.4.4 Specific energy

Specific energy (SE) represents the amount of energy required to produce one unit of REY, determined according to Equation 12:

$$SE = \frac{EI}{REY} \quad \text{equation 12}$$

SE = specific energy (MJ kg^{-1})

2.4.4.5 Energy Output-to-Nutrient Input Ratio

The Energy Output-to-Nutrient Input Ratio (EONIR) was calculated as the ratio between total energy output and the cumulative amount of N, P, and K applied as fertilizers over the eight-year experimental period, according to Equation 13. The amounts of N, P, and K used to calculate EONIR were expressed as elemental nutrients rather than as N, P_2O_5, and K_2O.

$$EONIR_{NPK} = \frac{EO}{(N+P+K)} \quad \text{equation 13}$$

where:

EONIR = energy output-to-nutrient input ratio (MJ kg^{-1} nutrient);
N = cumulative amount of N applied during the eight-year period (kg ha^{-1});
P = cumulative amount of P applied during the eight-year period (kg ha^{-1});
K = cumulative amount of K applied during the eight-year period (kg ha^{-1}).

2.4.5 Productivity and economic performance

2.4.5.1 Rice Equivalent Yield (REY)

REY was used to express the combined production of the systems on a common basis, converting soybean, maize, and beef production into rice equivalents based on their respective market prices. Rice, soybean, maize, and beef prices used in the analysis were obtained from the National Supply Company (CONAB) for July 2026. Using a single reference period for prices standardized the valuation of the different products and made the economic contribution of each component comparable across systems. To ensure a common basis of comparison, July 2026 prices were held constant for all products and applied to the cumulative production over the eight-year period, and therefore do not represent the historical prices practiced during the experimental period. REY was calculated according to Equation 14:

$$REY = Y_{rice} + \sum(\frac{Y_i . P_i}{P_{rice}}) \qquad \text{equation 14}$$

REY = rice-equivalent yield (kg ha^{-1});
Y_rice = cumulative rice production during the experimental period (kg ha^{-1});
Σ = sum of the contributions of the other crop and livestock products of the system;
Y_i = cumulative production of product i (soybean, maize, or beef) during the experimental period (kg ha^{-1});
P_i = market price of product i (US$ kg^{-1});
P_rice = market price of rice (US$ kg^{-1}).

REY was calculated for each experimental unit based on the cumulative production over the eight years of evaluation. Because the production systems generated multiple crop and livestock products, REY was used as a common production basis for calculating EP and SE, while the product-specific energy outputs were retained for the calculation of EO and EROI.

2.4.5.2 Gross revenue

Gross revenue (GR) was calculated from REY and the market price of rice, according to Equation 15:

$$GR = REY . P_{rice} \qquad \text{equation 15}$$

where:

GR = gross revenue equivalent (US$ ha^{-1});

GR corresponds to the monetary value of REY, obtained by multiplying the rice-equivalent yield by the reference rice price. GR therefore represents a direct monetary transformation of REY and was used as the basis for calculating NR and B:C. P_rice was fixed at US$0.27 kg^{-1}, corresponding to the reference price adopted for July 2026.

2.4.5.3 Net revenue

Net revenue (NR) was calculated as the difference between GR and total cost (TC), according to Equation 16:

$$NR = GR - TC \qquad \text{equation 16}$$

where:

NR = net revenue equivalent (US$ ha^{-1});
TC = total cost (US$ ha^{-1})

TC included the costs of seeds, fertilizers, pesticides, and fuel used in the production systems. For each component, cost was obtained by multiplying the cumulative amount used over the eight years by its reference price, with costs then summed to obtain TC. Reference prices were those adopted for July 2026. Because input amounts and reference prices were defined at the system level, TC was identical across the three replicates of each system and therefore was not treated as an independent response variable in the statistical analysis. All monetary indicators are expressed in US$ ha^{-1} for the full eight-year period. TC for each system are presented in Table S5.

2.4.5.4 Benefit-to-cost ratio

The benefit-to-cost ratio (B:C) was determined according to Equation 17:

$$B{:}C = \frac{GR_{REY}}{TC} \qquad \text{equation 17}$$

B:C = benefit-to-cost ratio

2.5 Statistical analysis

Each experimental plot constituted the experimental and statistical unit, with three independent replicates per production system. For each plot, energy, productivity, and economic indicators were calculated from the values accumulated over the eight years of the experiment, treating the full period as a single temporal unit of assessment. The cumulative values for each plot were therefore used as response variables in the comparison among systems, without modeling interannual variation or temporal trends.

The analysis considered the randomized block design, with production systems as the treatment effect and blocks as the factor controlling spatial variability. Normality of residuals was assessed using the Shapiro-Wilk test and homogeneity of variances using Levene's test. When the effect of production systems was significant, means were compared using Tukey's test at 5% probability. Analyses were performed in R (R Core Team 2017).

3. Results and discussion

3.1 Diversification reconfigured agroecosystem energy flows

Diversification altered energy flows in both magnitude and composition. EI ranged from 142,325.1 MJ ha^{-1} in S5 to 223,787.9 MJ ha^{-1} in S2, a reduction of approximately 36% (Table 2). Fertilizers remained the main source of EI (35-68% of the total), while irrigation fuel use declined from 35% of EI in S1 to 12% in S5 (Fig. 3a), reflecting the lower recurrence of water intake, pumping, and distribution operations associated with reduced rice irrigation frequency. The contribution of renewable and non-renewable sources to total energy input varied among production systems (Fig. 4). In rice-pasture systems in South America, Macedo et al. (2021) similarly reported lower energy use in integrated systems compared with continuous rice, attributing this pattern to rotation composition.

This reduction, however, was not uniform across resource categories: fertilizers, fuels, and machinery operations remained relevant components in all systems, indicating that diversification mainly altered the amount and relative distribution of inputs rather than the underlying structure of energy sources. This pattern is consistent with Alluvione et al. (2011), who attributed a substantial share of the reduction in EI to fertilization and tillage management. Partially replacing rice phases with upland crops and pastures reduces the recurrence of rice-specific operations but does not eliminate the demands of the remaining components, explaining why diversification acted predominantly on when and how much energy was required throughout the rotation, rather than eliminating its main sources.

The reduction in EI was accompanied by an even more pronounced decrease in EO, which ranged from 1,177,746.3 MJ ha^{-1} in S1 to 361,608.3 MJ ha^{-1} in S5, representing a reduction of approximately 69% relative to continuous rice (Table 2). The lower EO reflected the shift from rice-dominated production in S1 toward combinations of rice, soybean, maize, pastures, and animal production in diversified systems (Fig. 3b). Because these products differ in energy content per unit mass, aggregate EO depends on both production quantity and the energy coefficients assigned to each product (Alluvione et al. 2011; Emran et al. 2022). Thus, lower EO does not necessarily indicate lower productive performance, particularly in integrated systems, where forage biomass can be converted into animal product.

NE ranged from 979,654.8 to 219,283.2 MJ ha^{-1}, tracking the pattern of EO (Table 2); its higher value in S1 was associated with the elevated EO and should not be interpreted in isolation as greater efficiency, since systems with higher absolute EO may not display greater resource-use efficiency (Alluvione et al. 2011; Zentner et al. 2011). Taken together, these results show that diversification reduced absolute EI and EO through distinct mechanisms. For EI, this reduction was primarily associated with a lower recurrence of energy-intensive operations, whereas for EO, it reflected a shift in the composition of agricultural products. Thus, lower energy investment does not necessarily imply lower absolute energy returns, just as greater EO does not necessarily translate into higher energy-use efficiency. This dissociation justifies the use of normalized indicators, such as EP and SE, to assess the relationship between invested resources and the production obtained (Alluvione et al. 2011).

3.2 Rotation reorganization increased the efficiency of energy conversion

The improvement in energy efficiency was evidenced by the joint response of two normalized indicators: EP increased from 0.39 kg MJ^{-1} in S1 to 0.84 kg MJ^{-1} in S5, while SE decreased from 2.56 to 1.20 MJ kg^{-1} (Table 2). This joint response indicates that EI declined proportionally more than REY, thereby increasing production per unit of energy invested. Importantly, this gain in EP did not result from maximizing absolute EO, but from improving the efficiency with which invested resources were transformed into agricultural production.

This distinction matters because production and efficiency are not necessarily concordant: a system may increase production through proportionally larger increases in inputs, thereby reducing its efficiency, or reduce inputs while incurring relatively smaller productive losses, thereby increasing it. Alluvione et al. (2011) showed that management strategies can substantially reduce inputs without a proportional reduction in production, and Zentner et al. (2011) showed that systems with higher EO were not necessarily the most efficient. Our results demonstrate this second condition, also observed by Macedo et al. (2021) in rice-pasture systems, in which increased production intensity did not necessarily improve energy efficiency.

The main energy gain of the diversified systems was therefore not an increase in EO per unit area, but the maintenance of rice-equivalent production with a proportionally lower energy demand. This distinction is central to interpreting S5: despite its lower EO compared with continuous rice, its higher EP and lower SE indicate a more efficient conversion of invested resources into production. This response was strongly dependent on rotation configuration. The inclusion of soybean, maize, pastures, and animal production reorganized the frequency and sequence of field operations and associated inputs, indicating that diversification involved a restructuring of the production system rather than simply adding crops. This interpretation is consistent with Alluvione et al. (2011), who showed that rotation composition can be as important as management practices in determining energy efficiency.

The animal component adds a functional dimension to this reorganization: in integrated systems, pasture is not merely an alternative phase to rice, but a component capable of converting plant biomass into animal product, expanding the pathways for resource conversion throughout the rotation (Macedo et al. 2021). Even so, the configuration of S4 shows that a larger number of components does not guarantee greater efficiency: each additional component introduces its own demands for establishment, management, harvesting, and inputs, which can offset part of the savings achieved by reducing more intensive phases. Overall system performance therefore depends on the identity, sequence, frequency, and management of its components, highlighting the configuration-dependent nature of diversification. This interpretation is consistent with the nonlinear relationships between diversification and efficiency described by Wang et al. (2024), as well as with the findings of Liu et al. (2025), who showed that different levels of diversification can generate similar or contrasting benefits depending on how crop rotations are configured.

This configuration dependence also distinguishes diversification from intensification: whereas the latter can increase production by requiring additional inputs of energy, water, fertilizers, and operations, diversification redistributes demands among components with different resource requirements. In rice-based systems, Emran et al. (2022) showed that distinct intensification and diversification strategies produced contrasting responses for equivalent yield, energy and nutrient efficiency, greenhouse gas footprint, and B:C. The continued contribution of fertilizers to EI, however, highlights a limitation of this gain: improved energy efficiency does not eliminate dependence on external inputs, but rather reflects a more efficient use of the total energy invested. Further improvements will therefore depend on combining the reorganization of crop rotations with the optimization of the main sources of energy demand.

Assessment at the rotation scale is central to this interpretation, as it captures relationships among phases with different demands and products that cannot be inferred from the isolated performance of a single crop (Pittelkow et al. 2015; Emran et al. 2022; Liu et al. 2025). Even so, these indicators represent only one dimension of agroecosystem performance: greater energy efficiency should not be interpreted in isolation as greater sustainability, as it does not directly

incorporate greenhouse gas emissions, soil quality, biodiversity, water use, or economic return (Liu et al. 2025; Wang et al. 2026). In this experiment, diversification and crop-livestock integration were also associated with changes in soil carbon and nitrogen stocks (Reis et al. 2026), reinforcing that the assessment of diversified systems should jointly consider productive, energy, economic, and edaphic dimensions. In summary, the main energy benefit of rotation reorganization was not an increase in absolute energy production, but a more efficient conversion of invested resources into agricultural output. This finding highlights the importance of system redesign for advancing the sustainable intensification of lowland rice-based production systems.

3.3 Diversification reorganized resource use across the rotation

The greater energy efficiency observed in the diversified systems becomes more understandable at the temporal scale of the rotation. In specialized systems, production remains concentrated in a restricted set of crops, keeping resource demands associated with their management recurrent; in diversified systems, different crops, pastures, and animal production occupy the area during distinct periods, with specific input and operational demands (Wang et al. 2024; Liu et al. 2025). This dimension is particularly relevant in lowland systems based on irrigated rice, where reducing rice frequency interrupted the recurrent demand for irrigation, directly contributing to lower EI in the diversified systems. A similar effect was reported by Macedo et al. (2021) in rice-pasture systems in South America.

Temporal reorganization also changed the productive function of the area: upland crops, pastures, and animal production partially replaced periods devoted to rice, distributing production among components with different functions, with animal production adding a pathway for converting biomass into product and economic return. An analysis restricted to rice would capture only part of the resources mobilized and products generated by the system. Evaluating the complete rotation sequence as the unit of analysis makes it possible to account for interdependence among phases, whereby the contribution of each phase is partly determined by those that precede and follow it. This systems perspective is essential in integrated crop-livestock systems, where pasture contributes not only through biomass production but also through its subsequent conversion into animal-derived products.

Additional mechanisms may also contribute to this reorganization, including temporal and functional complementarities in the use of water, nutrients, radiation, and space, as well as opportunities for biomass and nutrient cycling among system components. Because these processes were not directly quantified in this study, they should be interpreted as plausible mechanisms rather than experimentally demonstrated effects. In contrast, the lower frequency of irrigated rice is directly determined by rotation configuration and is reflected in the observed energy flows. In summary, the rotation constitutes the most informative scale for understanding

how diversification modifies energy efficiency in lowland systems: the contribution of diversification lay not in increasing the number of crops, but in altering the sequence of activities and integrating plant production, pastures, and animal production, which reduced EI proportionally more than equivalent production.

3.4 Trade-offs among energy efficiency, production, and economic return define different pathways to sustainable intensification

Integrating energy and economic indicators revealed contrasting system performances: continuous rice showed the highest EO and NE, whereas diversified systems had higher EP and lower SE and, particularly in S5, better economic performance. Thus, maximizing absolute EO did not necessarily result in greater conversion efficiency or economic return, highlighting that productivity, resource-use efficiency, and profitability can respond differently to system composition and intensity (Emran et al. 2022; Liu et al. 2025; Wang et al. 2026).

This dissociation was even more evident in the economic results: diversified systems showed higher REY, GR, and NR despite lower EP, demonstrating that energy content and economic value are distinct properties of the products (Table 3). Gross revenue, net revenue, production costs, and benefit–cost ratio further revealed differences among the production systems (Fig. 5). Partially replacing rice with soybean, maize, forages, and animal production altered the composition of agricultural output and, consequently, its contribution to overall system performance. In integrated systems, animal production adds an economic dimension that cannot be captured by EO alone, because market value reflects factors beyond the energy content of the products generated.

This distinctive feature was central to the trade-off identified: continuous rice was superior when the criterion was the amount of energy produced per unit area, but this production was associated with higher energy demand and lower efficiency per unit of product, whereas the perennial-pasture system showed the opposite pattern. The relative performance of each system therefore depends on the criteria used to define success, reinforcing that sustainable intensification cannot be assessed through a single performance dimension. Rather, it requires a multi-objective perspective that considers production, resource-use efficiency, profitability, and environmental impacts jointly (Emran et al. 2022; Wang et al. 2026).

This feature is central to interpreting S5: despite lower absolute energy production than continuous rice, its combination of lower energy demand, higher EP, lower SE, and better economic performance reveals an advantage that lies not in maximizing EO, but in a more favorable relationship among invested resources, equivalent production, and economic return. In contrast, the configuration of S4 shows that greater diversity of system components does not, by itself, guarantee higher efficiency or economic returns. Each additional component introduces

specific requirements for establishment, management, harvesting, and external inputs, which can offset part of the gains achieved in other phases of the rotation. This finding is consistent with the nonlinear responses described by Wang et al. (2024) and with the trade-offs among productivity, profitability, energy efficiency, and environmental performance reported by Wang et al. (2026).

The indicators evaluated in this study capture important dimensions of system performance, particularly resource use, energy conversion, productivity, and economic return, but they represent only part of the broader sustainability assessment conducted within this long-term experimental framework. Other components of agroecosystem performance, including soil carbon and nitrogen dynamics, have been evaluated independently within the same experimental framework (Reis et al., 2026), providing complementary evidence of the effects of diversification and crop-livestock integration on soil attributes. Thus, the present study should not be interpreted as an isolated assessment of sustainability, but rather as one component of a broader, multidimensional evaluation of system redesign. Integrating evidence across these dimensions is essential because improvements in energy or economic performance may coexist with, or diverge from, changes in soil and other environmental attributes.

Accordingly, S5 should be interpreted as the configuration that achieved the most favorable balance among the energy and economic dimensions evaluated here, rather than as a universally superior system. When considered alongside soil evidence from the same long-term experiment (Reis et al., 2026), these findings contribute to a broader understanding of how redesigning rice-based systems can modify resource use, production, economic returns, and soil attributes. More broadly, crop-livestock integration and diversification can improve multiple dimensions of system performance while reducing the recurrence of resource-intensive production phases and maintaining aggregate productive output. Sustainable intensification therefore requires a system-level perspective that recognizes both complementary gains and trade-offs among productivity, resource-use efficiency, economic viability, and environmental performance.

4. Conclusion

Diversifying rice-based systems through the integration of crops, forages, and livestock increased resource-use efficiency and productive and economic performance in subtropical lowlands. Relative to rice monoculture, diversification reduced SE from 2.56 to 1.20 MJ kg^{-1} and increased EP from 0.39 to 0.84 kg MJ^{-1}, while rice-equivalent yield was 48-54% higher and NR reached US$25,953 ha^{-1}.

This study demonstrates that diversification can reduce dependence on continuous rice production without compromising aggregate productivity or economic return in subtropical lowland systems. Crop-livestock integration therefore constitutes a strategy for system redesign

and sustainable intensification by increasing resource-use efficiency, generating economic value, and contributing to the transition and food security of subtropical lowland rice systems. For farmers and policymakers in southern Brazil, these results reinforce that including perennial pastures and cattle grazing in rice rotations represents a concrete and economically viable pathway for this transition, although adoption will depend on local management and market conditions that were not directly evaluated in this study.

Acknowledgements

This study was financially supported by the Coordination for the Improvement of Higher Education Personnel (CAPES), the National Council for Scientific and Technological Development (CNPq), and the Rio Grande do Sul Research Support Foundation (FAPERGS, grant no. 24/2551-0001217-6).

Declarations

Funding: This work was supported by the Coordination for the Improvement of Higher Education Personnel (CAPES), the National Council for Scientific and Technological Development (CNPq), and the Rio Grande do Sul Research Support Foundation (FAPERGS, grant no. 24/2551-0001217-6).

Conflicts of interest / Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Ethics approval: Ethical approval was not required for this study because the animals were managed under standard commercial grazing practices and no experimental procedures involving animal intervention were performed.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability: Statistical analyses were performed using R (R Core Team 2017); the analysis scripts are available from the corresponding author upon reasonable request.

Authors' contributions: Conceptualization, R.B.R. and F.S.C.; Methodology, R.B.R., E.H.P., and R.O.S.; Formal analysis, R.B.R. and E.H.P.; Investigation, R.B.R., E.H.P., and R.O.S.; Resources, F.S.C. and P.C.F.C.; Data curation, R.B.R.; Writing - Original Draft, R.B.R.; Writing - Review & Editing, F.S.C., P.C.F.C., C.B., R.O.S., and E.H.P.; Visualization, R.B.R.; Supervision, F.S.C.; Project administration, F.S.C.; Funding acquisition, F.S.C.

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Fig. 1. Livestock component of an integrated crop-livestock system involving rice production in subtropical areas of southern Brazil. Photo credit: Filipe Selau.

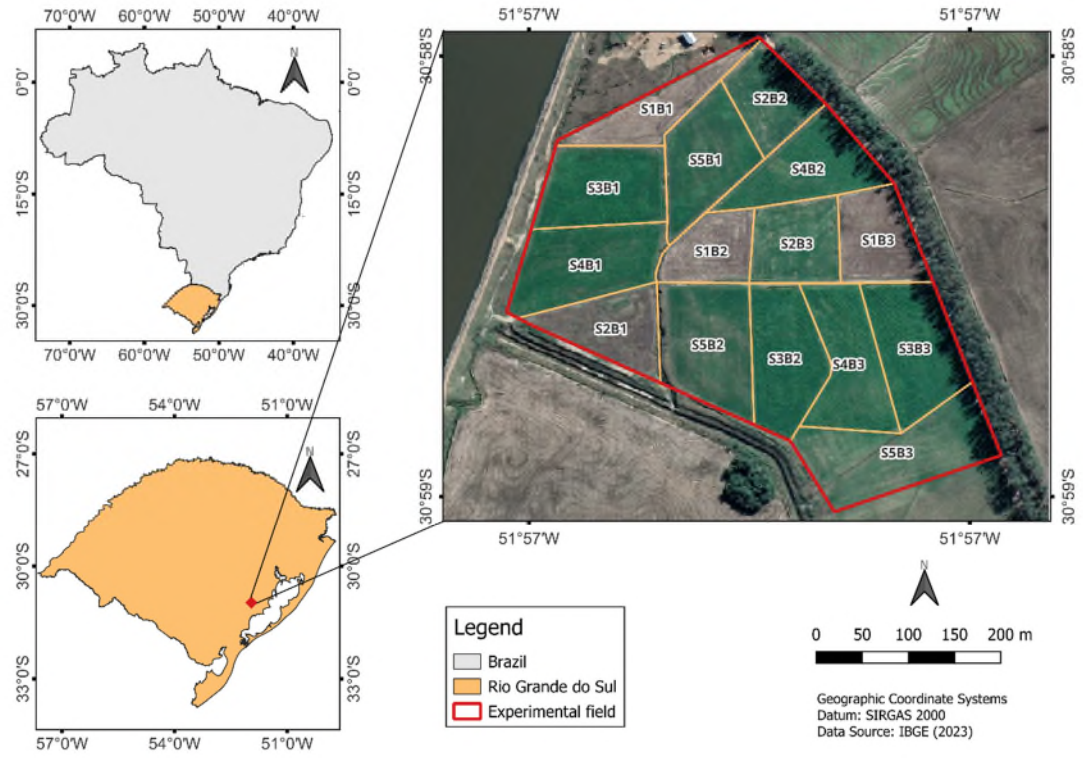


Fig 2. Location of the long-term field trial evaluating the adoption of different integrated crop-livestock systems in an Albaqualf, in Cristal, Rio Grande do Sul, Brazil.

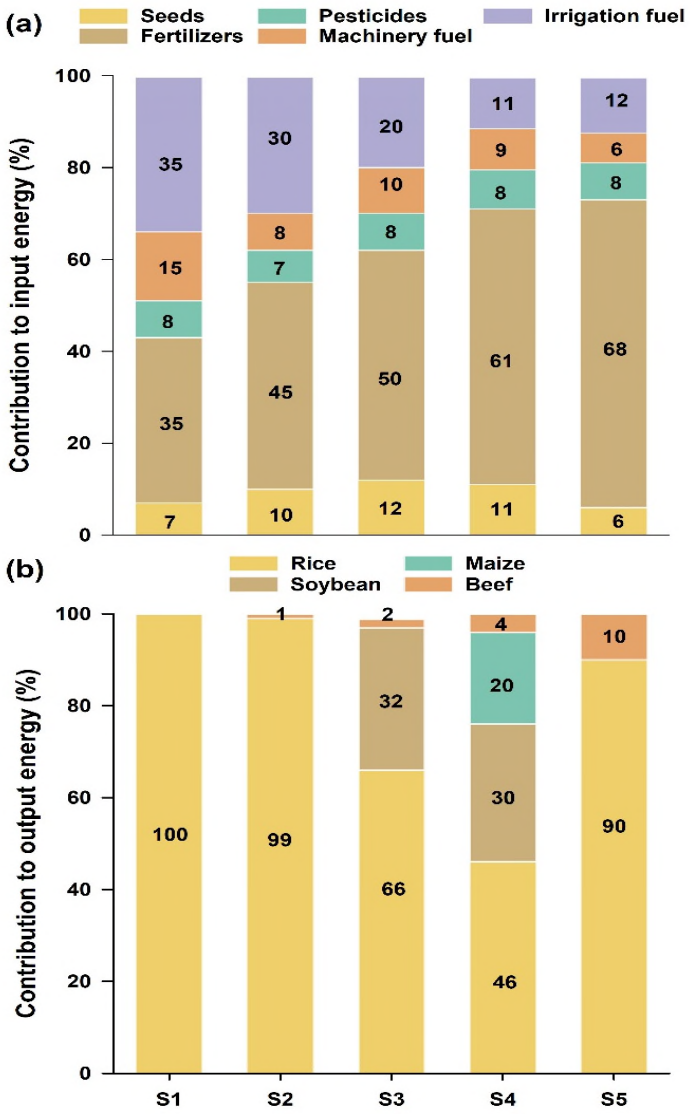


Fig. 3. Percentage distribution of input (a) and output (b) energy among the main energy categories in different rice-based production systems in southern Brazil.

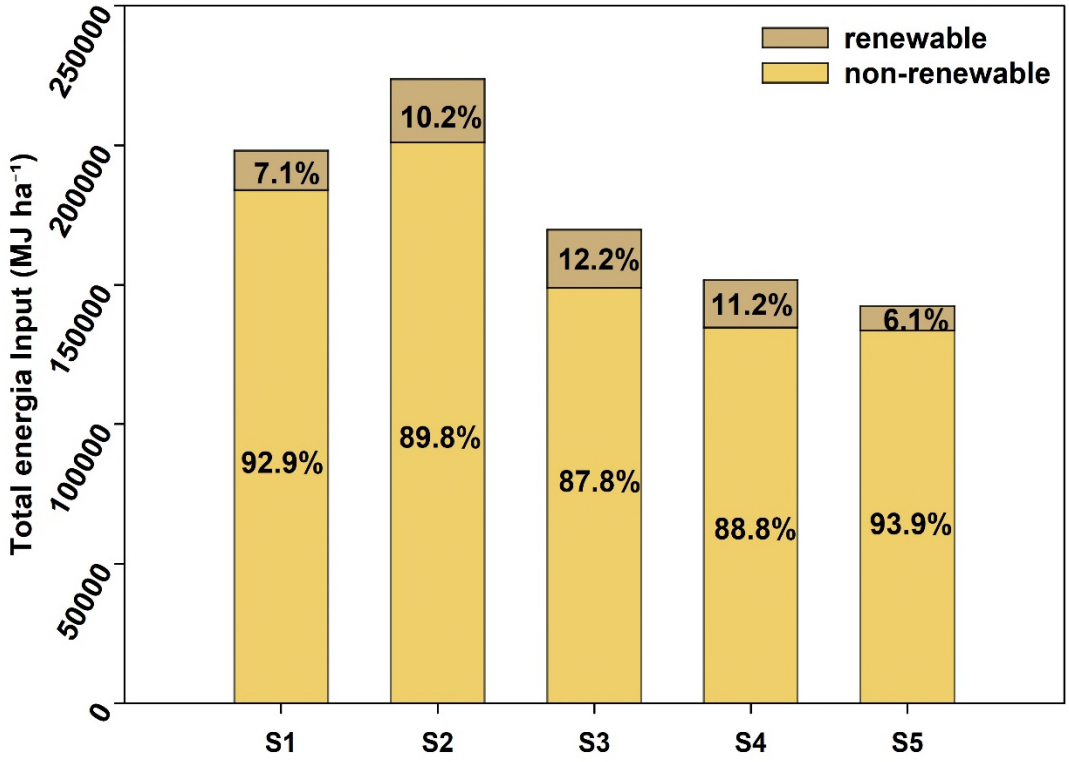


Fig. 4. Distribution of total energy input between renewable and non-renewable sources in different rice-based production systems in southern Brazil.

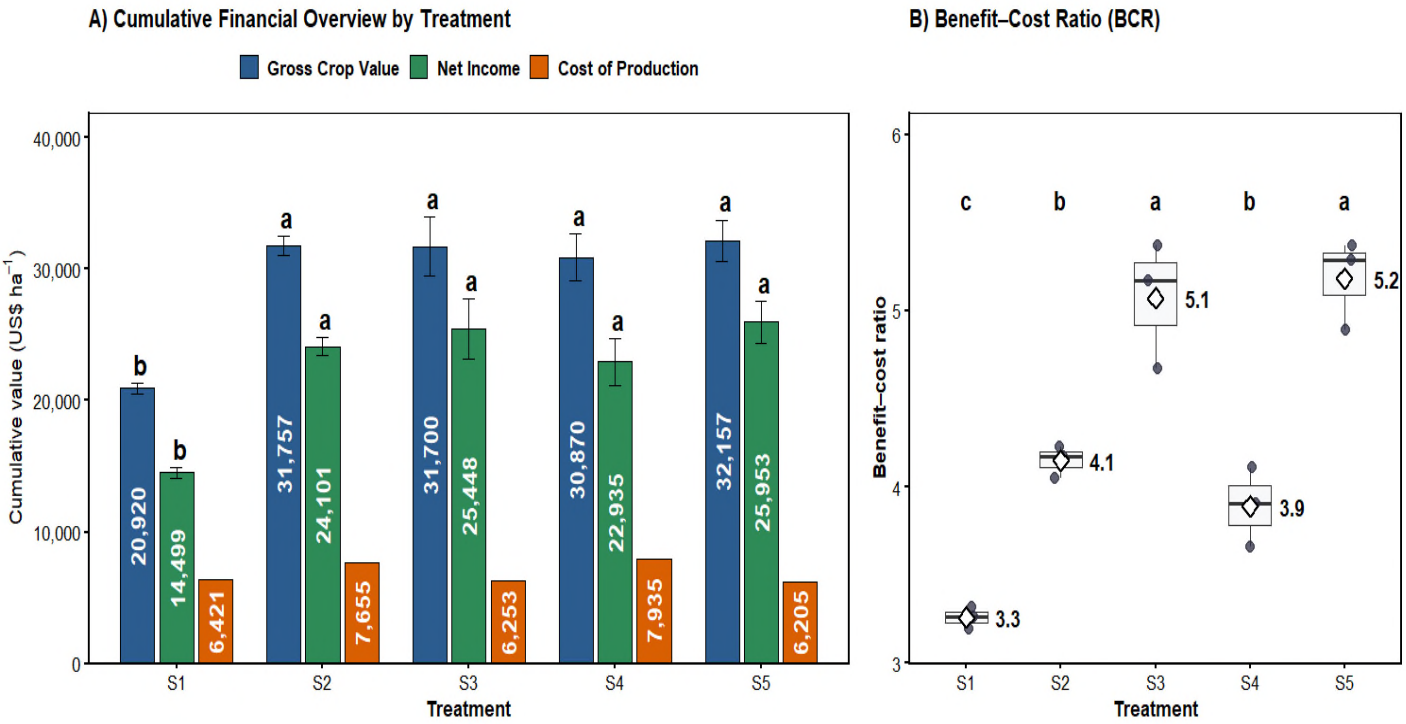


Fig. 5. Economic indicators of five rice-based production systems under different crop sequences and management strategies. (A) Cumulative GR, NR, and TC (US$ ha^{-1}). Values inside the bars represent treatment means, and error bars indicate the standard deviation (SD; n = 3). Different lowercase letters indicate significant differences among systems according to Tukey's test ($p < 0.05$). TC is presented without error bars because production costs were identical across replicates within each system. (B) B:C for each production system. Diamonds (◊) indicate treatment means (n = 3), horizontal lines within boxes represent the median, and different lowercase letters indicate significant differences according to Tukey's test ($p < 0.05$).

Table 1. Energy coefficients and calorific values of the inputs and outputs considered in the energy analysis of the rice production systems.

Category	Item (unit)	Value	Type	Reference
		Energy inputs (EI)		
Seeds	Rice (MJ kg^{-1})	17.60	Energy coefficient	Macedo et al. (2021)
	Soybean (MJ kg^{-1})	23.50		Macedo et al. (2021)
	Maize (MJ kg^{-1})	14.70		Pimentel & Pimentel (2008)
	Sudangrass (MJ kg^{-1})	16.70		*
	Forage legume (MJ kg^{-1})	17.20		Muhammad et al. (2014)
	Forage grass (MJ kg^{-1})	36.10		Fuksa et al. (2013)
Fertilizers	Nitrogen (MJ kg^{-1})	51.50		Hill et al. (2006)
	Phosphorus (MJ kg^{-1})	9.20		Hill et al. (2006)
	Potassium (MJ kg^{-1})	5.96		Hill et al. (2006)
Fuel	Diesel oil (MJ L^{-1})	43.99		Nagy (1999)
Pesticides	Herbicides (MJ kg^{-1} a.i.)	303.80		Pimentel & Pimentel (2007)
	Insecticides (MJ kg^{-1} a.i.)	418.40		Pimentel & Pimentel (2007)
	Fungicides (MJ kg^{-1} a.i.)	115.00		Pishgar-Komleh et al. (2011)
		Energy outputs (EO)		
Grains	Rice (MJ kg^{-1})	15.2	Calorific value	Pimentel & Pimentel (2008)
	Soybean (MJ kg^{-1})	23.6		**
	Maize (MJ kg^{-1})	14.7		Pimentel & Pimentel (2008)
Animal product	Beef (MJ kg^{-1})	9.3		Restle et al. (2001)

a.i.: active ingredient. Values in brackets are to be confirmed by the authors.; *Grass biomass was assigned an energy coefficient of 16.7 MJ kg^{-1} based on reported calorific values for forage grasses (Santiago et al., 2016; Said et al., 2019).; ** the soybean grain value (23.6 MJ kg^{-1} DM) was obtained from the INRA-CIRAD-AFZ feed tables (AFZ, 2017).

Table 2. Cumulative energy input (EI), energy output (EO), net energy (NE), Energy Output-to-Nutrient Input Ratio (EONIR), energy return on investment (EROI), energy productivity (EP), and specific energy (SE) of five rice-based production systems evaluated over an eight-year period in southern Brazil.

(A) Energy balance indicators

Sistemas	EI* (MJ ha^{-1})	EO (MJ ha^{-1})	EONIR (MJ kg^{-1} nutrient)	EROI (MJ MJ^{-1})
S1	198,091.5	1,177,746.3 ± 22,098.5 a	524.73 ± 9.85 a	5.9 ± 0.1 a
S2	223,787.9	1,127,649.6 ± 35,870.8 a	335.81 ± 10.68 b	5.0 ± 0.2 bc
S3	169,731.1	952,410.5 ± 105,549.1 b	309.49 ± 34.30 b	5.6 ± 0.6 ab
S4	151,739.6	672,193.2 ± 30,986.7 c	205.12 ± 9.46 c	4.4 ± 0.2 c
S5	142,325.1	361,608.3 ± 7,898.9 d	111.64 ± 2.44 d	2.5 ± 0.1 d

(B) Derived energy indicators

Sistemas	NE (MJ ha^{-1})	EP (kg MJ^{-1})	SE (MJ kg^{-1})
S1	979,654.8 ± 22,098.5 a	0.391 ± 0.007 c	2.557 ± 0.048 a
S2	903,861.7 ± 35,870.8 ab	0.526 ± 0.012 b	1.903 ± 0.043 b
S3	782,679.4 ± 105,549.1 b	0.692 ± 0.049 ab	1.451 ± 0.106 c
S4	520,453.6 ± 30,986.7 c	0.753 ± 0.043 ab	1.330 ± 0.077 c
S5	219,283.2 ± 7,898.9 d	0.837 ± 0.041 a	1.197 ± 0.060 c

Values are presented as means ± standard deviation (n = 3). Different lowercase letters within a column indicate significant differences among production systems according to Tukey's test ($p < 0.05$). * EI was identical among replicates within each production system because input quantities were defined at the system level; therefore, no standard deviation was calculated.

Table 3. Market prices used for the calculation of rice equivalent yield (REY) and rice equivalent yield by product category in five rice-based production systems evaluated over an eight-year period in southern Brazil.

A. Market prices used for REY calculation

Product	Commercial unit	Price (R$)	Price (US$)	Source
Paddy rice	kg	1.36	0.27	CONAB (Jul., 2026)
Soybean	kg	1.91	0.38	
Maize	kg	1.06	0.21	
Beef	kg carcass weight	36	7.1	

B. Cumulative rice equivalent yield by product category over the entire experimental period

Production system	Rice	Soybean	Maize	Beef	Cumulative REY
	.....kg ha^{-1}.....				
S1	77,483 ± 1,454	–	–	–	77,483 ± 1,454 b
S2	73,153 ± 2,395	–	–	44,465 ± 2,914	117,618 ± 2,625 a
S3	41,582 ± 4,795	17,961 ± 1,993	–	57,866 ± 1,890	117,409 ± 8,332 a
S4	20,355 ± 1,843	12,073 ± 263	7,130 ± 282	74,775 ± 5,438	114,333 ± 6,577 a
S5	21,520 ± 571	–	–	97,582 ± 6,092	119,101 ± 5,846 a