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REVIEW

Sustainability in sugarcane: a review in Brazil

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Abstract – Sugarcane cultivation in Brazil plays a central role in the national economy. However, the expansion of its cultivation raises environmental concerns, including deforestation, degradation and intensive use of water resources. This study aimed to conduct a systematic literature review to identify and analyze sustainable agricultural practices in sugarcane cultivation in Brazil, focusing on innovations that promote the sector's sustainability. The research involved a comprehensive literature survey using databases such as Scielo, Google Scholar, and Web of Science. After applying inclusion and exclusion criteria, articles published between 2004 and 2025 were selected. The findings indicate an increasing adoption of sustainable practices, such as mechanization, which reduces the need for burning and improves productive efficiency; the use of biological control to minimize the negative impacts of pesticides on agriculture and the environment; and soil management techniques that preserve soil properties and ensure the longevity of plantations, in addition to the application of reverse logistics, which reduces costs, generates energy and generates environmental gains. These findings underscore the importance of integrating sustainable methods to mitigate environmental impacts, promote the sector's economic and social sustainability, and contribute to the future of Brazilian agribusiness.

Keywords: Ethanol. Soil. Crops.

Sustentabilidade na cana-de-açúcar: uma revisão no Brasil

Resumo – A cultura da cana-de-açúcar no Brasil, desempenha um papel central na economia nacional. Contudo, a expansão do seu cultivo levanta preocupações ambientais, como desmatamento, degradação e uso intensivo de recursos hídricos. O objetivo desta pesquisa foi realizar uma revisão sistemática da literatura para identificar e analisar práticas agrícolas sustentáveis na cultura da cana-de-açúcar no Brasil, focando nas inovações que promovam a sustentabilidade do setor. A pesquisa consistiu em um levantamento bibliográfico abrangente, utilizando bases de dados como Scielo, Google Scholar e Web of Science. Após a aplicação de critérios de inclusão e exclusão, foram selecionados artigos publicados entre 2004 e 2025. Os resultados indicam uma crescente adoção de práticas sustentáveis, como a mecanização, que reduz a necessidade de queimadas e melhora a eficiência produtiva; o uso de controle biológico, que minimiza os impactos negativos dos pesticidas na agricultura e no meio ambiente; e técnicas de manejo do solo, que preservam suas propriedades e garantem a longevidade das plantações, além da aplicação da lógistica reversa, que reduz custos, gera energia e gera ganhos ambientais. Esses achados ressaltam a importância da integração de métodos sustentáveis para mitigar os impactos ambientais, promover a sustentabilidade econômica e social do setor e contribuir para o futuro do agronegócio brasileiro.

Palavras-chave: Etanol. Solo. Cultivos.

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Introduction

Sugarcane plays a central role in the global economy and agriculture, with Brazil being the world's largest producer (D'Alessandro; Cavichioli, 2024). Its versatility generates strategic products such as sugar and, notably, ethanol, which is considered one of the most efficient and sustainable biofuels in the world (Soares; Zukowski Junior, 2021). Furthermore, byproducts such as bagasse are crucial for bioenergy generation, optimizing the full utilization of the plant (Nocelli *et al.*, 2017).

Sugarcane, a plant of extreme economic and historical importance, plays a central role in word agriculture, especially in Brazil, where its production is deeply rooted in social, economic and environmental structures. Its versatility in the generation of various products, such as sugar, alcohol, biofuels and energy byproducts, makes sugarcane one of the most strategic and multifaceted crops on the planet. The history of sugarcane cultivation in Brazil dates to the colonial period, when the expansion of plantations, encouraged by European demand for sugar, transformed the country's agricultural landscape. Since then, sugarcane has played a structuring role in the economy, promoting the development of a complex and influential production chain (Pereira; Wesz Junior, 2020; Rodrigues; Ross, 2020; Silva *et al.*, 2021a).

However, the expansion of large-scale cultivation raises environmental and social challenges inherent in intensive monoculture. Issues such as soil degradation, pressure on water resources, and the social impact of intensive mechanization (Oliveira *et al.*, 2022) demand attention. Although the sector has been adopting practices to mitigate these impacts – such as soil conservation and integrated pest management – the transition to fully sustainable methods still faces significant barriers, including resistance to technology and a lack of economic incentives (Silva *et al.*, 2021a). This discrepancy between the potential for sustainability and actual challenges in the field creates a gap in the understanding and effective application of innovations.

In Brazil, sugarcane production is mainly concentrated in the states of São Paulo, Minas Gerais, Goiás, and Mato Grosso do Sul (CONAB, 2025). These states stand out for the adoption of advanced agricultural management techniques, including the use of machinery for planting and harvesting, maximizing the efficiency and productivity of cultivation (Rodrigues; Ross, 2020; Silva *et al.*, 2021a). The mechanized system has grown significantly in recent years, replacing the traditional method of manual harvesting, especially in easily accessible and large areas (Castro; Gilio; Machado, 2022; Moretto; Cavichioli, 2022). However, in some smaller and hard-to-reach regions, manual harvesting is still a common practice, which reflects the heterogeneity of cultivation conditions in the country (CONAB, 2025).

In addition to sugar, which remains one of the main products generated by sugarcane and widely used in the global food industry, Brazil is the second largest producer of ethanol, an essential biofuel for the national and international market (Vidal, 2024). Brazilian ethanol, produced from the fermentation of sugarcane, is considered one of the most efficient and sustainable in the world, both in terms of reducing greenhouse gas (GHG) emissions and energy efficiency (Brito; Matai; Santos, 2024). The use of ethanol as a fuel is an important alternative to the use of fossil fuels, positioning Brazil as a protagonist in the global renewable energy scenario (Soares; Zukowski Junior, 2021).

The sustainable cultivation of sugarcane, combined with technology and innovation, not only ensures long-term productivity, but also strengthens

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Brazil's image as a responsible producer, committed to environmental preservation and global sustainability. This approach is in line with the growing demands of the international market for agricultural products from sustainable production chains, in addition to contributing to the fulfillment of the carbon emission reduction goals established in international agreements, such as the Paris Agreement (Silva *et al*., 2021a; Soares; Zukowski Junior, 2021).

However, the transition to more sustainable agricultural practices faces significant barriers, such as the resistance of some producers to the adoption of new technologies, the lack of adequate economic incentives, and logistical difficulties in remote regions. These challenges make the investigation on the current state of sustainable practices in sugarcane cultivation in Brazil even more relevant. A detailed understanding of the impacts and challenges associated with these practices, based on a critical analysis of the scientific literature, is crucial to identify existing gaps and propose effective solutions that promote a balance between high productivity and sustainability (Silva *et al*., 2021a).

Therefore, this study aimed to conduct a review of the scientific literature to identify and analyze the sustainable agricultural practices adopted in sugarcane cultivation in Brazil. Through the critical analysis of innovations, it seeks to provide subsidies for the improvement of public policies and agricultural strategies that promote the balance between high productivity and the economic and environmental sustainability of the sector in the future of Brazilian agribusiness.

Materials and Methods

The methodology adopted for this research consists of a narrative review of the literature. This type of review, also known as traditional review, involves a search, selection and critical analysis of the literature relevant to the topic, being conducted in a comprehensive way to provide an overview of current knowledge (Dorsa, 2020; Galvão; Ricarte, 2019). The research was limited to articles and materials published in the period between 2004 and 2025. The search was carried out in the following databases, selected for their relevance and comprehensiveness: Scielo, Google Scholar, Capes Journals, Web of science using the terms "Sustainable agricultural practices in sugarcane", "Sustainable cultivation", "Environmental impacts" and "History of cultivation in Brazil".

Initially, the titles and abstracts of the identified studies were screened, with the objective of evaluating the relevance of each study to the research objectives. Only studies that showed direct relevance to the analysis of sustainable agricultural practices in sugarcane cultivation were selected for further review. After this screening stage, the curated articles were fully reviewed, allowing the selection of the information necessary to compose the analysis.

The analysis of the data collected was qualitative. The focus was the identification and synthesis of sustainable agricultural practices in sugarcane cultivation, as well as the assessment of their environmental, economic and social impacts. In addition, the study presented the challenges and barriers faced by producers in adopting these practices, with a focus on those specific to the Brazilian context.

The results obtained were defined in a detailed way, with the aim of identifying emerging trends in sustainable practices, as well as gaps in current knowledge. The challenges associated with implementing these practices were also analyzed, considering the specific conditions of the regions in Brazil with sugarcane products. The critical analysis of the data provided relevant insights into future research

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and the development of public policies and strategies aimed at promoting a more sustainable and resilient cultivation of sugarcane in the country.

Results and Discussion:

The systematic review on sugarcane cultivation and its sustainability in Brazil was based on 76 articles and other publications between 2004 and 2025. It is possible to observe that a) the reuse of sugarcane byproducts derived from the production of alcohol and sugar, such as the use of vinasse and the filter cake, b) the prohibition of burning before harvest, c) the biological control and d) the use of technology has made this kind of cultivation more sustainable. However, these practices are not yet present in all regions of Brazil (Table 1).

For a better understanding, the results were organized into thematic areas, allowing a clearer and more structured analysis of the information found. The thematic areas include: (1) History and evolution of sugarcane cultivation in Brazil; (2) Sustainable cultivation practices; (3) Mechanization and its contribution to sustainability; and (4) Biological control strategies and their impact on production. The main results of each of these areas are presented below, with an emphasis on innovations and practices that promote sustainability in the sector.

History and evolution of sugarcane cultivation in Brazil

Sugarcane has played a fundamental role in Brazil's agricultural and economic history, consolidating itself as one of the most important crops in the country, with Brazil being the world's largest producer (Pereira; Wesz Junior, 2020, Rodrigues; Ross, 2020, Silva *et al.*, 2021a, D'Alessandro; Cavichioli, 2024). Since its introduction in the colonial period, the crop has adapted to Brazilian climatic and soil conditions, especially in the Northeast and Center-South regions.

Over the years, sugarcane cultivation has undergone significant transformations, driven by technological advances and innovations in agricultural management, with the implementation of sustainable practices aimed at reducing environmental impacts (Maciel *et al.*, 2020; Silva; Marestoni, 2020; Soares; Zukowski Junior, 2021). These innovations not only improve the efficiency of the sector, but also promote agricultural practices that minimize soil degradation and the intensive use of water resources, challenges often associated with intensive monoculture (Ferreira; Araújo Sobrinho, 2019).

Sustainable farming practices

Sustainability is promoted by the rational use of byproducts and resources, and by reducing the emission of Greenhouse Gases (GHG) (Soares; Zukowski Junior, 2021), proving to be more advantageous than other biofuels (SILVA & MARESTONI, 2020). "Flex" mills, through the integrated production of sugarcane and corn, increase profitability in the off-season and stabilize prices in the market (Carvalho *et al.*, 2013). Bagasse is biomass for cogeneration of electricity (Nocelli *et al.*, 2017; Larsen Filho *et al.*, 2024), and can be used in civil construction, with pozzolanic potential to produce concrete (Maciel *et al.*, 2020). Other residues such as vinasse and filter cake provide nutrients such as potassium, nitrogen, phosphorus, calcium, and magnesium, as well as other micronutrients (Chitolina; Harder, 2020) which significantly improves soil fertility and reduces the need for chemical fertilizers (Martíni *et al.*, 2021; Oliveira; Cavichioli, 2024). However, Silva and Périco (2022) warn that the effectiveness of these practices is heterogeneous, varying according to local management capacity and technological level.

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Table 1. Research sources used for the description of the Results and Discussion of the article.

Author (s)	Year	Title	Type of Publication	Journal/ Publisher
ALCOLUMBRE; PINHEIRO	2023	Novas tendências construtivas: utilização das cinzas do bagaço da cana de açúcar na construção civil.	Article	RevistaFT
ALMEIDA, L. C.	2020	Monitoramento e controle do bicudo de cana-de-açúcar, *Sphenophorus levis* Vaurie, 1978.	Book	SENAR
ALMEIDA, M. E. B. *et al.*	2020	Aplicação de *Metarhizium anisopliae* (Ascomycota: Clavicipitaceae) para o controle de *Mahanarva fimbriolata* (Stal, 1854) (Hemiptera: Cercopidae) em cana-de-açúcar sob condições de campo.	Article	Research, Society and Development
ANDRADE JUNIOR, A. S. *et al.*	2017	Demanda hídrica da cana-de-açúcar, por balanço de energia, na microrregião de Teresina, Piauí.	Article	Agrometeoros
AQUINO, A. F. *et al.*	2014	O etanol da cana de açúcar: possibilidades energéticas da região de Ceará-Mirim-RN.	Article	Holos
AQUINO, I. S. *et al.*	2021	Aspectos comportamentais do hospedeiro *Diatraea saccharalis* produzidos em Laboratório.	Article	Research, Society and Development
AVILEZ, A. M. A. *et al.*	2018	Necessidade hídrica da cana-de-açúcar no noroeste paulista.	Article	Irriga
ARAÚJO; ARAÚJO SOBRINHO	2021	Análise do impacto social da mecanização da colheita de cana-de-açúcar no triângulo mineiro.	Article	Revista Eletrônica da Associação dos Geógrafos Brasileiros

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Author (s)	Year	Title	Type of Publication	Journal/ Publisher
ARAUJO, F. E. L. *et al.*	2025	Queimadas no cultivo da cana-de-açúcar e doenças respiratórias associadas em um município de Pernambuco	Article	Saúde Debate
BARBOSA; ASMUS	2019	Densidade populacional do nematoides-das-lesões-radiculares em cana-de-açúcar em função de cultivares, manejo do palhiço e escarificação do solo.	Article	Revista de Agricultura Neotropical
BHUIYAN; SHERRING; EGLINTON	2024	Parasitic Nematodes of Sugarcane: A Major Productivity Impediment and Grand Challenges in Management	Article	Plant Disease
BRITO; MATAI; SANTOS	2024	Inovação e a produção do etanol de cana-de-açúcar.	Article	Revista de Gestão e Secretariado
CANISARES, L. P. *et al.*	2020	Soil microstructure alterations induced by land use change for sugarcane expansion in Brazil.	Article	Soil Use and Management
CARVALHO, L. C. *et al.*	2013	Cana-de-açúcar e álcool combustível: histórico, sustentabilidade e segurança energética.	Article	Enciclopédia Biosfera
CARVALHO; FERRAREZI JUNIOR; CARRASQUEIRA	2024	Fertirrigação com vinhaça utilizando o sistema localizado.	Article	Interface Tecnológica
CARVALHO, T, R. *et al.*	2023	Fitonematoides de importância para a cultura da cana-de-açúcar no Brasil.	Article	Interface Tecnológica
CARVALHO, V. P.	2023	Monitoramento de nematóides fitoparasitas na cultura da cana-de-açúcar.	Article	Cuadernos de Educación y Desarrollo

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CASTRO; GILIO; MACHADO	2022	Impactos da mecanização na produtividade agrícola agregada da cana-de-açúcar no estado de São Paulo 2007 a 2013.	Article	Revista de Economia e Sociologia Rural
CATOLICO, A. C. *et al.*	2015	Análise de sustentabilidade do etanol 2G e bioenergia da cana.	Article	Periódico Eletrônico Fórum Ambiental da Alta Paulista
CHITOLINA; HARDER	2020	Avaliação da viabilidade do uso de vinhaça como adubo.	Article	Bioenergia em Revista: Diálogos
CONAB	2025	Acompanhamento da safra brasileira de cana-de-açúcar	Technical report	Conab
D'ALESSANDRO; CAVICHIOLI	2024	A importância do setor sucroalcooleiro na economia brasileira.	Article	Interface Tecnológica
DEBOLETTA; SCHEMMER; YOKOMIZO	2009	Gestão de práticas ambientais no setor sucroalcooleiro da região de Marilia/SP.	Article	Revista Eletrônica de Graduação do UNIVEM
DORSA, A. C.	2020	O papel da revisão da literatura na escrita de artigos científicos	Article	Interações
ECKARDT; ABREU	2017	Gestão para mecanização da colheita da cana-de-açúcar utilizando-se de coeficientes técnicos.	Article	Custos e @gronegócio online
EGGERS, H. S. *et al.*	2025	Impactos do manejo agrícola na resistência a penetração do solo: comparação entre cultivos de cana-de-açúcar e floresta nativa.	Article	Revista DELOS
FELTRE; TULON	2023	Estudo comparativo da mecanização da cultura de cana-de-açúcar sobre o emprego nas regiões brasileiras.	Article	Revista Econômica do Nordeste

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FERREIRA; ARAÚJO SOBRINHO	2019	A produção canavieira e o mito do progresso: agronegócio e agricultura familiar na microrregião de Ceres, Goiás, Brasil.	Article	PatryTer
GALVÃO; RICARTE	2019	Revisão sistemática da literatura: conceituação, produção e Publicação.	Article	LOGEION: Filosofia da Informação
GOMES; OLIVEIRA	2020	Eficácia para o combate da broca da cana-de-açúcar	Article	Interface Tecnológica
GRILLO, V. *et al.*	2024	Alteração da densidade do solo por operações agrícolas mecanizadas: interação entre ambiente e equipamentos.	Article	Brazilian Journal of Animal and Environmental Research
HAYWOOD, S. T. T. et *al*.	2021	Efficiency in the control of *Diatraea saccharalis* with releases of *Cotesia flavipes* in sugarcane crops in Paraguay	Article	Brazilian Journal of Animal and Environmental Research
KASSAB, S. O. *et al*.	2012	Alteração no método de amostragem de *Mahanarva fimbriolata* (Stål, 1854) (Hem.: Cercopidae) e avaliação da eficiência de *Metarhizium anisopliae* (Metschnikoff, 1879) Sorokin, 1883 (Hyp.: Clavicipitaceae).	Article	Arquivos do Instituto Biológico
LARSEN FILHO, L. L. *et al.*	2024	Panorama do setor sucroalcooleiro brasileiro: da produção ao processamento dos resíduos associados a cadeia de cana-de-açúcar.	Article	Observatório de La Economía Latinoamericana

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Author (s)	Year	Title	Type of Publication	Journal/ Publisher
LEAL, J. E. T. *et al.*	2008	Influência da cigarrinha-das-raízes *Mahanarva fimbriolata* (stal,1854) (Hemiptera: Cercopidade) e seus métodos de controle sobre a produtividade e a qualidade da cana-de-açúcar.	Article	Nucleus
LEITE, L. A. B. *et al.*	2024	Potencial de bagaço e vinhaça da cana de açúcar para a matriz energética no Estado do Paraná.	Article	Revista Caribeña de Ciências Sociales
LOUREIRO, E. S. *et al.*	2012	Eficiência de isolados de *Metarhizium anisopliae* (Metsch.) Sorok. no controle da cigarrinha-da-raiz da cana-de-açúcar, *Mahanarva fimbriolata* (Stal, 1854) (Hemiptera: Cercopidae), em condições de campo.	Article	Arquivos do Instituto Biológico
MACIEL, D. L. O. *et al.*	2020	Reutilização da cinza do bagaço da cana-de-açúcar na confecção de concreto: uma revisão narrativa.	Article	Caderno de Graduação - Ciências Exatas e Tecnológicas - UNIT
MARTÍNI, A. F. *et al.*	2021	Long-Term Trial of Tillage Systems for Sugarcane: Effect on Topsoil Hydrophysical Attributes.	Article	Sustainability
MARTINS, R. V.	2015	Etanol de Beterraba.	Article	Intr@ciência
MORETTO; CAVICHIOLI	2022	Plantio mecanizado da cana-de-açúcar: aspectos desse processo.	Article	Interface Tecnológica
MUNDIM; PELISSARI; PEREIRA	2009	Panorama da colheita mecanizada de cana-de-açúcar e seu impacto no manejo da cultura.	Article	Nucleus

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Author (s)	Year	Title	Type of Publication	Journal/ Publisher
NOCELLI, R. C. F *et al*.	2017	Histórico da cana-de-açúcar no Brasil: contribuições e importância econômica.	Book chapter	Canal 6
OLAK; AMARANTE	2014	Análise dos custos de produção dos agentes biológicos para controle de *Diatraea saccharalis* em cana-de-açúcar: um estudo de caso em laboratório de produção massal.	Article	ABCustos
OLINTO, T. M. *et al*.	2024	Atuação benéfica do fungo entomopatogênico *Metarhizium anisopliae* em mudas pré-brotadas de cana-de-açúcar infectadas com *Fusarium*	Article	Revista Caderno Pedagógico
OLIVEIRA; CAVICHIOLI	2024	Uso de torta de filtro na cultura da cana-de-açúcar.	Article	Interface Tecnológica
OLIVEIRA, M. R. *et al.*	2022	Os impactos ambientais do setor sucroenergético e o uso de Indicadores de sustentabilidade	Article	Revista de Desenvolvimento Econômico
OLIVEIRA; RAMOS; SILVA	2025	Avaliação da sustentabilidade de alternativas da utilização da vinhaça.	Article	Bioenergia em Revista: Diálogos
PABLOS; ZAGO	2023	Estudo para reutilização das cinzas da palha e do bagaço de cana-de-açúcar geradas na produção do Etanol de segunda geração em matrizes cimentícias.	Article	Contribuciones a Las Ciencias Sociales
PALUCCI; MOREIRA	2015	Viabilidade econômica de uma Biofabrica para controle da Cigarrinha das Raízes em Usina de Açúcar e Álcool.	Article	Revista iPecege

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Author (s)	Year	Title	Type of Publication	Journal/ Publisher
PELLOSO, M. F. *et al.*	2019	Perdas na colheita mecanizada da cana-de-açúcar em resposta a diferentes velocidades da colhedora e de rotação do extrator primário.	Article	Colloquium Agrariae
PEREIRA;WESZ JUNIOR	2020	Da Colônia à República: desenvolvimento do setor sucroenergético e a economia brasileira.	Article	Campo-Território: Revista de Geografia Agrária
PERES; SOUZA; LAVORENTI	2010	Avaliação dos efeitos da cobertura de palha de cana-de-açúcar na umidade e na perda de água do solo.	Article	Engenharia Agrícola
PRUDENCIO, M. F. *et al.*	2025	Atualizações no manejo integrado das principais pragas da cana-de-açúcar no Brasil: uma revisão dos últimos 10 anos	Article	Aracê
RENZI, A. *et al.*	2019	Evolução do controle biológico de insetos e pragas no setor canavieiro: uma análise na perspectiva econômica.	Article	Revista em Agronegócio e Meio Ambiente
RITZINGER; FANCELLI	2006	Manejo integrado de nematoides na cultura da bananeira.	Article	Revista Brasileira de Fruticultura
RODRIGUES; ROSS	2020	A trajetória da cana-de-açúcar no Brasil: perspectivas geográfica, histórica e ambiental	Book	EDUFU
SAMPAIO; ASSIS	2023	Etanol de milho: novas perspectivas no mercado brasileiro.	Article	Interface Tecnológica

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Author (s)	Year	Title	Type of Publication	Journal/ Publisher
SAMPAIO; SOUZA; GOUVEIA	2014	Análise da influência das cinzas do bagaço de cana-de-açúcar no comportamento mecânico de concretos.	Article	Revista IBRACON de Estruturas e Materiais
SANTANA; XAVIER	2022	Levantamento da intensidade de infestação de broca (*Diatraea saccharalis*) em diferentes variedades de cana de açúcar.	Article	Científic@ - Multidisciplinary Journal
SANTOS, N. B. *et al.*	2014	Simulação da eficiência de campo da colheita mecanizada de cana-de-açúcar (*Saccharum* spp.).	Article	Energia na Agricultura
SERRANO, G. R. *et al.*	2023	O uso de cinzas do bagaço de cana de açúcar (CBC) no concreto: uma revisão de literatura.	Article	Revista Caderno Pedagógico
SILVA; BONO; PEREIRA	2014	Aplicação de vinhaça na cultura da cana-de-açúcar: Efeito no solo e na produtividade de colmos.	Article	Revista Brasileira de Engenharia Agrícola e Ambiental
SILVA, D. L. G. *et al.*	2021a	Cana-de-açúcar: Aspectos econômicos, sociais, ambientais, subprodutos e sustentabilidade.	Article	Research, Society and Development
SILVA; DELGADO	2025	Importância do manejo integrado de pragas na agricultura.	Article	RevistaFT
SILVA; PÉRICO	2022	Eficiência e sustentabilidade: uma análise econômica, social, ambiental e sustentável das usinas paulistas de cana-de-açúcar.	Article	Revista de Economia e Sociologia Rural

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SILVA; MARESTONI	2020	Produção do etanol de cana-de-açúcar como tema interdisciplinar no ensino médio.	Article	EDUCA - Revista Multidisciplinar em Educação
SILVA, J. D. C. *et al.*	2020	Sugarcane froghoppers in northeast Brazil	Article	Arquivos do Instituto Biologico
SILVA, R. M. *et al.*	2021b	Um estudo de caso da remoção da palhada de cana-de-açúcar do solo: quais são as implicações no conteúdo de matéria orgânica do solo?	Article	Research, Society and Development
SILVA; MANTESE; FLORIAN	2023	O bagaço da cana-de-açúcar na geração de energia.	Article	RECIMA21 - Revista Científica Multidisciplinar
SILVA, S. D. A. *et al.*	2016	Sistema de produção de cana-de-açúcar no Rio Grande do Sul.	Technical report	Embrapa
SILVA; BORGES; ALBUQUERQUE	2014	Necessidades hídricas da cana-de-açúcar cultivada em clima tropical.	Article	Semina: Ciências Agrárias
SOARES; ZUKOWSKI JUNIOR	2021	O Brasil como grande player no mercado mundial de etanol.	Article	Revista de Política Agrícola
TOIGO; CASAGRANDE	2024	Colheita mecânica da cana-de-açúcar: alguns parâmetros.	Article	Nucleus
VIDAL, M. F.	2024	Etanol.	Article	Caderno Setorial ETENE
VOLK; COGO; STRECK	2004	Erosão hídrica influenciada por condições físicas de superfície e subsuperfície do solo resultantes do seu manejo, na ausência de cobertura vegetal.	Article	Revista Brasileira de Ciência do Solo

The analysis of the literature on sugarcane in Brazil reveals the depth and complexity of this crop both from an economic point of view and in terms of environmental and social sustainability. Brazil, as the world's leading producer of sugarcane, occupies a strategic position in the global market, being responsible for more than half of the ethanol produced in the world and about 25 % of world sugar production (Vidal, 2024). However, the expansion of this crop brings with it challenges related to environmental management and the efficient use of natural resources (Canisares *et al.*, 2020; Castro; Gilio; Machado, 2022; Oliveira; Ramos; Silva, 2025).

One of the main challenges faced by sugarcane cultivation is the environmental impact caused by soil degradation and the intensive use of water resources (Canisares *et al.*, 2020; Martíni *et al.*, 2021; Grillo *et al.*, 2024). Large tracts of sugarcane plantations require significant use of water, often from underground sources or rivers, which can lead to a decrease in water reserves and the impairment of local ecosystems (Silva; Borges; Albuquerque, 2014; Andrade Junior *et al.*, 2017; Avilez *et al.*, 2018). In addition, intensive sugarcane monoculture, associated with the inappropriate use of agricultural practices, can result in degradation of soil structure, loss of nutrients, and increased vulnerability to erosion (Canisares *et al.*, 2020; Oliveira *et al.*, 2022; Grillo *et al.*, 2024). In this sense, agricultural management practices that promote sustainability, such as the rational use of irrigation and the preservation of soil vegetation cover, are essential to mitigate these impacts (Peres; Souza; Lavorenti, 2010; Silva *et al.*, 2021b; Silva; Périco, 2022). Recent studies suggest that the development and adoption of more advanced technologies, as well as the creation of public policies aimed at the sustainable management of natural resources, are essential for long-term environmental preservation (Silva *et al.*, 2021b).

The context of sugarcane cultivation in Brazil is also characterized by a profound transformation of the capitalist economy, where the growing concern with sustainability has shaped production chains in a heterogeneous way, depending on local policies and regional characteristics (Oliveira *et al.*, 2022). In certain regions, more efficient agricultural management practices and technological advances have been implemented to optimize the use of resources and minimize environmental impacts. However, in places where access to technologies is more limited or where policies to encourage sustainability are less effective, sugarcane cultivation still faces significant challenges (Deboletta; Schemmer; Yokomizo, 2009; Oliveira *et al.*, 2022; Larsen Filho *et al.*, 2024). Silva and Périco (2022) point out that the heterogeneity in the efficiencies of production chains is closely related to the ability of local managers to implement and maintain these policies and practices, in addition to factors such as environmental conditions and the level of technological development.

The Brazilian sugarcane sector has stood out for the adoption of innovative solutions to maximize the value of sugarcane byproducts (Silva; Mantese; Florian, 2023; Leite *et al.*, 2024). The use of biomass, for example, has been one of the main strategies adopted to promote the generation of clean energy. Sugarcane bagasse, a byproduct of juice extraction, is widely used for the cogeneration of electricity in the mills, which has contributed significantly to the country's energy transition towards renewable sources (Catolico *et al.*, 2015; Silva; Mantese; Florian, 2023). This practice has not only allowed the reduction of dependence on fossil fuels, but also generated an additional source of income for the sector, increasing the competitiveness of the mills (Leite *et al.*, 2024). In addition, the diversification of sugarcane-derived products, such as second-generation ethanol and biogas, has broadened the spectrum of uses of this crop, integrating economic development with environmental sustainability (Brito; Matai; Santos, 2024; Larsen Filho *et al*., 2024).

The mechanization of sugarcane harvesting, one of the most significant milestones in the sector in recent decades, also plays a crucial role in the sustainability of the crop (Eckardt; Abreu, 2017; Pelloso *et al*., 2019). The mechanized harvesting process, besides increasing operational efficiency, has reduced the need for burning, a previously common practice to facilitate manual harvesting (Mundim; Pelissari; Pereira, 2009). The elimination of fires directly contributes to the reduction of greenhouse gas emissions, in addition to improving air quality and the health conditions of rural workers and communities neighboring the plantation areas (Araujo *et al*., 2025). The mechanization of harvesting has boosted the creation of specialized jobs, promoting the development of qualified labor and contributing to the socioeconomic growth of producing regions (Larsen Filho *et al*., 2024).

Regarding sustainable soil management, it is important to note that sugarcane is a demanding crop in terms of soil preparation and the use of heavy machinery (Toigo; Casagrande, 2009; Castro; Gilio; Machado, 2022; Moretto; Cavichioli, 2022; Feltre; Tulon, 2023). These operations, when performed improperly, can lead to soil compaction, a problem that directly affects water's ability to infiltrate, aeration, and plants' nutrient uptake (Eggers *et al*., 2025). Soil compaction also increases surface runoff, favoring erosion and the loss of essential nutrients for the development of subsequent crops (Grillo *et al*., 2024). The use of the Controlled Traffic System (STC) reduces the area compacted by the passage of agricultural machinery and is considered one of the most promising conservation practices to reduce the impacts of mechanization on soil structure (Volk; Cogo; Streck, 2004). However, the author points out that there is still a lack of detailed data on the effects of compaction on different types of soils and agricultural systems, which limits the development of more efficient management strategies.

Inadequate practices, such as the removal of straw after harvest, contribute to the vulnerability of the soil to erosion, especially in regions with steep slopes or heavy rainfall (Volk; Cogo; Streck, 2004). Sugarcane straw, when left in the field, acts as a protective layer, dissipating the energy of raindrops and reducing the impact of water on the soil surface (Peres; Souza; Lavorenti, 2010). Its removal, on the other hand, exposes the soil directly to the elements, facilitating erosion and compaction caused by agricultural machinery traffic. Additionally, the removal of straw compromises soil quality by reducing the incorporation of organic matter, an essential factor for maintaining fertility in the long term (Silva *et al.,* 2021b). Thus, conservation practices, such as the maintenance of vegetation cover and proper planning for land use, are essential to ensure the sustainability of sugarcane cultivation in Brazil (Canisares *et al*., 2020).

In the field of the use of sugarcane byproducts, a relevant highlight is the reuse of bagasse and straw to produce biofuels and construction materials, such as concrete (Sampaio; Souza; Gouveia, 2014; Alcolumbre; Pinheiro, 2023; Pablos; Zago, 2023; Serrano *et al*., 2023). Maciel *et al*. (2020) demonstrate that sugarcane bagasse ash, a byproduct of bagasse burning for energy generation, has high potential as a pozzolanic material in concrete production. The use of this waste in civil construction not only contributes to the reduction of improper disposal of solid waste, but also offers a sustainable and low-cost solution for the construction

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industry, reducing the demand for non-renewable natural resources (Sampaio; Souza; Gouveia, 2014; Maciel *et al*., 2020; Serrano *et al*., 2023).

Another important byproduct of the ethanol production process is vinasse, a liquid residue rich in potassium and organic matter, which has been widely used as a natural fertilizer in sugarcane plantations (Silva; Bono; Pereira, 2014; Carvalho; Ferrarezi Junior; Carrasqueira, 2024). Oliveira, Ramos and Silva (2025) highlights that the controlled application of vinasse in crops can significantly improve soil fertility, reducing the need for chemical fertilizers and contributing to the sustainability of agricultural production. Furthermore, filter cake, a solid waste obtained after filtering sugarcane juice, is another resource that can be reused as a soil conditioner, helping to improve its physical and chemical properties and promoting the conservation of nutrients in the field (Martíni *et al*., 2021).

When it comes to renewable fuels, ethanol stands out as a less polluting alternative to fossil fuels, playing a central role in the Brazilian energy matrix (Aquino *et al*., 2014). Proálcool, created in 1975, boosted ethanol production in Brazil, consolidating the country as one of the largest producers and consumers of this biofuel in the world. The use of ethanol from sugarcane, in addition to significantly reducing greenhouse gas emissions, has been shown to be economically advantageous compared to other biofuels, such as corn or beet ethanol (Silva; Marestoni, 2020).

The integrated production of ethanol from sugarcane and corn in flex mills has been a strategic innovation to increase the efficiency and profitability of mills during the sugarcane off-season (Brito; Matai; Santos, 2024). Carvalho *et al*. (2013) state that this integration allows the mills to continue operating even in periods of lower sugarcane supply, stabilizing ethanol production and prices in the domestic market. In addition, the diversification of raw materials used in ethanol production contributes to the country's energy security, reducing dependence on fossil fuels and expanding Brazil's role as a leader in biofuel production (Aquino *et al*., 2014; Martins, 2015; Sampaio; Assis, 2023; Brito; Matai; Santos, 2024).

Mechanization and its contribution to sustainability

The growing demand for high-quality and environmentally friendly agricultural products has led the sugarcane sector to eliminate the practice of burning and implement sustainable measures. The mechanization of harvesting has become an essential step, especially in traditional regions, such as São Paulo, and in expansion areas in the Midwest (Castro; Gilio; Machado, 2022). Although this transition has brought significant environmental benefits, producers still face challenges such as high production costs and environmental requirements, which impact the economic sustainability of the sector (Araújo; Araújo Sobrinho, 2021).

The sugarcane production cycle requires high levels of mechanical energy, from soil preparation to harvesting and transportation of inputs (Toigo; Casagrande, 2009; Castro; Gilio; Machado, 2022; Moretto; Cavichioli, 2022; Feltre; Tulon, 2023). With the introduction of mechanized harvesting, significant changes were made to increase the operational efficiency of harvesters. The prohibition of fires, especially in São Paulo, brought substantial improvements in air quality and soot reduction, while previous practices caused soil degradation, loss of biodiversity and emission of polluting gases, negatively impacting the environment and public health (Santos *et al*., 2014). Mechanization is a milestone in environmental and social sustainability, which resulted in the elimination of fires, with the direct effect of

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reducing GHG and soot, besides improving air quality (Santos *et al*., 2014; Oliveira *et al*., 2022). Mechanized harvesting keeps the straw in the soil, which blocks sunlight, acting to control weeds and reducing the use of herbicides (Santos *et al*., 2014). However, the high costs of mechanization challenge the economic sustainability of the sector (Araújo; Araújo Sobrinho, 2021). Through the Controlled Traffic System (STC) it is possible to reduce the traffic of machines in the cultivation area, which makes it a promising alternative in reducing impacts on the soil (Volk; Cogo; Streck, 2004; Canisares *et al*., 2020). Mechanization not only increases efficiency but also boosts the creation of skilled jobs, promoting regional socioeconomic development (Larsen Filho *et al*., 2024).

Manual harvesting, which often relied on burning to be effective, is no longer viable from an environmental point of view. Burning favored the growth of weeds, harming the development of sugarcane. On the other hand, mechanized harvesting offers advantages, such as the formation of a layer of straw in the soil, which blocks sunlight and prevents the emergence of weeds, reducing the need for herbicides. Moreover, straw can be used to generate energy in mills, which are already largely self-sufficient by using sugarcane bagasse as an energy source (Santos *et al*., 2014).

The management of sugarcane production involves operations that demand high levels of mechanical energy, compared to other crops. These operations include soil preparation, transportation of inputs and the removal of large volumes of production per hectare, including straw, whose use is becoming increasingly relevant for the sustainability of the sector (Santos *et al*., 2014).

In summary, the sustainability of sugarcane production in Brazil depends on the adoption of mechanized and environmentally responsible practices. The elimination of fires, the use of straw for weed control and energy generation, in addition to the constant adaptation to environmental requirements, are fundamental to ensure the economic and ecological viability of this essential crop. These practices increase productivity, as well as it contributes significantly to environmental preservation and public health, consolidating the role of sugarcane as one of the pillars of Brazilian agribusiness.

Biological control strategies and their impact on production

Sugarcane plays a key economic role in Brazil, but it is highly vulnerable to pests and diseases that proliferate in the vast areas of monoculture. Pests, such as the sugarcane borer, root leafhopper, and termites are the most harmful, compromising agricultural productivity and increasing control costs (Aquino *et al*., 2021; Santana; Xavier, 2022). To face these challenges, it is essential to adopt integrated management practices that involve the use of biological, chemical, physical, and legislative methods (Prudencio *et al*., 2025; Silva; Delgado, 2025). Such practices aim to reduce the incidence of pests and diseases, promoting more sustainable and efficient agricultural production.

Nematodes are a growing concern in sugarcane crops, causing serious damage to plants. Nematode management is largely based on preventive strategies, such as crop rotation, the use of resistant varieties and chemical control (Ritzinger; Fancelli, 2006; Barbosa; Asmus, 2019; Carvalho, 2023; Carvalho *et al*., 2023; Bhuiyan; Sherring; Eglinton, 2024). An essential practice in this management is the correct identification of nematode species present in cultivated areas, using both morphological and molecular methods. Precision in identification allows the selection of appropriate

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techniques for control, optimizing the response to infestations (Silva *et al*., 2016; Bhuiyan; Sherring; Eglinton, 2024).

Production is under constant threat from pests that can cause from premature plant death to perforation in the stalks, which compromises the quality and yield of the crop. The use of biological control, such as the use of the parasitoid *Cotesia flavipes* (Cameron, 1891) (Hymenoptera: Braconidae) to combat the sugarcane borer, has been shown to be an effective and sustainable solution (Haywood *et al*., 2021). This wasp, introduced in Brazil to specifically control the sugarcane borer, has as its main characteristic the parasitism of the pest's larvae, reducing its population naturally and without causing negative effects to the environment (Gomes; Oliveira, 2020). The release of 200 thousand wasps per hectare reduces the infestation of the sugarcane borer between 60 % and 90 %, leading to a reduction of up to 70 % in the use of chemical insecticides and a 30 % decrease in management costs, compared to methods that depend only on chemicals (Olak; Amarante, 2014; Haywood *et al*., 2021).

The success of biological pest control in Brazil, especially with the use of *C. flavipes*, stands out as an alternative to the intensive use of pesticides, promoting ecological balance and reducing damage to the environment (Gomes; Oliveira, 2020).

In addition to the sugarcane borer, other pests, such as the root and leaf leafhopper, also affect the crop (Leal *et al*., 2008; Silva *et al*., 2020). The use of the entomopathogenic fungus *Metarhizium anisopliae* has been a viable solution for the control of these pests (Palucci; Moreira, 2015). This fungus infects and kills leafhoppers, significantly decreasing their populations and offering a sustainable approach to pest management (Kassab *et al*., 2012; Loureiro *et al*., 2012; Almeida *et al*., 2020). Biological control is increasingly valued, as it preserves the health of agricultural ecosystems, reducing dependence on chemical insecticides (Olinto *et al*., 2024).

Brazilian agriculture has sought to balance high productivity with environmentally responsible practices, promoting the adoption of bioinputs and biotechnology in phytosanitary management. These advances are essential to reduce the environmental impact of agriculture and ensure the preservation of natural resources. In the context of sugarcane, biological pest control is one of the pillars for more sustainable production. Pests such as the sugarcane boll weevil (*Sphenophorus levis*; Vaurie, 1970) (Coleoptera: Curculionidae) that cause great economic losses, are efficiently controlled through biological methods, contributing to agriculture that is less dependent on chemicals (Almeida, 2020).

In summary, sugarcane is a crop of strategic importance for Brazil, but it faces serious challenges related to pests and diseases. Success in adopting integrated pest management practices, including biological control, has been crucial for the sustainability of the sector (Renzi *et al*., 2019; Prudencio *et al*., 2025; Silva; Delgado, 2025). The implementation of these practices, combined with the correct identification of pests and the use of biotechnologies, can ensure not only crop productivity, but also the preservation of natural resources and long-term economic viability (Prudencio *et al*., 2025; Silva; Delgado, 2025).

Conclusion

A detailed analysis of 76 articles published between 2004 and 2025 highlighted the crucial role of sugarcane throughout Brazil's history and the evolution of its cultivation practices, with an emphasis on innovations aimed at sustainability. Among the main strategies highlighted, mechanization and biological control have emerged as fundamental solutions to mitigate the environmental impacts associated with large-scale monoculture, while promoting more efficient production and reducing greenhouse gas emissions. These innovations were accompanied by the adoption of soil management techniques and conservation practices that contributed to the longevity and resilience of plantations, preserving the quality of natural resources and ensuring the economic viability of the sector.

However, sugarcane cultivation continues to face considerable challenges. Fierce competition in the international market and the volatility of agricultural product prices represent constant obstacles to the stability of the sector. On top of that, the pressure to increase productivity without compromising environmental resources reinforces the need for safe and efficient practices. Despite this, the sector has demonstrated a growing commitment to responsible production, adopting approaches that balance productivity with environmental sustainability.

Technological innovation, driven by advances in biotechnology, and the implementation of sustainable strategies are essential factors to ensure Brazil's competitiveness in the global sugar and ethanol market. Furthermore, the integration of these practices also promotes significant environmental benefits, such as conserving biodiversity and improving the health of agricultural ecosystems. The use of bioinputs, for example, has been shown to be an effective and ecologically responsible alternative to chemical pest control, reducing negative impacts on soil, water, and biodiversity.

Ultimately, the future of sugarcane in Brazil depends on the sector's ability to continue innovating and implementing practices that reconcile productivity with social and environmental responsibility. The adoption of sustainable technologies and integrated pest management are fundamental steps to ensure the competitiveness of the crop in the global market, along with ensuring that sugarcane production contributes to a more sustainable and resilient agricultural development.

Conflict of Interest

The authors declare that the research was conducted in the absence of any potential conflicts of interest.

Ethical Statements

The authors confirm that the ethical guidelines adopted by the journal were followed by this work, and all authors agree with the submission, content and transfer of the publication rights of the article to the journal. They also declare that the work has not been previously published nor is it being considered for publication in another journal.

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