Crop and Environment 4 (2025) 256–262

Contents lists available at ScienceDirect

Crop and Environment

journal homepage: www.journals.elsevier.com/crop-and-environment

Review

Rice-based cropping systems in Brazil: Irrigated and rainfed

Giovana Ghisleni Ribas [a,*], Alexandre Bryan Heinemann [b], Luís Fernando Stone [b], Adriano Pereira de Castro [b], Nereu Augusto Streck [c], Alberto Baêta dos Santos [b], Michel Rocha da Silva [d], Silvio Steinmetz [e], Camille Flores Soares [c], Alencar Junior Zanon [c]

[a] Universidade de São Paulo, São Paulo, SP, Brazil
[b] Embrapa Arroz e Feijão, Santo Antônio de Goiás, GO, Brazil
[c] Universidade Federal de Santa Maria, Santa Maria, RS, Brazil
[d] CropsTeam, Santa Maria, RS, Brazil
[e] Embrapa Clima Temperado, Pelotas, RS, Brazil

ARTICLE INFO

Keywords:
Brazil
Cropping system
Crop management
Irrigated rice
Rainfed rice
Soybean

ABSTRACT

Brazil, a major global rice producer outside Asia, has two key rice-growing regions: subtropical lowlands, where irrigated rice accounts for 78% of national production (1.1 Mha), and tropical uplands, covering 0.31 Mha of rainfed rice. This review provides a comprehensive analysis of rice-based cropping systems in Brazil, discussing agronomic management, sustainability challenges, and potential improvements. The integration of rice, soybean, and pasture systems has enhanced land-use efficiency, soil health, and productivity. Irrigation practices, soil fertility management, and pest control strategies play a crucial role in maximizing yield. Additionally, climate-smart agriculture and no-till adoption are emerging as key strategies for mitigating environmental impacts and improving resilience. Despite advancements, challenges such as climate variability, weed resistance, and water-use efficiency remain critical. This review highlights the importance of continued research and innovation in sustainable rice-based systems.

1. Introduction

Brazil is the largest rice producer outside Asia, with an estimated 11 MMT for the 2024/2025 season (CONAB, 2025). Unlike small-scale, labor-intensive systems in tropical Asia, Brazilian rice farming is highly mechanized. Farms range from 5 to 30,000 ha, averaging 200 ha per household (IRGA, 2024). Rice production is concentrated in two main regions (Fig. 1A, B). The South dominates with 1.1 Mha of irrigated lowland rice, accounting for 78% of national output. In the Cerrado, rice is grown under both rainfed (0.31 Mha) and irrigated (0.1 Mha) systems (Embrapa Arroz e Feijão, 2023). This review explores Brazil's key rice-producing regions, their cropping systems, and strategies to enhance productivity, sustainability, and efficiency.

2. Rice production systems in Brazil

2.1. Subtropical lowlands (Southern Brazil)

Irrigated rice in Southern Brazil is mainly cultivated between 28° S and 33° S, with Rio Grande do Sul (69%) and Santa Catarina (9%) as the main producing states (Fig. 1) (IRGA, 2024). Due to the region's subtropical climate and hydromorphic soils, rice is grown in a single annual cycle, typically planted in spring (September-October-November) and harvested in summer-autumn (February-March-April). During the winter, fields are left fallow (System 1, Fig. 2). Incorporating pasture (System 2, Fig. 2) or cover crops such as ryegrass (*Lolium multiflorum* Lam.) in the winter has improved soil health and prepared fields for subsequent soybean or rice planting (Nascente et al., 2013).

Historically, irrigated rice has been cultivated as a monoculture. However, increasing weed pressure and rising production costs led to the adoption of crop rotations, particularly with soybean, which experienced widespread adoption around 2010 due to its economic and agronomic benefits (Ribas et al., 2021b; Fig. 1D). Today, approximately 50% of irrigated rice fields in Rio Grande do Sul follows a rice-soybean rotation, reducing production costs by 30% and increasing rice yields by 20% compared to continuous rice cultivation (IRGA, 2023) (System 3, Fig. 2).

Emerging alternative cropping systems, such as rice-maize and rice-wheat, are also being explored for their potential to enhance productivity and improve weed control effciency. The rice-maize system

* Corresponding author.
E-mail address: gribas@usp.br (G.G. Ribas).

https://doi.org/10.1016/j.crope.2025.07.002
Received 11 January 2025; Received in revised form 12 July 2025; Accepted 13 July 2025

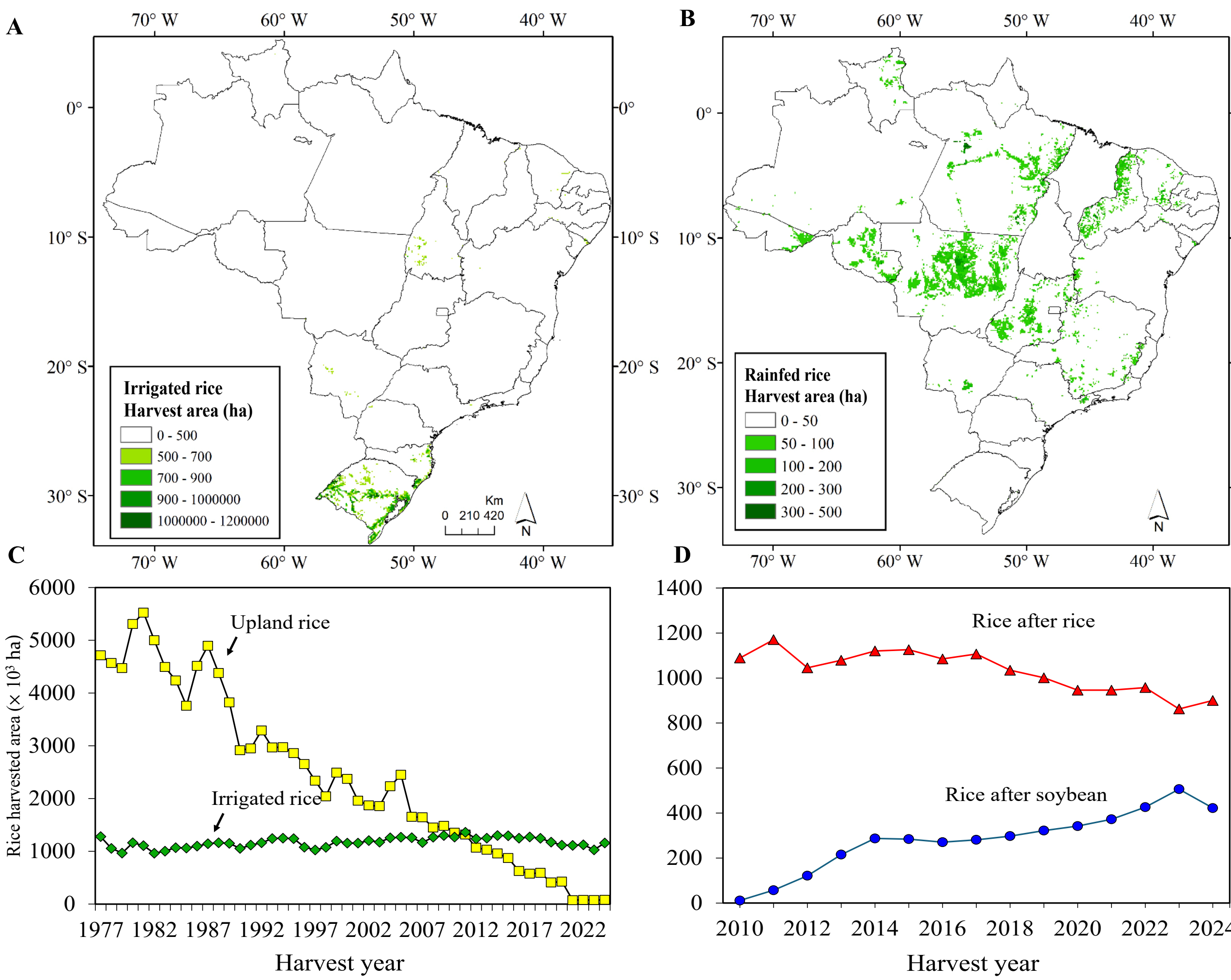

Fig. 1. Map of Brazil showing the location of the subtropical (A) and tropical (B) environments, representing irrigated and rainfed rice systems, respectively. Panel C shows harvested area trend for upland rainfed rice and lowland irrigated rice in Brazil and panel D shows harvested area trend in southern Brazil for rice after rice and rice after soybean. Source: Ribas et al. (2021a); Global Yield Gap Atlas (GYGA) (https://www.yieldgap.org/).

follows a spring/summer cycle, while rice-wheat allows for two annual crops. Although these systems currently account for less than 5% of rice fields in southern Brazil, they show promising yields, with maize producing 4–10 Mg ha^{-1} and wheat 2–5 Mg ha^{-1} (IRGA, 2023). However, broader adoption remains limited due to equipment requirements and logistical challenges.

2.2. *Tropical rice (Northern and Central Brazil)*

Rainfed rice is primarily grown in Mato Grosso (26.6%), Maranhão (21.1%), Rondônia (16.2%), Pará (14.5%), and Tocantins (8.8%) (Embrapa Arroz e Feijão, 2023) (Fig. 1B). Although rainfed rice accounts for only 7% of Brazil's total rice output, it plays a crucial role in food security, especially in the central-west, north, and northeast regions. Rainfed rice production has significantly declined, particularly in central Brazil (Fig. 1C). Between 1986 and 2022, the area planted with rainfed rice decreased by 93% (from 4.5 Mha to 0.3 Mha). Despite this decline, rice yield has more than doubled, increasing from 1.1 to 2.6 Mg ha^{-1} (CONAB, 2025), owing to improvements in water retention, the development of high-yielding cultivars, and better farming practices (Heinemann et al., 2015b; Pinheiro et al., 2006).

In Tocantins, the tropical climate allows two cropping seasons per year: irrigated rice during the rainy season and mainly soybeans during the dry season (Heinemann et al., 2015a). For example, irrigated rice is grown from October to March, followed by soybean from April to September in 77% of the rice area. The dry season conditions, characterized by low humidity and cool nights, are favorable for high-quality soybean seed production. Other crops, such as sorghum, cotton, and watermelon, also follow rice cultivation, benefiting from the region's favorable climate.

Sprinkler-irrigated rice is expanding in central Brazil, offering high productivity and superior grain quality while enabling multiple cropping cycles: early (August/September), regular (November), and off-season (January/February). While early plantings require more irrigation, later crops benefit from natural rainfall, enhancing both cost-effectiveness and sustainability.

3. Agronomic management practices

3.1. *Fertility*

Fertility management practices in irrigated rice fields in Brazil are designed to optimize crop growth through structured fertilization.

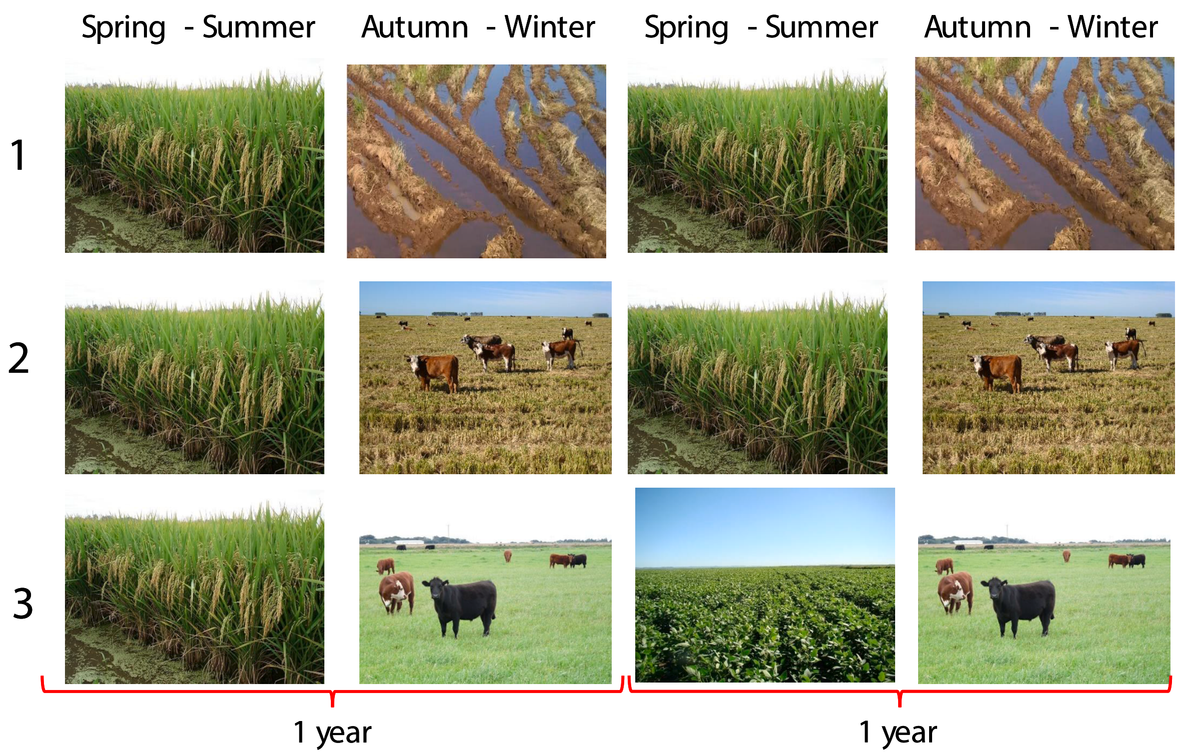

Fig. 2. The three main rice-based cropping systems in the southern subtropics of Brazil: System 1, Rice-fallow sequence; System 2, Rice-pasture integration sequence; and System 3, Rice-livestock-soybean integration sequence. Source: Meus et al. (2020).

Farmers typically apply 100% phosphorus (P), 70% potassium (K), and 10% nitrogen (N) at sowing, using a planter. The remaining 30% of K is applied at V_3 stage - when the third leaf is fully expanded, along with 60% N, before irrigation begins in the field. The final 30% N is applied during the R_0 (panicle initiation) and R_1 (beginning of panicle differentiation) stages. Fertilization rates are generally about 130 kg N ha^{-1}, 30 kg P ha^{-1}, and 60 kg K ha^{-1}, with minimal application of other nutrients.

Most rainfed rice is cultivated on red and yellow-red Latosols, which are deficient in essential nutrients such as N, P, and K. These soils require strategic fertilization, especially for N and P fertilization, which must be based on soil tests. Zinc deficiencies are commonly managed through additional fertilization, particularly in regions with high soil pH. They also have high aluminum content ($\geq$ 4 cmol kg^{-1}), low cation exchange capacity, and a strong tendency to fix P. Although these soils contain moderate organic matter, their acidic pH (ranging from 4.0 to 5.5) and high levels of iron and aluminum oxides contribute to low microbial activity. Iron oxide levels range from 13.1 to 247.8 g kg^{-1}, and aluminum oxide levels range from 41.4 to 410.3 g kg^{-1}, depending on soil texture, as reported by Vendrame et al. (2011).

Iron toxicity in rice areas is a common issue in tropical and subtropical regions, causing significant yield losses (12%–100%) due to high iron concentrations in the soil solution (Sahrawat, 2010). Strategies to manage this problem include selecting tolerant cultivars and enhancing soil and nutrient management practices.

3.2. *Diversity in cultivar selection*

In Brazil, rice breeding programs are primarily driven by public institutions (such as IRGA, Instituto Rio Grandense do Arroz; Embrapa, Empresa brasileira de pesquisa agropecuária; Epagri, Empresa de pesquisa agropecuária e extensão rural de santa catarina) and private companies (including BASF, RiceTec, and Oryza), with over 18 years of experience in the field (Embrapa Arroz e Feijão, 2023; IRGA, 2023). Rice cultivation in Brazil is dominated by Clearfield (CL) cultivars (70%), followed by conventional cultivars (25%) and hybrids (5%), with Provisia hybrid technology beginning to gain ground. Despite the increasing use of CL cultivars, the repeated use of this technology has led to the emergence of resistant weeds, making rice cultivation increasingly unfeasible in some areas (Ribas et al., 2021b).

3.3. *Sowing date and environmental limitations*

Irrigated rice has a yield potential (Yp) of 14.8 Mg ha^{-1}, while rainfed rice reaches up to 9.0 Mg ha^{-1} (GYGA, 2025). However, irrigated rice achieves 51% of its Yp, compared to just 29% for rainfed rice (Fig. 3), indicating significant room for improvement for rainfed rice through sustainable intensification.

In irrigated rice, solar radiation plays a crucial role in determining yield. Delays in sowing can lead to substantial losses, as observed in Rio Grande do Sul, where each day of delayed sowing results in a loss of 42 kg ha^{-1} (Fig. 5A). A detailed analysis of the Yp for the IRGA 424 RI cultivar in Rio Grande do Sul reveals yield reductions of 30 kg ha^{-1} d^{-1} from September 1st to November 13th, 80 kg ha^{-1} d^{-1} from November 14th to December 21st, and a significant 290 kg ha^{-1} d^{-1} after December 21st (Duarte Júnior et al., 2021). Early sowing maximizes Yp, while delayed sowing requires reduced inputs to maintain profitability.

In Tocantins, the ideal sowing window for irrigated rice spans from October to mid-November. Delays beyond this period reduce the Yp due to decreased solar radiation during grain filling and increased air temperatures. In lowland and irrigated rice, increased yields of irrigated rice often lead to excess straw, complicating tillage and sowing. The knife-roller method (Fig. 4), which incorporates straw using a steel drum with sharp knives, facilitates early soil preparation. This approach saves time, labor, and fuel, while maintaining both yields and soil quality (Santos et al., 2022).

For tropical rainfed rice, the main sowing period is from September to November, with water deficiency being the primary environmental constraint on yield. Rainfall distribution and soil water-holding capacity play crucial roles in determining yield stability. Early sowing is

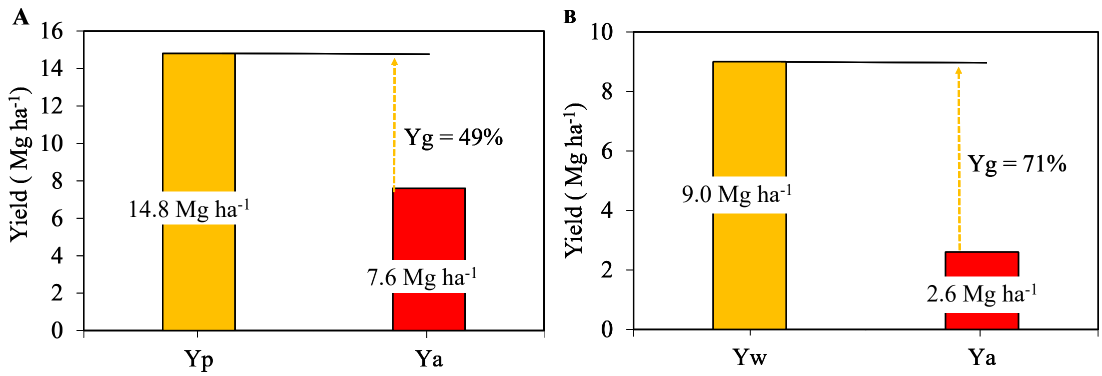

Fig. 3. Yield potential (Yp), water-limited yield potential (Yw), actual yield (Ya), and yield gap (Yg) for (A) irrigated rice and (B) rainfed rice in Brazil. Source: Global Yield Gap Atlas (GYGA) (https://www.yieldgap.org/).

Fig. 4. Knife-roller (A) and management of irrigated rice straw with a knife-roller (B). Source: Alberto Baêta dos Santos.

recommended in regions with irregular precipitation to take advantage of the soil moisture stored from previous rains. Additionally, selecting drought-tolerant cultivars and implementing conservation tillage practices, such as no-till system and cover cropping, can enhance water-use efficiency and mitigate the impacts of dry spells.

3.4. Irrigation methods and water-use efficiency

Irrigated rice cultivation in Brazil relies on flooded conditions for water supply and weed control. In regions such as Rio Grande do Sul and Tocantins, direct seeding is followed by shallow flooding from 30 to 45 d after sowing, extending to 15 d before harvest. In Santa Catarina, low water levels are initially used for seedling emergence, with drainage applied to manage issues such as zinc deficiency and pest outbreaks.

Water-use efficiency is a critical factor in enhancing the sustainability of rice production. In South America, the average water-use efficiency is 1.4 m^3 per kg grain, exceeding global benchmarks (Bouman et al., 2007). Efforts to optimize irrigation management have led to higher yields and reduced water consumption. In Rio Grande do Sul, delaying irrigation after the V_3 stage results in a daily yield loss of about 180 kg ha^{-1} (Fig. 5B). Early irrigation, combined with N topdressing and disease-resistant cultivars, enhances production efficiency (Ribas et al., 2021a).

Alternative irrigation strategies, such as intermittent wetting and drying, direct dry seeding, and sprinkler irrigation, can improve water-use efficiency by 15–346% and save up to 56% of water compared to continuous flooding (de Avila et al., 2015). In tropical Brazil, Santos et al. (2021) demonstrated that maintaining saturated soil conditions can increase grain yield by 16% while reducing water use by up to 82%.

Supplemental irrigation plays a crucial role in managing water stress in rainfed rice systems. Studies indicated that sprinkler irrigation can improve yields by 30%–177% (Stone and Silveira, 2004). Irrigation during critical growth stages prevents grain quality issues, such as chalkiness. Additionally, effective management of sprinkler irrigation systems involves maintaining soil water tension below 25 kPa at 15 cm depth to balance productivity and cost (Stone and Silveira, 2004).

Finally, alternative irrigation systems require careful weed management to prevent extended weed emergence. However, supplemental irrigation not only supports higher rice yields, but also enables equipment use during the fall-winter season for other crops, such as beans, wheat, and vegetables, enhancing overall farm profitability.

3.5. Pests and disease management

High air humidity in subtropical rice regions poses challenges for disease control (Silva et al., 2009). Fungicide efficacy varies depending on cultivar choice, sowing date, and seasonal weather, all of which are critical for optimizing yield-focused management (Fig. 5C).

Rice blast (*Magnaporthe oryzae*) is the most damaging disease in Brazil, causing significant yield losses (Meus et al., 2020). Management strategies include the use of disease-free seeds, resistant cultivars, and timely fungicide applications. While no fully resistant cultivars exist, seed and foliar fungicide treatments, crop rotation, and optimized N use help mitigate disease severity, with early planting reducing late-season risk (Ogoshi et al., 2018, 2020).

Rice crops are also susceptible to major insect pests, including the fall armyworm (*Spodoptera frugiperda*), which reduces photosynthetic capacity, and the rice water weevil/root borer (*Oryzophagus oryzae*), whose larvae damage roots, leading to yield losses up to 10% (Fritz et al., 2013). Other key pests include the stem stink bug (*Tibraca limbativentris*), which weakens plants and causes lodging, and rice stink bugs (*Oebalus poecilus, O. ypsilongriseus*), which reduce grain quality by feeding on developing panicles. Additionally, panicle caterpillars

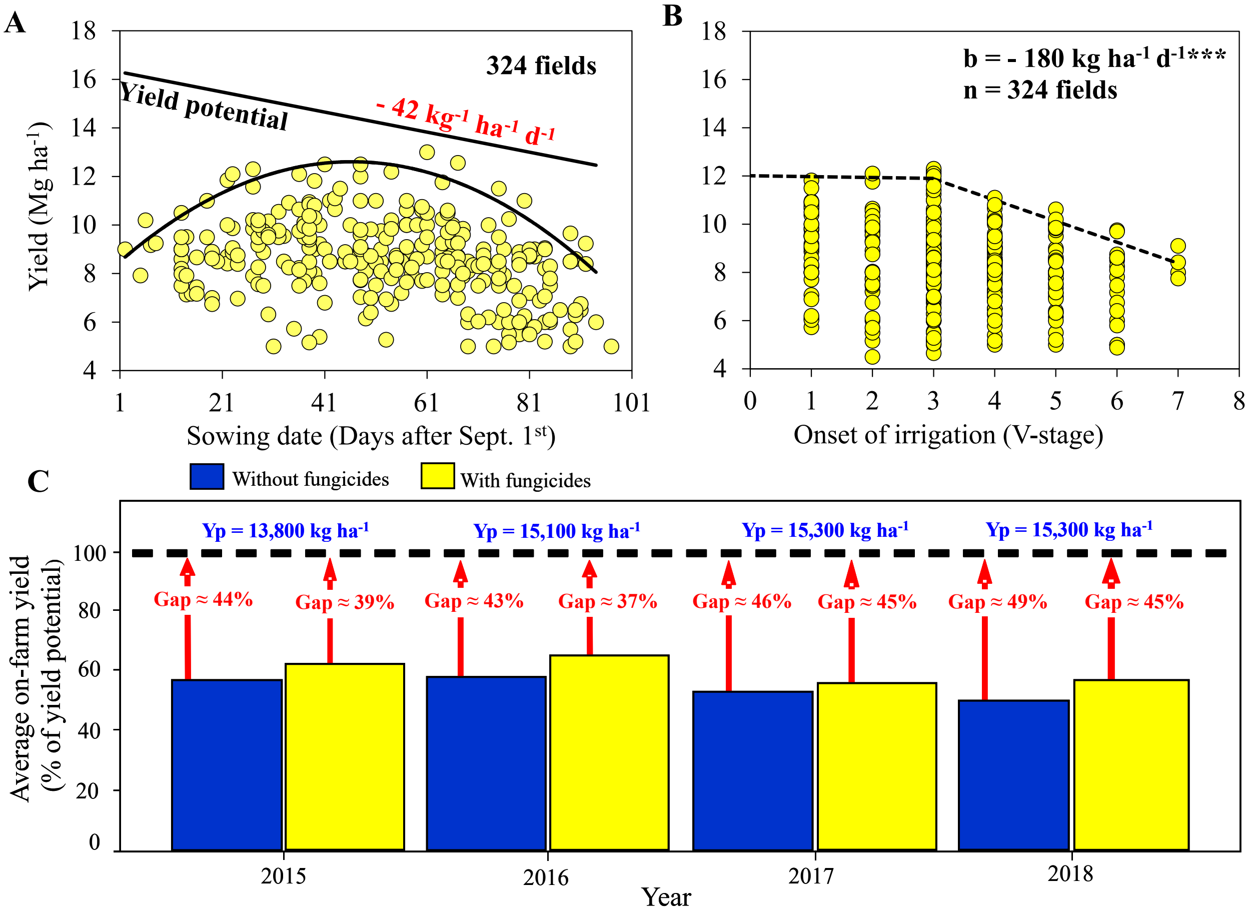

Fig. 5. The response of grain yield to sowing date (A) and onset of irrigation (B) and irrigated rice yield with and without fungicide application in the Rio Grande do Sul region (C). Boundary functions are shown in (A) and (B). Data were collected from 324 fields over five harvest years (2016–2020). V-stages correspond to key development phases: tillering around V_3–V_7, panicle initiation typically around V_8–V_{10}, and flowering near V_{14}–V_{16}. *** indicate significant differences at $P < 0.001$. Source: Meus et al. (2020) and Ribas et al. (2021a).

(*Pseudaletia* spp.) hinder grain formation, while snails (*Physa acuta, Biomphalaria* spp.) damage seedlings in flooded systems (Meus et al., 2020). Rice fields typically receive one to two insecticide applications per season, depending on pest pressure and environmental conditions. Integrated pest management strategies, such as adjusting sowing dates, using biological control, and selecting resistant cultivars, help reduce chemical reliance while maintaining productivity.

4. Sustainability and climate adaptation strategies

4.1. Sustainability and environmental impact in rice production

Rice paddies are significant sources of CH_4 and N_2O, two potent greenhouse gases that contribute to global warming (Yuan et al., 2021). However, environmental impact is closely linked to yield efficiency (Ratio of actual yield to Yp) and overall resource management.

An analysis of irrigated rice fields in southern Brazil during the 2021/2022 and 2022/2023 growing seasons revealed that higher yield efficiency not only increased the return on investment but also helped reduce greenhouse gas emissions (Fig. 6). However, achieving these benefits requires optimized production costs, which means identifying and addressing the key factors limiting productivity in rice fields.

A study led by the FieldCrops Team in Brazil highlighted essential management practices to enhance sustainability, including optimizing N and P use, adjusting sowing dates, and improving irrigation timing (Fig. 7). These strategies increase resource efficiency, improve yields, and reduce the environmental footprint of rice production.

4.2. Challenges and opportunities in rice-based production systems

Rising temperatures from climate change could extend the rice sowing window, potentially increasing productivity in cold regions such as southern Rio Grande do Sul. On the other hand, drier areas, such as western Rio Grande do Sul, may experience reduced yields due to climate stress. This will require breeding programs focused on developing resistant rice cultivars to ensure resilience in the face of higher temperatures and water scarcity. Climate models predict potential yield losses in central Brazil, making supplemental irrigation a crucial strategy for adapting to these changes.

Rice production also faces challenges beyond climate change, including weed resistance, aggravated by the overuse of CL rice cultivars, and disruptions caused by extreme weather events such as El Niño and La Niña, which affect rainfall patterns and crop growth cycles. Lowland areas prone to excess water present challenges for rainfed crops, such as soybean. Effective drainage systems are crucial for mitigating waterlogging and maintaining optimal soil conditions. Specialized mechanization is also needed to manage water and retain soil moisture, ensuring crop survival and high yields, especially in areas transitioning from irrigation to rainfed systems.

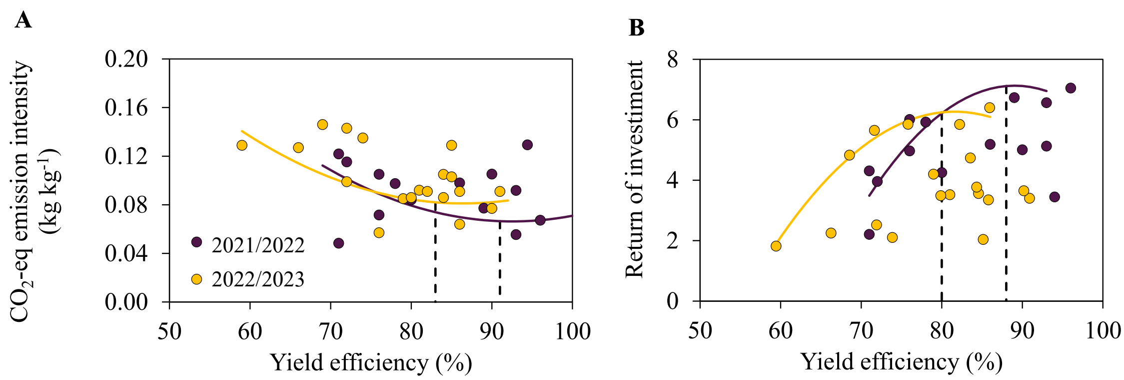

Fig. 6. Influence of yield efficiency (Ratio of actual yield to yield potential, %) on CO_2-eq emission intensity (A) and return on investment (B) in irrigated rice fields in Latin America during the 2021/2022 and 2022/2023 seasons. Source: FieldCrops team (https://www.equipefieldcrops.com/).

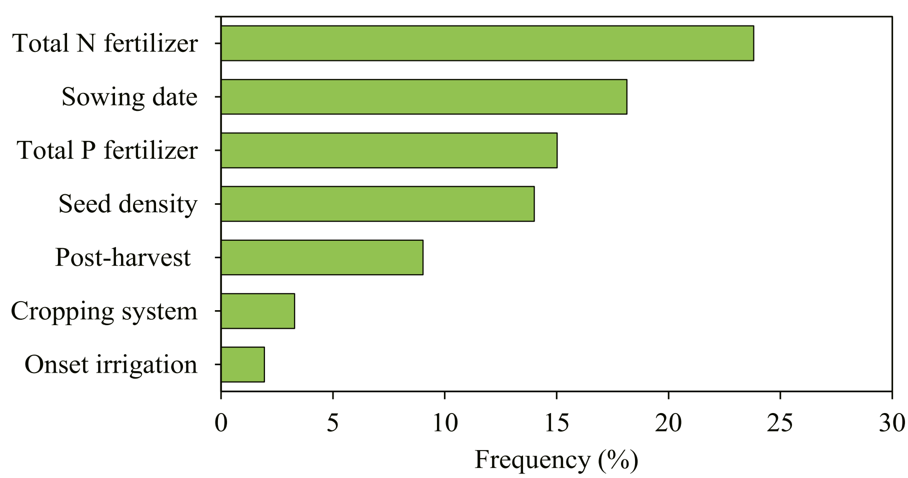

Fig. 7. Importance degree of management practices in irrigated rice fields in Latin America, related to the sustainability index during the 2021/2022 and 2022/2023 seasons. Source: FieldCrops team (https://www.equipefieldcrops.com/).

Knowledge transfer to farmers remains a major challenge, particularly in Brazil, where initiatives aimed at bridging the gap between research and practice are relatively rare and, when implemented, are seldom disseminated on a broader scale. There is a critical need to establish robust and structured outreach programs that effectively translate and deliver the knowledge generated within universities and research stations to agricultural producers.

5. Conclusions

Brazil's rice-based cropping systems have evolved significantly, with increasing adoption of crop rotations, irrigation advancements, and climate-smart strategies. However, challenges such as climate variability, water management, and weed resistance remain. Future research should focus on enhancing sustainability, improving production efficiency, and fostering innovation in rice-based systems to ensure long-term food security.

Abbreviations

N nitrogen
P phosphorus
K potassium
CL Clearfield
Yp yield potential

Authors' contributions

Giovana Ghisleni Ribas: Writing – review & editing and Writing – original draft; Alexandre Bryan Heinemann: Writing – review &editing and Writing – original draft; Luís Fernando Stone: Writing – review & editing, Writing – original draft, and Conceptualization; Adriano Pereira de Castro: Writing – review & editing and Writing – original draft; Nereu Augusto Streck: Writing – review & editing, Writing – original draft, Visualization, and Conceptualization; Alberto Baêta dos Santos: Writing – review & editing, Writing – original draft, and Conceptualization; Silvio Steinmetz: Writing – review & editing and Writing – original draft; Michel Rocha da Silva: Writing – review & editing and Writing – original draft; Camille Flores Soares; Writing – review & editing and Writing – original draft; and Alencar Junior Zanon: Writing – review & editing, Writing – original draft, and Conceptualization.

Availability of data and materials

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Author Alencar Junior Zanon (Editorial Board member) was not involved in the journal's review nor decisions related to this manuscript.

Acknowledgements

We thank the FieldCrops team at the Federal University of Santa Maria (UFSM), the Department of Crop Science at the University of São Paulo (USP-ESALQ), the São Paulo Research Foundation (FAPESP, Project No. 2024/01631–9), the Global Engagement Office at the Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln (UNL), and the Crops Team – Consulting, Research, and Development for their valuable support of this research.

References

Bouman, B.A.M., Lampayan, R.M., Tuong, T.P., 2007. Water Management in Irrigated Rice: Coping with Water Scarcity. International Rice Research Institute, Los Baños, Philippines.

Companhia Nacional de Abastecimento (CONAB), 2025. Séries históricas das safras. Available at: https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras/itemlist/category/900-arroz (in Portuguese).

de Avila, L.A., Martini, L.F.D., Mezzomo, R.F., Refatti, J.P., Campos, R., Cezimbra, D.M., Machado, S.L.O., Massey, J.H., Carlesso, R., Marchesan, E., 2015. Rice water use efficiency and yield under continuous and intermittent irrigation. Agron. J. 107, 442–448. https://doi.org/10.2134/agronj14.0080.

Duarte Júnior, A.J., Streck, N.A., Zanon, A.J., Ribas, G.G., Silva, M.R., Cera, J.C., Pilecco, I.B., Nascimento, M.F., Puntel, S., 2021. Rice yield potential as a function of sowing date in southern Brazil. Agron. J. 206, 1–10. https://doi.org/10.1002/agj2.20610.

Embrapa Arroz e Feijão, 2023. Dados conjunturais da produção de arroz (*Oryza sativa* L.) no Brasil (1986 a 2022): área, produção e rendimento. Santo Antônio de Goiás, Brazil. Available at: http://www.cnpaf.embrapa.br/socioeconomia/index (in Portuguese).

Fritz, L.L., Heinrichs, E.A., Machado, V., Andreis, T.F., Pandolfo, M., de Salles, S.M., 2013. Impact of lambdacyhalothrin on arthropod natural enemy populations in irrigated rice fields in southern Brazil. Int. J. Trop. Insect Sci. 33, 178–187. https://doi.org/10.1017/S1742758413000192.

GYGA, 2025. Global Yield Gap Atlas. https://www.yieldgap.org/ (Accessed March 2025).

Heinemann, A.B., Barrios-Perez, C., Ramirez-Villegas, J., Arango-Londoño, D., Bonilla-Findji, O., Jarvis, A., 2015a. Environmental characterization and drought profile for upland rice in Brazil. Asp. Appl. Biol. 124, 91–92.

Heinemann, A.B., Barrios-Perez, C., Ramirez-Villegas, J., Arango-Londoño, D., Bonilla-Findji, O., Medeiros, J.C., Jarvis, A., 2015b. Variation and impact of drought-stress patterns across upland rice target population of environments in Brazil. J. Exp. Bot. 66, 3625–3638. https://doi.org/10.1093/jxb/erv126.

Instituto Rio Grandense do Arroz (IRGA), 2023. Soybean Harvest Area. Available at: https://irga.rs.gov.br/soja (in Portuguese).

Instituto Rio Grandense do Arroz (IRGA), 2024. Rice Yield. Available at: https://irga.rs.gov.br/historicos (in Portuguese).

Meus, L.D., Silva, M.R., Ribas, G.G., Zanon, A.J., Rossato, I.G., Fogliato, V., Pilecco, I.B., Ribeiro, B.S.M.R., Souza, P.M., Nascimento, M.F., Poersch, A.H., Duarte Júnior, A.J., Quintero, C.E., Garrido, G.C., Carmona, L.C., Streck, N.A., 2020. Ecophysiology of Rice for Reaching High Yield, first ed. FieldCrops Team, Rio Grande do Sul, Brazil.

Nascente, A.S., Crusciol, C.A.C., Cobucci, T., 2013. The no-tillage system and cover crops—alternatives to increase upland rice yields. Eur. J. Agron. 45, 124–131. https://doi.org/10.1016/j.eja.2012.09.004.

Ogoshi, C., Carlos, F.S., Ulguim, A.R., Zanon, A.J., Bittencourt, C.R.C., Almeida, R.D., 2018. Effectiveness of fungicides for rice blast control in lowland rice cropped in Brazil. Trop. Subtrop. Agroecosyst. 21, 505–511.

Ogoshi, C., Carlos, F.S., Waldow, D., Miranda, F.F., Reginato, J.L., Ulguim, A., 2020. Influence of blast on the nutrition and yield of irrigated rice in Southern Brazil. J. Soil Sci. Plant Nutr. 20, 1378–1386. https://doi.org/10.1007/s42729-020-00219-9.

Pinheiro, B. da S., Castro, E. da M. de, Guimarães, C.M., 2006. Sustainability and profitability of aerobic rice production in Brazil. Field Crops Res. 97, 34–42. https://doi.org/10.1016/j.fcr.2005.08.013.

Ribas, G.G., Streck, N.A., Ulguim, A. da R., Carlos, F.S., Alberto, C.M., de Souza, P.M., Barcellos, T., Puntel, S., Zanon, A.J., 2021a. Assessing factors related to yield gaps in flooded rice in southern Brazil. Agron. J. 113, 3341–3350. https://doi.org/10.1002/agj2.20754.

Ribas, G.G., Zanon, A.J., Streck, N.A., Pilecco, I.B., Souza, P.M., Heinemann, A.B., Grassini, P., 2021b. Assessing yield and economic impact of introducing soybean to the lowland rice system in southern Brazil. Agric. Syst. 188, 1–36. https://doi.org/10.1016/j.agsy.2020.103036.

Sahrawat, K.L., 2010. Reducing iron toxicity in lowland rice with tolerant genotypes and plant nutrition. In: Plant Stress, pp. 70–75. https://oar.icrisat.org/166/1/nset1.pdf.

Santos, A.B. dos, Heinemann, A.B., Silva, M.A.S. da, Stone, L.F., Pimenta, L.B., Santos, D., 2021. Manejo da irrigação na cultura do arroz irrigado e na eficiência do uso da água em várzeas tropicais. Agric. Environ. Sci. 7, e021002. https://doi.org/10.36725/agries.v7i2.5294.

Santos, A.B. dos, Silva, M.A.S. da, Stone, L.F., Heinemann, A.B., 2022. Management of rice straw in rice-soybean succession in tropical lowland. Rev. Ceres 69, 390–399. https://doi.org/10.1590/0034-737X202269040002.

Silva, D.R.O., Avila, L.A., Agostinetto, D., Dal Magro, T., Oliveira, E., Zanella, R., Noldin, J.A., 2009. Pesticides monitoring in surface water of rice production areas in Southern Brazil. Ciência Rural 39, 2383–2389 (in portuguese).

Stone, L.F., Silveira, P.M. da, 2004. Arroz irrigado por aspersão. Informe Agropecuário 25, 70-76. https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/926552/1/StoneIA2.pdf.

Vendrame, P.R.S., Eberhardt, D.N., Brito, O.R., Marchão, R.L., Quantin, C., Becquer, T., 2011. Formas de ferro e alumínio e suas relações com textura, mineralogia e carbono orgânico em Latossolos do Cerrado. Ciênc. Agrár, pp. 1657–1666 (in Portuguese).

Yuan, S., Linquist, B.A., Wilson, L.T., Cassman, K.G., Stuart, A.M., Pede, V., Saito, K., Agustiani, N., aristya, V.E., Krisnadi, L.Y., Zanon, A.J., Heinemann, A.B., Carracelas, G., Subash, N., Brahmanand, P.S., Li, T., Peng, S., Grassini, P., 2021. Sustainable intensification for a larger global rice bowl. Nat. Commun. 12, 7163. https://doi.org/10.1038/s41467-021-27424-z.