Review [Revisión]

Sweet sorghum and the future of first-generation bioethanol in Mexico: A review †

[El sorgo dulce y el futuro del bioetanol de primera generación en México: Una revisión]

Ma. Eugenia Cisneros-López* and Ruben Dario Garza-Cedillo

*Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Noreste, Campo Experimental Río Bravo, Tamaulipas. Kilometro 61 Carretera Matamoros-Reynosa, C.P. 88900, Río Bravo, Tamaulipas, México. E-mail: *ecl631211@gmail.com or cisneros.maria@inifap.gob.mx, garza.ruben@inifap.gob.mx*
**Corresponding author*

SUMMARY

Background. The oil crisis of the 1970s spurred the global search for alternative fuels, and in Mexico, sweet sorghum (*Sorghum bicolor* (L.) Moench) has emerged as a promising feedstock for first-generation bioethanol due to its adaptability to diverse agroecological regions. **Objective.** To conduct a descriptive study on the technological advances, limitations, and challenges in the production of first-generation ethanol from sweet sorghum juice in Mexico. **Methodology.** A bibliometric analysis was performed using Semantic Scholar, retrieving 84 publications. Of these 20 were directly relevant, complemented by 109 additional references from Scopus, Latindex, and Google Scholar, resulting in a total of 129 analyzed references. **Results.** Research activity peaked between 2010 and 2020, with English-language publications dominating (68.6%). The main thematic trends included sweet sorghum juice applications for bioethanol (22%), syrup, and lactic acid (7.1%). Other trends differences between grain and juice based feedstocks, agronomic practices, genetic resources, fermentation processes, and regulatory and economic aspects. **Implications.** The lack of an integrative framework linking agricultural production with industrial processing limits economic feasibility assessments, regional planning, and policy development in Mexico. **Conclusion.** Industrial bioethanol production from sweet sorghum in Mexico remains in an early stage. This this study represents one of the first comprehensive analyses combining bibliometric, technological, and industrial perspectives, highlighting critical research gaps and future priorities for sustainable bioethanol development.
Key words: feedstock; juice utilization; industrial processing; sustainability.

RESUMEN

Antecedentes. La crisis petrolera de la década de 1970 impulsó la búsqueda global de combustibles alternativos, y en México, el sorgo dulce (*Sorghum bicolor* (L.) Moench) ha surgido como una materia prima promisoria para bioetanol de primera generación debido a su adaptabilidad a diversas regiones agroecológicas y su capacidad de producir jugo con alto contenido de azúcares fermentables. **Objetivo.** Realizar un estudio descriptivo sobre los avances tecnológicos, limitaciones y desafíos en la producción de etanol de primera generación a partir del jugo de sorgo dulce en México. **Metodología.** Se realizó un análisis bibliométrico en Semantic Scholar, recuperando 84 publicaciones. Las 20 referencias fueron directamente relevantes, complementadas con 109 referencias de Scopus, Latindex y Google Scholar, sumando 129 referencias. **Resultados.** La investigación alcanzó su pico entre 2010 y 2020, predominando las publicaciones en inglés (68.7%). Las tendencias principales incluyeron aplicaciones del jugo de sorgo para bioetanol (22%), jarabe y ácido láctico (7.1%). Otras tendencias fueron diferencias entre materias primas de grano y jugo, prácticas agronómicas, recursos genéticos, procesos de fermentación y aspectos regulatorios y económicos. **Implicaciones.** La falta de un marco integrador que conecte la producción agrícola con el procesamiento industrial limita la evaluación de la viabilidad económica, la planificación regional y el desarrollo de políticas en México. **Conclusión.** La producción industrial de bioetanol a partir de sorgo dulce en México sigue siendo incipiente. Este estudio constituye uno de los primeros análisis integrales que combinan perspectivas bibliométricas, tecnológicas e

† *Submitted August 6, 2025 – Accepted October 24, 2025.* http://doi.org/10.56369/tsaes.6500

ISSN: 1870-0462.
ORCID = M.E. Cisneros-López: http://orcid.org/0000-0002-9177-5818; **R.D. Garza-Cedillo**: http://orcid.org/0000-0002-3168-3321

industriales, resaltando brechas de investigación y estableciendo prioridades para el desarrollo sostenible del bioetanol en contextos tropicales y subtropicales.
Palabras clave: materia prima; uso del jugo; procesamiento industrial; sostenibilidad.

INTRODUCTION

The global economy relies heavily on fossil fuels such as oil, coal, gasoline, and natural gas, which currently supply approximately 80% of the world's total energy demand (IEA, 2023). These fuels are used to produce electricity, fuel, and other goods (Megía *et al*., 2021). However, their excessive use significantly increases greenhouse gas levels in the atmosphere (Abbass *et al.*, 2022). The advancement of electric vehicles in the global market is expected to influence short, medium, and long term projections for the use of conventional and alternative fuels, such as ethanol (Diouf, 2025), potentially causing price fluctuations. As electric vehicles reduce the demand for traditional fossil fuels, the role of ethanol may shift, with potential increases in demand as a renewable fuel in hybrid and non-electric vehicles, or market uncertainties due to changing fuel preferences (Costa *et al*., 2017). This situation demands improvements in the efficiency of processes for obtaining sugar, alcohol, and electricity, as well as increasing the value of byproducts such as vinasse (a liquid byproduct from the distillation process), fiber (the residual fibrous material after juice extraction), and filter cake (the solid waste generated during filtration), which are often discarded or underutilized (Danelon *et al*., 2023).

Bioethanol is a renewable, non-polluting energy source. Currently, ethanol is produced from a variety of raw materials, including agricultural crops, crop and forestry residues, and industrial waste (Núñez, 2022). Due to their high sugar content, agricultural crops are considered the best option to meet the projected large-scale ethanol demand (Alonso-Gómez and Bello-Pérez, 2018). These crops include sugarcane, sugar beets, yellow corn, and sorghum (Bušić et al., 2018). In Mexico, grains are primarily directed to the food industry, limiting their availability for bioethanol production. Additionally, the national production deficit further constrains supply (Rebollar *et al.*, 2016). Consequently, alternative crops such as sweet sorghum, a versatile species known for its shorter growth cycle, adaptability to diverse environmental conditions, and lower input requirements compared to sugarcane and corn, have been proposed (Chuck-Hernández *et al*., 2012; Zegada-Lizarazu and Monti, 2015).Biodiversity of energy sources is essential for sustainable production (Immerzeel *et al.*, 2014); therefore, supply chains must be tailored specifically to each bioenergy source (Canabro *et al.*, 2023).

The objective of this study was to synthesize and critically analyze the technological advances, existing limitations, and current challenges associated with bioethanol production in Mexico. This review aims to provide a comprehensive overview of the state of the art to inform future research directions and support the development of sustainable bioenergy strategies.

METHODOLOGY

This study is a scoping review designed to identify key concepts, research gaps, and the existing body of evidence (Arksey and O'Malley, 2005; López-Cortes *et al*., 2022), serving as an alternative approach to a systematic review. Incorporating a consultation phase within this type of review can further enhance the findings, increasing their relevance and usefulness for integrative agronomic decision making concerning the utilization of alternative crops—such as sweet sorghum as sources of bioproducts. However, in this study, no formal consultation with experts or stakeholders was conducted; this remains a recommendation for future research to improve the applicability of the findings. Gaps in the research that arise from its quality will not be identified by a scoping study (Arksey and O'Malley, 2005). The language was English as criterion during the information search in Semantic Scholar database. The review was structured as follows:

Stage 1: Defining scope and limitations.

Stage 2: Search and Organization of the bibliography.

Stage 3: Analysis of the information, covering the sequence of the industrial process from the field phase for raw material acquisition to the final stage of producing anhydrous bioethanol as an alternative biofuel.

A search was conducted in the Semantic Scholar database (Table 1), which offers five search commands: *sort by number of citations*, *sort by relevance*, *sort by influential articles*, *sort by age*, and *sort by author*. The search used the keywords "bioethanol," "juice," and "sweet sorghum," with the publication period limited to the years 2000–2025. A key aspect of this study was the elimination of redundant information by applying the filter for "review works" through additional keywords: "review," "sweet sorghum," and "biofuels. Chapnick, (2019) highlights that titles and abstracts are the most read parts of a paper, essential for search engines and databases. A clear title with keywords and a concise abstract improve visibility and help readers judge relevance quickly.

Table 1. Search Strategy Summary (based on actual data).

Step	Element	Description
1	Databases searched	a) First option: Semantic Scholar b) Second option: Scopus, Web of Science, Google Scholar, ScienceDirect, MDPI, SciELO, Agricola and Sematic scholar
2	Search period	Articles published between **2000 and 2025**
3	Keywords / Search terms	“sweet sorghum”, “bioethanol Mexico”, “sweet sorghum bioenergy”, “ethanol yield”, “first-generation ethanol”, “sweet sorghum varieties”, “ethanol production technologies” — combined using Boolean operators (AND / OR)
4	Inclusion criteria	- Peer-reviewed journal articles - Studies specifically involving sweet sorghum for bioethanol production from juice - Studies conducted in Mexico or providing relevant data for Mexican conditions - Articles with experimental or field data (yields, sugar content, ethanol volume) - Articles published in English or Spanish - Articles published between 2000 and 2025
5	Exclusion criteria	- Studies not involving sweet sorghum juice Reviews or meta-analyses without original data Grey literature (theses, reports without peer review) Studies focused solely on second-generation biofuels
6	Number of references at each step	1) Initial records identified: **84**
7	Inclusion final references	After removing duplicates, highly specific industrial processes, and filtering by year of publication: **20**

Due to the narrative nature of this review, not all consulted literature is included in the final reference list. However, the broader body of literature reviewed played a crucial role in shaping the conceptual framework and guiding the research direction. In Mexico, additional searches were conducted across several databases, including Dialnet which encompasses journal articles, books, and theses SCOPUS, LATINDEX (a regional online information system for scientific journals from Latin America, the Caribbean, Spain, and Portugal), and Google Scholar. The number of citations related to first-generation bioethanol production (from juice) was compared with those related to second-generation bioethanol production (from bagasse or biomass), with publications categorized by year. These results were further grouped into five-year intervals for a clearer temporal analysis.

RESULTS AND DISCUSSION

Stage 1: Scope and limitations of the review

Biomass, a renewable resource that stores chemical energy in the form of sugars through photosynthesis and convertes it into alcohol via fermentation can originate from various unconventional and alternative sources (Sun *et al*., 2024). For example, the sugar in sweet sorghum is stored in its stalks, making it a promising feedstock for bioethanol production (Khalil *et al*., 2015). Other unconventional sources include agricultural residues such as corn stover, sugarcane bagasse, and forestry wastes, as well as dedicated energy crops like switchgrass and miscanthus (Wheatley, 2023). Sweet sorghum has three main byproducts grains, stalks, and bagasse which are used to produce fuels such as bioethanol (Punia and Kumar, 2025).

The development of bioethanol has been significantly constrained by an excessive focus on securing biomass supply neglecting downstream challenges across the bioenergy chain and, crucially, by the weak or absent integration of social dimensions (Mohr and Raman, 2013). Recent reviews and sectoral analyses confirm and update this critique, identifying persistent gaps in social-life-cycle assessment uptake, land tenure and benefit sharing safeguards, community acceptance, and governance mechanisms that together hinder socially and environmentally sustainable upscaling of bioethanol (Messmann *et al*., 2023). Many factors influence the overall cost of ethanol production, strongly affecting the success of ethanol plants, including feedstock price, ethanol price, natural gas price, and conversion efficiency (Linton *et al*., 2011). Pilot-scale studies of promising processes an essential prerequisite for industrial scale production are scarce for this crop in Mexico (Aguilar and Montes, 2017) and the rest of the world (Andrzejewski e*t al*., 2013a; Wen *et al*., 2022).

In this analysis, sorghum grain was ruled out as a substrate for ethanol production, given that 100% of domestic and imported grain sorghum is used for animal feed in México (Rebollar *et al.*, 2016). Although grain sorghum and sweet sorghum belong to the same botanical species (*Sorghum bicolor* (L.) Moench), they exhibit contrasting morphological and phenotypic characteristics, including plant height, total biomass production, and sugar concentration in the stalk (Dillon *et al.*, 2007). Agronomic management also differs, particularly in harvesting methods (López-Sandin *et al.*, 2021). Ethanol production from sweet sorghum follows a direct process, while production from grain sorghum involves an indirect process (Dutra *et al.*, 2018); therefore, results are not extrapolable.

This analysis considers sweet sorghum as the ideal raw material for first-generation bioethanol production due to technological and economic limitations in producing second-generation bioethanol from cellulosic biomass (López-Sandin *et al.*, 2022). The main obstacle is the additional cost of pretreatment needed to extract simple carbohydrates from cellulosic material (Alonso-Gómez and Bello-Pérez, 2018). Zhao *et al.* (2012) highlight the challenges of integrating first- and second-generation ethanol production technologies. First, the production cost of second-generation ethanol is high, as the waste produced during manufacturing must be burned to supply energy to the plant. While this improves the energy balance and reduces carbon emissions, current integration remains unfeasible despite promising long-term projections.

Technological progress in sweet sorghum cultivation in México is still limited, and the experience with breeding and management prectices is generally scarce (Nolasco-Hipólito *et al.*, 2023). The quality of the raw material supply chain—from field to processed end product is influenced by the plant's genotype, maturity, production conditions, harvesting methods, collection and storage practices, seasonality, presence of extraneous matter (e.g., trash, leaves, or tops), and environmental conditions (Uchimiya *et al.*, 2017; Eggleston *et al.*, 2013; Galicia-Juárez *et al.*, 2022). Initial total sugars, a key industrial factor in ethanol yield, are strongly correlated with sugar yield. Juice traits, in turn, influence the rate of sugar fermentation over time (Bunphan *et al.*, 2015). This includes progress in first-generation ethanol production based on the Brazilian production model, as well as its applicability in México. Brazil was the first country in the world to conduct industrial-scale testing with sweet sorghum cultivation (Fraga, 2012).

Research restrictions stem from the lack of econometric analysis. This is mainly due to the absence of an economic feasibility study assessing the financial viability of using sweet sorghum juice as a first-generation ethanol source in México (Appiah-Nkansah *et al.*, 2019). Existing estimates are based on ethanol production from grain sorghum (Núñez, 2022). The standard process for ethanol production from grain sorghum requires preparing the grain and converting starches into fermentable sugars, which adds to production costs (Nghiem *et al.*, 2018; Nolasco-Hipólito *et al.*, 2023).

In México, requirements and provisions for certifying environmental sustainability in plant-based liquid biofuel production are defined in the Mexican Standard NMX-AA-174-SCFI-2015 (SE, 2015). The new Biofuels Law, published in the Diario Oficial de la Federación (DOF) on March 8, 2025, Section II, Article 1, states: "Promote the sustainable production of biomass for biofuel production on marginal soils that do not come from primary plant-based inputs intended for human consumption, except for surplus sugarcane and sorghum." This is the first regulation governing the production of liquid biofuel from sorghum, which is not intended for human consumption, except when produced as surplus. This opens the possibility of using sweet sorghum as a substitute for grain sorghum under surplus conditions. Established sixteen years after initial adaptation tests for sweet sorghum cultivation began in México, this regulatory framework aligns with international sustainability standards such as the EU Renewable Energy Directive (RED II) and ISO guidelines, which emphasize overall environmental and social safeguards, yet it is notable for its specific focus on marginal land use, restrictions on primary food crops, and explicit consideration of social integration and community benefits, reflecting a locally adapted strategy that balances renewable energy development with food security, sustainable land management, and social responsibility (Messmann *et al*., 2023; IEA, 2024).

Despite efforts to produce biomass sustainably on marginal lands, several risks remain. Environmental risks include droughts and high temperatures, which can limit water availability and affect crop establishment (Domínguez, 2016; Abbas *et al*., 2022) or under saline conditions (Yang *et al*., 2020). Agronomic risks involve variability among sorghum genotypes in stem yield, Brix, sugar content, and potential ethanol yield under stress conditions (Alhajturki *et al*., 2012; Luquet *et al*., 2018; López-Sandin *et al*., 2019). Economic risks stem from uncertain raw material supply, the need to identify suitable marginal lands, and potential input costs (Esparza, 2014; Dong *et al*., 2019). Notably, a trade-off exists between high Brix and low juice content: high sugar concentration is offset by reduced juice volume, which limits total sugar yield and may reduce ethanol production feasibility.

References in this review were selected based on predefined criteria to ensure relevance, recency, and methodological quality, prioritizing peer-reviewed studies, institutional reports, and academic books. Foundational works were included when relevant. This scoping review is not exhaustive and aims to map available evidence rather than critically appraise studies. Limitations include the absence of formal quality assessment, no quantification of effect sizes or causal relationships, and reliance on available literature, which may introduce selection biases or geographical and methodological limitations. Highly technical or process specific information, such as that reported by Heredia-Olea *et al*. (2015), was included due to its detailed guidance on industrial process specifications.

Stage 2: Bibliometric structure

The Semantic Scholar database indexes a total of 248,000 publications related to sweet sorghum across diverse research of crop. For the purpose of this study, only those publications examining sweet sorghum as a feedstock for first generation bioethanol from juice. Highlighting its significance within renewable energy research, the most frequently cited study is that of Yang *et al*. (2020), which has been referenced 319 times to date according to Frontiers in Plant Science. This work examines the photosynthetic capacity of sweet sorghum under salinity stress. Although not directly focused on bioenergy, this topic is included in the analysis due to its relevance to the selected subjet of environmental constraints affecting sweet sorghum. Prior to the advent of electronic bibliographic databases, Frolkova and Raeva (2010) conducted an extensive review on a specific subject ethanol dehydration which was cited by 134 authors and included 86 references. In the present analysis, ethanol dehydration is considered a cross-cutting issue, given the market focus on biofuels (Alonso-Gómez and Bello-Pérez, 2018).

The overall downward trend in publications (Table 2), likely reflects a shift in research priorities toward second-generation bioethanol technologies that utilize lignocellulosic feedstocks more broadly, as well as potential funding constraints for first-generation bioethanol studies. This suggests that while sweet sorghum remains relevant, the scientific focus has increasingly moved toward more sustainable and scalable bioenergy solutions. Furthermore, Table 2 does not encompass all macro-level data for the crop (247,000 records), but instead emphasizes more recent records from 2000 to 2025 pertaining to its use as biofuel feedstock.

These results can be attributed to differences in the production processes. The production of second-generation bioethanol from sweet sorghum involves key stages, including the pretreatment of lignocellulosic biomass (bagasse), the optimization of enzymatic hydrolysis to release sugars, and the efficient fermentation of both hexoses and pentoses to produce ethanol (Lennartsson *et al.*, 2014; Dutra *et al.*, 2018). This makes it a complex process that requires further research.

Important areas for future investigation in sweet sorghum bioethanol production include genetic improvement to develop varieties with high biomass and sugar content (López-Sandin *et al*., 2022); assessment of the impact of agronomic practices such as the removal of crop residues like panicles on ethanol yield (Ferreira *et al*., 2016); and analysis of bagasse-derived co-products (Chuck-Hernández *et al*., 2011; Alonso-Gómez and Bello-Pérez, 2018). Despite the push for sustainable biomass production on marginal lands, several risks persist. Environmental risks include recurrent droughts and high temperatures, which can limit water availability and affect crop establishment and growth (Domínguez, 2016; Abbas *et al*., 2022). Agronomic risks involve variability among sorghum genotypes in stem yield, Brix percentage, sugar content, and potential ethanol yield under stress conditions (Alhajturki *et al*., 2012; Luquet *et al*., 2018; López-Sandin *et al*., 2019). Economic risks stem from uncertainties in raw material supply, the need to define and locate suitable marginal lands (Esparza, 2014; Dong *et al*., 2019), and potential costs of inputs and infrastructure. A trade-off exists between high Brix and low juice content: while high sugar concentration is favorable, reduced juice volume limits total sugar availability, constraining ethanol yield and production feasibility. Bibliometric analysis shows a downward

Table 2. Temporal and Bibliometric Trends of Sweet Sorghum Publications Relevant to Bioethanol Production.

Filter / Search Criteria	Number of Citations	Time Frame	Peak Publication Period	Earliest Citation	Trend
Second filter: Year 2000–2025	99,300	2000–2025	2010–2020 (73%)	1998	Downward
Third filter: “sweet sorghum,” “juice,” “first generation,” “ethanol”	84	2000–2025	2010–2020 (73%)	1998	Downward
Search: “ethanol + bagasse + sweet sorghum”	6,450	1933–2025	2010–2020 (84%)	1933	Downward

trend in publications focused on first-generation sweet sorghum bioethanol, likely due to a shift toward second-generation lignocellulosic technologies and potential funding constraints, although the peak of research activity occurred between 2010 and 2020. Urgent research gaps remain in reducing pretreatment costs, improving enzymatic hydrolysis efficiency, and conducting large-scale trials to validate laboratory results, all of which are essential to enhance economic feasibility and the scalability of sweet sorghum bioethanol production.

The bibliographic search identified 22 literature reviews using the keywords "review," "sweet sorghum," and "biofuels." The report by Turhollow *et al.* (2010) was the most cited, with 35 authors referencing it. However, it was excluded from the present analysis because this reference is a technical project report from Oak Ridge National Laboratory that summarizes sorghum production practices for bioenergy. While useful for historical context, its data may be outdated, and it lacks detailed economic and sustainability analyses, so it should be complemented with more recent literature.

That report cited 128 references, 84 of which were also retrieved from the Semantic Scholar database using the primary keyword filters ("sorghum," "juice," "first generation," and "ethanol"), along with publication year as a filter. Only 20 of those publications were ultimately cited in this study because there were no redundant references, and the remaining references were deemed unrelated to the research topic. The rest of the information was gathered by consulting specific works aligned with the criteria and parameters described in the Materials and Methods section. When including references in a scoping review, they should be relevant, high-quality, and preferably recent. They must provide unique or complementary evidence or methodology, consider the geographical or population context, and come from recognized authors or institutions. Transparency and rigor in reporting are essential. References meeting these criteria are suitable for inclusion, while others may be used only for context or excluded. For example, studies focused solely on technical details of grain, bagasse, or juice processing, such as those by Heredia-Olea *et al.* (2015). Additional grounds for exclusion include sources that repeat information already presented in the review.

This manuscript includes 129 references on the subject, categorized according to the main criteria used for the literature search (Chapnick, 2019), as follows: 70 correspond to sweet sorghum as a feedstock for biofuels; the term "sweet sorghum" in English accounted for 68.6%; "sorgo dulce" in Spanish represented 21.4% (mainly related to new cultivars of sweet sorghum); "sorghum" in general comprised 8.5%; and "sorgo sacarino" in Portuguese accounted for 1.5%. Regarding the potential applications of sweet sorghum juice, three main uses were identified: (i) bioethanol production, (ii) traditional beverage syrup, and (iii) potential lactic acid production. Within this context, of the 70 references specifically addressing sweet sorghum juice, only 22 (31.4%) focused on bioethanol; both sweet sorghum syrup three and lactic acid were mentioned in only two references (7.1%) (Table 3). The remaining references were classified as complementary for this review, totaling 45.7 (50%). Finally, it is important to note that the proposal of sweet sorghum juice as a feedstock does not correspond to second-generation biofuels, since the term "juice" explicitly excludes that category.

This classification refers to the typology and language distribution of the 129 references included in the review. Among them, 107 (82.9%) were original research articles, 15 (11.6%) were review papers, and the remaining seven (5.4%) included two technical manuals, two book chapters, and two reports, with one reference unspecified. Regarding language, 48 references were written in English, 15 in Spanish, and one in Portuguese (Fraga, 2012). English publications dominate the scientific literature on sweet sorghum biofuels due to several factors. English is the primary language of global scientific communication, offering greater visibility, citation potential, and access to international audiences. Leading research countries in bioenergy, such as the USA, China, India, and Brazil, publish predominantly publish in English. In contrast Latin American studies, though present, often aim for

Table 3. Final results of the bibliometric analysis: sweet sorghum as a feedstock for first-generation bioethanol.

Title (Keywords)	Number of references	Title (Specific keywords)	Number of references	Language
Sweet Sorghum	48	Sweet Sorghum Juice	22	English
		Sweet Sorghum Syrup	3	
		Sweet Sorghum Lactic Acid	2	
Sorgo dulce	15			Spanish
Sorghum	6			English
Sorgo sacarino	1			Portugues
Total	70			

international impact by using English. Funding agencies and international collaboration programs also favor English publications. Additionally, major bibliographic databases index mainly English language articles, creating a cumulative effect of higher visibility and citations. Finally, technical terminology in biofuel research has been standardized in English, facilitating communication among global researchers. Consequently, Spanish-language literature exists but tends to have a more regional scope and limited international visibility.

The concept of biofuels is part of a broader framework that encompasses fuels and energy in general (Mohrn and Raman, 2013). For the purposes of this review, 64 complementary references were included, covering both general and specific topics to explain the origin of biofuels, bioethanol or ethanol derived from organic sources, their economic implications, the differences between grain- and juice-based feedstocks for sweet sorghum bioethanol, and a brief overview of the regulatory framework for biofuels (Table 4). Within this group, 15 references corresponded to review articles, representing 23.4%.

Following the search strategy using the title as the primary criterion and adding a second specific keyword the main terms identified were bioethanol (17 references; 27.0%) and ethanol (11 references; 17.2%). The most relevant complementary references totaled 44 (Table 4). The remaining ten references addressed topics such as sorghum bagasse, sugarcane clarification, fermentation overviews, sorghum genetic resources and breeding, sugarcane juice, grain sorghum economics, sustainability, and the regulatory framework for biofuels.

Stage 3: Analysis of information on the technological process

Raw material: Sorghum

Sweet sorghum, a C4 crop from the grass family, is characterized by its high photosynthetic efficiency, which confers advantages in water-use efficiency and productivity. As a multipurpose crop producing grain, biomass for fodder, and ethanol fuel from its stem juice, sweet sorghum represents a sustainable and attractive alternative for bioenergy production (Sun *et al*., 2024). Sweet sorghum plants can reach heights between 120 and 400 cm and have sugar contents ranging from 16 to 23° Brix, depending on the variety and cultivation location (Montes *et al*., 2019; Jiménez-Ocampo *et al*., 2024). Its juice contains total soluble sugars ranging from 110 to 190 gL^{-1} (Wu *et al.*, 2010; Guigou *et al*., 2011). While these values are slightly lower than those typically observed in sugarcane, which can reach 18 to 25° Brix and 150 to 250 gL^{-1} of total soluble sugars, sweet sorghum offers advantages in terms of faster growth cycles, adaptability to marginal lands, and multipurpose use, making it a viable alternative feedstock for ethanol production (Sun *et al*., 2024).

Sweet sorghum is often considered one of the most drought-resistant crops, as it can remain dormant during dry periods and requires minimal fertilization. For example, the 'Dulcina' variety has been developed with wide environmental adaptability, including tolerance to limited water availability in northwestern Mexico (Williams-Alanís *et al*., 2025). Furthermore, it grows quickly and is easy to sow; therefore, the cost of total fermentable sugars would be lower (Rao *et al.*, 2013), since sweet sorghum's production cost is lower than that of corn (Alejandro *et al.*, 2020). When sorghum is used as a source of ethanol, economic projections are often based on estimates for grain sorghum (Núñez, 2022). This approach can introduce bias, as grain sorghum differs from sweet sorghum in

Table 4. Bibliometric complementary analysis of references on bioethanol, bioenergy, and related topics.

Title (Keywords)	Number of references	Title (Specific keywords)	Number of references	Language
Bioethanol	17	Sugarcane	3	English
		Grain sorghum	1	
Ethanol	11	Sugarcane	2	Enlish
		Obtain	9	
Etanol	4	Caña de azucar	2	Spanish
		Obtención	2	
Bioenergy	4	Overview		English
Biofuels	3	Overview		English
Energy	3	Overview		
Clima	2	Overview		Spanish
Subtotal	**44**			
Other keywords	**10**			
Total	**64**			

biomass allocation, sugar content, and ethanol yield potential. Grain sorghum requires converting starch from the grain into fermentable sugars, which involves additional processing steps and higher costs. By contrast, sweet sorghum can produce ethanol directly from stem juice, providing greater conversion efficiency and potentially higher ethanol yields per hectare (Wu *et al*., 2010). In this analysis, both sources have been considered to provide a more accurate assessment of sweet sorghum's true economic and bioenergy potential.

Importance of uses of sweet sorghum a source of bioproducts

Sweet sorghum is considered a promising alternative to conventional crops such as corn and sugarcane due to its global genetic diversity and suitability for producing raw materials with industrial potential (Enyew *et al*., 2022). Compared to corn, sweet sorghum has a shorter growth cycle and requires lower fertilizer and water inputs. In contrast to sugarcane, it is more resilient to drought and can be cultivated on marginal lands, making it a versatile and sustainable feedstock for bioethanol production (Sun *et al*., 2024). In México, sweet sorghum varieties have been developed for different agroecological environments to obtain juice, sugar, foliage, and bagasse (Williams-Alanís *et al.*, 2017; Montes *et al.*, 2019; Espinosa-Paz *et al.*, 2019; Jiménez-Ocampo *et al.*, 2024).

Furthermore, regarding the technological package for crop management, the first technical guide for sweet sorghum production was published in the state of Tamaulipas, Mexico. Beyond its publication, this guide has practical significance as it provides standardized recommendations that facilitate adoption by farmers, support mechanization of cultivation practices, and serve as a training resource for producers, ultimately improving crop management efficiency and enhancing bioethanol production potential (Montes *et al.*, 2010), and was subsequently extended to other regions, such as the subhumid tropics of the state of Jalisco (Álvarez and Montes, 2017). This crop possesses important agronomic characteristics as a source of raw materials for generating renewable or green energy (Uchimiya *et al.*, 2017). It is cultivated from seeds and has a short growth cycle of approximately four months, which facilitates double harvesting. Its production can be fully mechanized (Ghahraei *et al.*, 2014) to obtain sugar from the stem and starch from the grain. Field trials conducted in Mexico with the sweet sorghum variety 'Roger' demonstrated efficient water and nutrient use. López-Sandin *et al*. (2021) reported that under limited irrigation conditions, 'Roger' achieved biomass yields of up to 95 tha^{-1} and sugar accumulation of 18 to 22° Brix, with minimal fertilizer inputs. These results highlight the crop's ability to maintain high productivity in water-scarce environments, supporting its potential as a sustainable feedstock for bioethanol production.

Bagasse, a sweet sorghum byproduct with high biological value (Wright *et al.*, 2016), is used as fodder (Montes *et al.*, 2019) and for obtaining second-generation ethanol (López-Sandin *et al.*, 2022).

Sweet sorghum has a high juice and bagasse content, making it a crop with great potential for various uses. However, most applications worldwide have so far been limited to animal feed (Mejía-Kerguelén *et al*., 2019) and syrup production (Chibrikov *et al*., 2024). The expansion of industrial applications, such as bioethanol production and bioproducts, is constrained by factors including limited mechanization, variability in sugar content across varieties, insufficient processing infrastructure, and high initial investment costs. Addressing these barriers is essential to fully exploit sweet sorghum's industrial potential. Among the products derived from sweet sorghum is ethanol. Sweet sorghum has a juicy biomass production potential of 30 to 50 tha^{-1} and juice recovery rates of 40 to 60%, making it a promising alternative feedstock for fuel ethanol production (Sun *et al*., 2024). For comparison, sugarcane typically yields 70 to 90 tha^{-1} of biomass with juice recovery around 65–75%, while corn for starch-based ethanol produces 10–12 $t{\cdot}ha^{-1}$ of grain. These comparisons highlight that, despite slightly lower biomass yields than sugarcane, sweet sorghum offers rapid growth, adaptability to marginal lands, and dual-use potential, reinforcing its attractiveness as a sustainable bioenergy crop (Wu *et al*., 2010; Luquet *et al*., 2018). Concentrated and sterilized natural sweet sorghum syrup can be used industrially to obtain lactic acid (Olszewska-Widdrat *et al.*, 2019) and as a sweetener in the confectionery industry (Datta *et al.*, 2012). This syrup can replace honey and is known as "sorghum honey." Its chemical composition is similar to that of honey (Eggleston *et al.*, 2016; Chibrikov *et al.*, 2024). The sugars present in sweet sorghum stalks include sucrose, glucose, and fructose; thus, depending on the sugar profile of the juice, the average yield of concentrated syrup varies according to cultivar and sowing date (Williams-Alanís *et al.*, 2017; Uchimiya *et al.*, 2017).

Sweet sorghum juice composition

Upon reviewing the article by Chibrikov *et al*. (2024) titled "Sweet sorghum juice clarification and concentration: a review," it is observed that the 40 references cited in this work are primarily international studies on the clarification and concentration of sweet sorghum juice. No studies conducted specifically in Mexico were identified among these references. This suggests that the evidence presented in the review mainly reflects global research trends, without significant representation of Mexican studies in this field. The accumulation of primary sugars in sweet sorghum juice, including glucose (40 to 60 gL^{-1}), fructose (35 to 55 gL^{-1}), sucrose (50 to 80 gL^{-1}), and total sugars (110 to 190 gL^{-1}) is influenced by significant effects of cultivar and planting date. Similar trends are observed for secondary compounds such as trans-aconitic acid, phenolic compounds, proteins, minerals (P, Ca, K, and Mg), and pH (Uchimiya *et al*., 2017; Galicia-Juárez *et al*., 2022). These quantitative data highlight the variability in sugar composition depending on genotype and management practices, providing a more detailed understanding of the feedstock quality for ethanol production. Moreover, the phenology of each sweet sorghum genotype affect the profile of sugar accumulation in the stalk over time (Gomes *et al*., 2021). Due to genetic and environmental variations influencing juice quantity and quality, it is expected that each production area has a specific field technology package for this crop.

Advances in agronomic management in Mexico

Grain sorghum cultivation is a well-established practice in Mexico (Alejadro *et al*, 2020) with varieties adapted to diverse agroclimatic conditions (Montes *et al*., 2021). The physiological maturity of grain sorghum typically occurs between 100 and 120 days after planting, depending on variety and environmental conditions (Gutiérrez *et al*., 2020). In contrast, sweet sorghum remains at an early stage of research and adoption. For instance, the Tom 3 variety exhibits panicle emergence at 93 days after sowing, indicating a shorter cycle compared to grain sorghum (Jiménez-Ocampo *et al*., 2024). These differences underscore the need for further research to optimize agronomic practices and facilitate the broader adoption of sweet sorghum as a sustainable bioenergy crop in Mexico. Sweet sorghum cultivation in Mexico is considered an alternative to conventional crops such as corn and sugarcane for producing raw materials with agroindustrial potential, due to its diverse genetic base (Enyew *et al.*, 2022; Williams-Alanís *et al.*, 2020).

The first challenge faced by sweet sorghum was the lack of domestic varieties. The initial commercial varieties were developed at the Meridian Experimental Station in Mississippi, United States, during the 1960s and 1970s (Murray *et al.*, 2009), primarily for syrup extraction (Eggleston *et al.*, 2016). However, some of these varieties struggled to adapt to Mexican conditions (Montes *et al.*, 2019). RB-Cañero, Mexico's first nationally released sweet sorghum variety, produces 62.9 to 118.2 tha^{-1} of stalk biomass, with juice containing 13.8–17.1 °Brix. Adaptable to spring–summer and autumn–winter cycles in regions such as Tamaulipas, Nuevo León, and the Huasteca Potosina, it represents a versatile feedstock for sustainable bioenergy production (Montes *et al.*, 2021).

Currently, there are sweet sorghum varieties developed for juice, sugar, fodder, and bagasse production (Williams-Alanís *et al.*, 2017; Montes-García *et al.*, 2019; Jiménez-Ocampo *et al.*, 2024). It was necessary to define agronomic management factors such as row spacing, plant density, sowing and harvesting times, and total soluble stem solids (Da Silva *et al.*, 2017), tailored to the specific conditions of each location.

Furthermore, the first technical guide for crop management was published in the state of Tamaulipas, México, in 2010 (Montes *et al.*, 2010), and later extended to other regions, such as the subhumid tropics of the state of Jalisco (Álvarez and Montes, 2017). Experiments conducted in Ocozocoautla and Suchiapa, Central Chiapas, Mexico, during 2015-2017 revealed significant effects of environment, variety, and genotype × environment interactions on sweet sorghum performance. These interactions primarily influenced juice sugar content (°Brix), with varieties such as RB-Cañaveral and Fortuna achieving 15.92 and 14.28 °Brix at flowering, and 17.9 and 15.86 °Brix at physiological maturity, respectively. Although yield differences were observed, the data indicate that °Brix was more sensitive to genotype × environment effects than total biomass, highlighting the importance of selecting varieties adapted to specific environmental conditions for optimal ethanol production (Espinosa-Paz *et al*., 2019). The main technological advance has been the development of varieties adapted to different agroecological zones in Mexico, did not exist before. The crop is propagated by seed with an annual cycle lasting approximately four months from sowing to harvest, allowing double harvesting. Moreover, complete mechanization from sowing to harvest is a significant technological advantage (Alonso-Gómez and Bello-Pérez, 2018).

Obtaining bioethanol

Ethanol, also known as bioethanol or ethyl alcohol, is a colorless, volatile, flammable, and water-soluble liquid compound composed of carbon, hydrogen, and oxygen atoms (Bint *et al.*, 2016). It is produced through the fermentation of grains or biomass rich in starches and sugars, whereby carbohydrates are converted into alcohol by the action of microorganisms. Ethanol can be used as an automotive fuel either in its pure form, with an alcohol content by volume (ABV) of 99.3%, or blended with gasoline in varying proportions ranging from 5% to 85% ethanol (Vázquez and Dacosta, 2007). In Mexico, the Energy Regulatory Commission (CRE) authorized through NOM-016-CRE-2016 the use of ethanol–gasoline blends of up to 10% ethanol (E10) in most of the country, excluding metropolitan areas with critical air quality issues such as Mexico City, Guadalajara, and Monterrey (CRE, 2017).

Technically, ethanol can be obtained from any organic material containing fermentable sugars (Lennartsson *et al*., 2014). First-generation raw materials, such as sugarcane and corn, currently account for more than 90% of global ethanol production (Bušić *et al*., 2018) due to their high sugar or starch content and well-established processing methods. In contrast, second-generation raw materials, including agricultural residues, lignocellulosic biomass, and forestry by-products, require additional pretreatment and enzymatic hydrolysis to release fermentable sugars, offering a more sustainable alternative that does not compete directly with food crops (López-Sandin *et al*., 2022). Recent studies highlight that second-generation bioethanol production can be considered a technological innovation that addresses environmental concerns and offers a more sustainable alternative to first-generation bioethanol (Guimarães *et al*., 2023). In Mexico, ethanol from molasses (Figure 1), a sugarcane by-product, contributes approximately 3.17% total ethanol production, based on an estimated 15.84 million liters from 1.76 million tons of molasses annually (Argote, 2015; Aburto and Martínez-Hernández, 2021).

The use of this raw material presents an opportunity for the national sugar industry, as it is relatively easy to make adjustments to expand the instantaneous capacity of existing factories (Becerra-Pérez, 2009). However, ethanol production directly from sugarcane juice is also feasible (Carrillo-Ávila, 2016; Silva *et al.*, 2021).

Ethanol production technologies are categorized by both feedstock type and processing requirements: first-generation crops like sugarcane and corn undergo conventional fermentation, whereas second-generation lignocellulosic biomass requires pretreatment and enzymatic hydrolysis to release fermentable sugars. Materials rich in simple sugars such as sugarcane, molasses, and sweet sorghum and those abundant in starch such as potatoes, sweet potatoes, and cereals utilize so-called "first-generation" technology, in which the cost of raw materials represents between 60% and 80% of the final bioethanol cost (Lennartsson *et al.*, 2014). Ethanol production varies by country based on feedstock and policies: Brazil's corn ethanol production reached approximately 8.2 billion liters in 2024/25, accounting for 22% of total ethanol output (Grandis *et al*., 2024); the United States, the world's leading ethanol producer, generated around 15.6 billion gallons (59.1 billion liters) from corn in 2023 (Kumar and Sinha, 2025); and in Mexico, ethanol from molasses constitutes a small fraction of total fuel consumption (USDA-FAS, 2024).

Conversely, ethanol obtained from agricultural residues (lignocellulosic wastes), such as grasses and, more generally, fibrous materials composed mainly of hemicellulose, cellulose, and lignin, is classified as "second-generation" ethanol (López-Sandín *et al.*, 2022). This process requires additional steps compared to first-generation methods, as it is necessary to release monomeric sugars primarily glucose, xylose, and arabinose trapped within a matrix of hemicellulose, cellulose, and lignin. The resulting sugars are then fermented by microorganisms capable of assimilating and fermenting both hexoses and pentoses (Dutra *et al.*, 2018).

The basic approach for sweet sorghum production is derived from the experience of sugarcane cultivation, as practiced in Brazil (Figure 2). The technologies used to produce bioethanol can be classified according to the type of raw material (Carrillo-Ávila, 2016).

Technology experience: first-gneration biothanol

The Brazilian government developed policies that created an optimal environment for establishing the first biorefinery based on sugarcane cultivation. This biorefinery produces biofuels, sugar, and bioelectricity with the goal of providing sustainable solutions at low cost (Vandenberhe *et al.*, 2022). Brazil technological expertise in ethanol production enabled industrial trials for producing ethanol from sweet sorghum (Dutra *et al.*, 2018). To date, Brazil is the only country to report industrial-level results for this crop (Fraga, 2012).

Most available information derives from experiments aiming to estimate the theoretical ethanol production (Dávila-Gómez *et al.*, 2011), which serves as a criterion for determining the potential of different varieties (Galicia-Juárez *et al.*, 2022). Subsequently, it is necessary to scale up these results, advancing the process from initial development to higher levels of study that allow increased production volumes (Alonso-Gómez and Bello-Pérez, 2018), as shown Figure 4. In response to this demand, the first pilot plant to produce first-generation bioethanol from sweet sorghum juice was built in Veracruz, México (Álvarez and Montes, 2017). The process consists of five steps to obtain the final product (Figure 3). To date, advances have focused on maximizing the use of raw materials and byproducts during processing (Vandenberhe *et al.*, 2022).

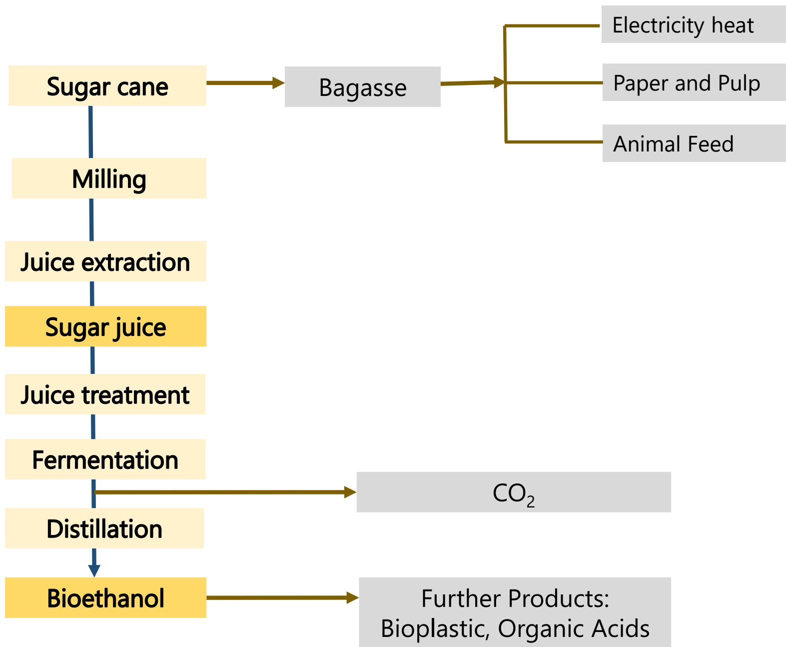

Figure 1. Process diagram of conventional first-generation sugarcane production. Gray boxes indicate secondary products. Source: Prepared with information from Vandenberghe *et al*. (2022).

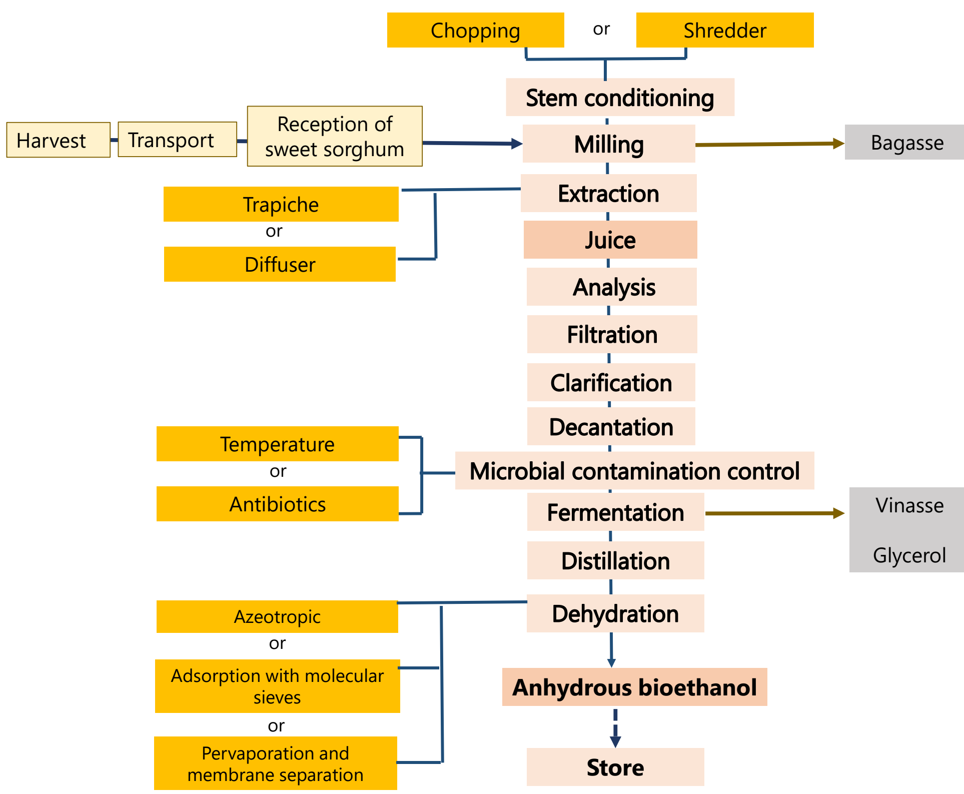

Figure 2. Process diagram for the production of bioethanol from sweet sorghum, adapted from the sugarcane process in Brazil. Gray boxes indicate secondary products. Source: Prepared with information from Fraga (2012).

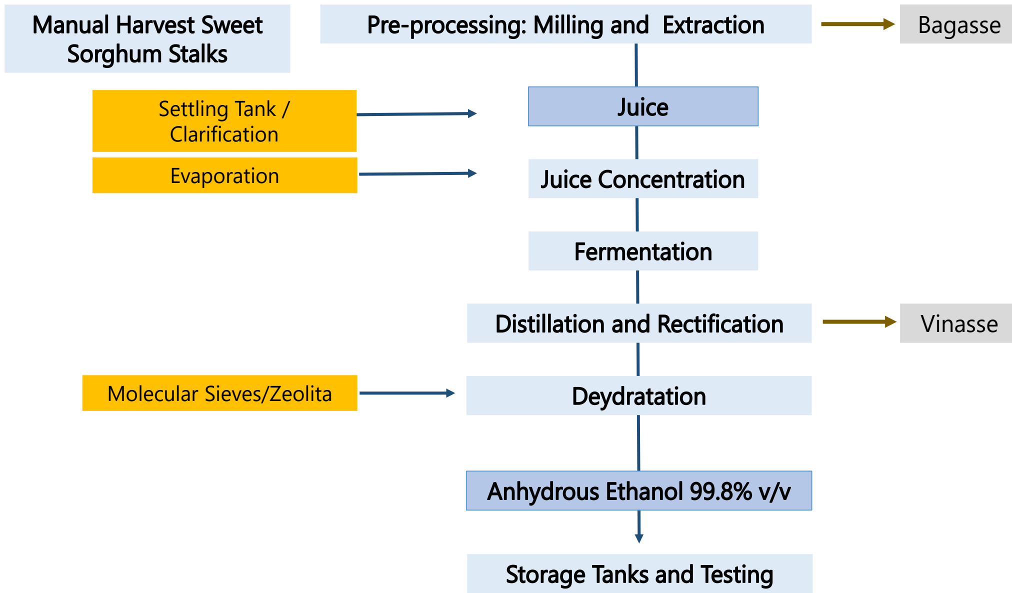

Figure 3. Process diagram for conventional sweet sorghum ethanol production in a pilot biofactory. Gray boxes indicate secondary products. Source: Prepared with information from Aguilar and Montes (2017).

First-generation bioethanol production process

This traditional method of bioethanol production involves using conventional techniques to convert these crops into fuel, primarily ethanol (Figure 4). The alcohol is produced through the microbial fermentation of edible crops rich in sugars or starches, such as corn, sugarcane, and sugar beets.

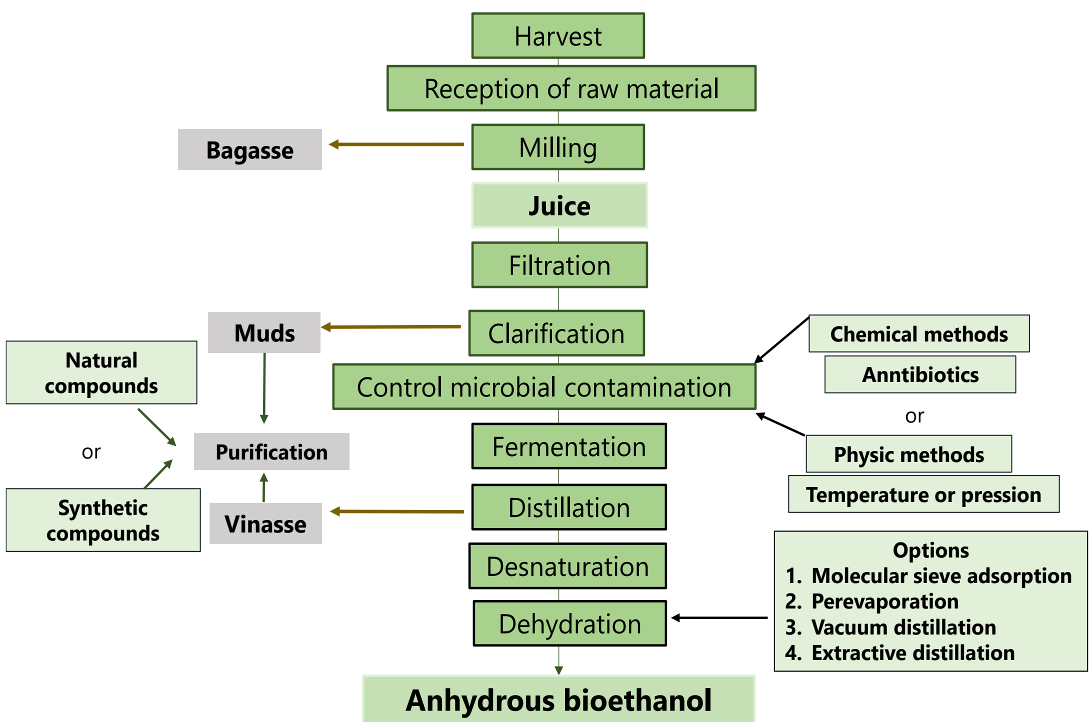

Figure 4. Theoretical proposal for obtaining bioethanol from sweet sorghum juice. Gray boxes indicate secondary products. Source: Prepared with information from Alonso-Gómez and Bello-Pérez (2018).

Harvest and transportation

The process begins with harvesting, ideally coordinated closely with processing, due to potential deterioration of the raw material caused by significant decreases in glucose during storage and bacterial spoilage (Attchelouwa *et al.*, 2018). A key difference between sugarcane and sweet sorghum harvests is the presence of residues; sorghum panicles and leaves must be removed to avoid starch and phenolic compounds in the juice (Ferreira *et al.*, 2016). Brazilian industries processing sweet sorghum have observed plant impurities ranging from 1% to 12% (Fraga, 2012).

The harvesting method is critical at this stage because it influences impurity levels, production volume, and cost. Manual harvesting increases raw material costs (Alonso-Gómez and Bello-Pérez, 2018). In Brazil and the United States, mechanized harvesting is feasible due to the possibility of adapting sugarcane harvesting machinery (Ghahraei *et al.*, 2008; Kumar *et al.*, 2024). Mechanization efforts for sweet sorghum harvesting focus on machines capable of harvesting the entire plant, preferably defoliated, to minimize stem damage a crucial factor in reducing sugar loss during storage (Lingle *et al.*, 2011; Amaducci *et al.*, 2018).

In Mexico, the lack of mechanization during harvesting limits the expansion of sweet sorghum cultivation, as cutting is still done manually (Montes *et al.*, 2010). This situation necessitates the design of new machinery prototypes or the adaptation of existing equipment used for sugarcane (Ortíz *et al.*, 2012). Differences in field crop management, particularly furrow width, must be considered to avoid biomass loss due to crushing.

Compared to traditional burning and manual cutting methods, mechanical harvesting increases the presence of inorganic compounds such as potassium, calcium, silicon, iron, and copper, which can negatively affect fermentation efficiency (Costa *et al*., 2015). These minerals can inhibit yeast activity, reduce sugar uptake, and interfere with enzymatic processes, ultimately decreasing ethanol yield and overall process efficiency (Liu *et al.*, 2008). Currently, equipment exists either for harvesting grain from grain sorghum or for extracting liquid sugar from sweet sorghum, but no machinery efficiently harvests all three components grain, stalk juice, and biomass from a single crop (Srinivasa *et al.*, 2014).

Sorghum has promising agroindustrial qualities for bioethanol production (Chuck-Hernández *et al.*, 2012); however, its high biomass moisture content (70%) and low bulk density limit transport distances after harvest (Zegada-Lizarazu and Monti, 2015). An economic feasibility study specific to regions in Mexico must be developed, considering raw material transportation as a critical component of the supply chain (Linton *et al.*, 2011; Pérez-Lechuga *et al.*, 2019).

Extraction and removal of impurities

Juice yield is a commercially significant factor influenced by mill adjustment, feeding rate, moisture content of the stalks, their hardness, dryness, and maturity (Eggleston *et al.*, 2016). On average, sweet sorghum can yield approximately 700-800 liters of juice per ton of fresh stalks (Liu *et al*., 2008. Juice obtained through milling must be filtered (Chibrikov *et al.*, 2024). The sorghum preparation process begins by increasing the material density during extraction. The sorghum stalks are cut into small pieces to release the juice and increase milling capacity (Jia *et al.*, 2013). In Mexico, this operation can be performed with traditional mills that grind whole stalks (Arvizu *et al.*, 2016).

At the industrial level, there are two extraction processes: milling and diffusion. Both are efficient and economically competitive (Palacios-Bereche *et al.*, 2014). Milling, the conventional extraction method, involves passing the material through pressurized rolls with hot water to release the juice (Barroga *et al.*, 2015; Yuwono *et al.*, 2020). The efficiency of sweet sorghum extraction can vary depending on the chemical composition of the fiber and the anatomical structure of the stalk (Mengistie *et al.*, 2024). The proportion of bagasse, based on fresh or dry weight, varies significantly depending on genotype, as well as climatic and agronomic conditions. For instance, across ten sweet sorghum genotypes, bagasse accounted for 49% ± 6.7 of fresh biomass, with an 8% difference observed between two consecutive years (Galicia-Juárez *et al*., 2022). These values are comparable to those reported for sugarcane (N da Silva *et al*., 2014).

Depending on the fiber content in the stems, milling and soaking parameters must be adjusted to avoid clogging and ensure high efficiency (Ungureanu *et al.*, 2022). Operational problems during milling reduce juice extraction wich consequently increases the final moisture content of the bagasse and sugar concentration (Jia *et al.*, 2013). This complicates burning the residue due to combustion failures (Nazli *et al.*, 2024). Sweet sorghum can lose up to 10% of juice due to extraction problems during processing (Fraga, 2012).

Diffusion is an efficient alternative to traditional milling systems (Palacios-Bereche *et al.*, 2014). However, in the case of sweet sorghum, diffusers have not yet been employed in the sugar extraction process (Fraga, 2012). During this step, the sucrose content of the solution is determined either by direct polarization or by using a normal-weight solution in a saccharimeter, following procedures adapted from sugarcane practices (Mendieta and Escalante, 2013). A large amount of soluble impurities and insoluble substances must be removed by filtration or centrifugation during extraction (Alonso-Gómez and Bello-Pérez, 2018).

Clarification

To improve ethanol quality and optimize subsequent processes, such as distillation, clarification is a crucial step. This process removes suspended solids and impurities, which can inhibit yeast activity and reduce fermentation efficiency, thereby minimizing contamination and enhancing overall ethanol yield (Thai *et al*., 2012). Typical values for raw and clarified sugarcane juice serve as a reference for developing a commercially viable clarification method for sweet sorghum juice (Andrzejewski *et al.*, 2013b). Common clarifying agents include lime ($Ca(OH)_2$), phosphoric acid (H_3PO_4), and aluminum sulfate, which help remove suspended solids, reduce turbidity, and minimize impurities that could inhibit yeast activity during fermentation (Taher *et al*., 2020; Kumar and Singh, 2023). The choice and dosage of the clarifying agent are critical for optimizing ethanol yield and process efficiency.

The scale of extraction significantly influences the volume of waste generated (Eggleston *et al.*, 2016). Conventional or traditional mills produce a small amount of residue in the juice (Hernández-Cely and Torres-Zamudio, 2021). For this reason, clarification is sometimes omitted, as seen in the proposed scheme for a sweet sorghum pilot plant in México (Álvarez and Montes, 2017).

Compared to raw sugarcane juice, clarified sugarcane juice is more stable due to the removal of microorganisms, enzymes, and other suspended and turbid impurities through heating and precipitation (Costa *et al.*, 2015). Studies have demonstrated that enzymatic treatment of sweet sorghum juice is essential to stabilize its composition (Chibrikov *et al*., 2024). Commonly used enzymes include pectinases, which break down pectins to reduce viscosity and prevent juice gelation, and amylases, which hydrolyze starch residues to soluble sugars, improving juice clarity and stability during storage and fermentation (Saleh *et al.*, 2022; Kumar and Singh, 2023). Enzymatic treatment enhances sugar availability, reduces microbial contamination, and optimizes ethanol yield.

Decantation and evaporation

Decantation concludes the purification stage of the broth, a process similar to that used for sugarcane. This step is essential for removing suspended solids and other impurities, which can interfere with subsequent processing and fermentation (Mendieta and Escalante, 2013). Evaporation then concentrates the sugar content by removing water and soluble substances, preparing the juice for efficient ethanol production (Taher *et al*., 2020). Proper decantation enhances juice clarity, reduces microbial contamination, and improves overall fermentation efficiency. Generally, a concentration of 18 to 22% is used. In the case of sweet sorghum, if this concentration is achievable, lower values can increase the fermentation rate but may reduce overall productivity (Fraga, 2012). In this review, specific studies addressing the decantation and evaporation processes for sweet sorghum are limited. The available information is primarily drawn from pilot-scale and industrial investigations, which highlight the importance of these steps in removing suspended solids, concentrating sugars, and preparing the juice for efficient ethanol production (Andrzejewski *et al*., 2013a, 2013b; Hryhorenko *et al*., 2021; Harlen *et al*., 2023).

Fermentation

Bioconversion is a critical stage in ethanol production, where yeast converts sugars into ethanol. The efficiency of this process affects ethanol yield and production costs, and is influenced by factors such as temperature, pH, nutrient availability, oxygen levels, and alcohol tolerance (Table 5). Optimizing these conditions is essential for maximizing productivity. Industrial fermentation can be performed in batch or continuous systems, each with advantages and limitations. Research has focused on selecting robust yeast strains, adjusting substrate composition, and controlling contamination. Mixed cultures and specific strains, such as thermotolerant native yeasts, have shown potential for improved ethanol yields (Table 5). Optimal fermentation parameters include moderate temperature, slightly acidic pH, and appropriate inoculation rates. Variations in strains, sorghum genotypes, and operational conditions can lead to differences between theoretical and experimental ethanol yields, as summarized in Table 5 summarizes these differences highlighting the contributions of various studies to the understanding and optimization of sweet sorghum fermentation.

Table 5. Key contributions and findings on sweet sorghum fermentation, organized by year and author.

Year	Author(s)	Key Contribution / Findings
2007	Vázquez and Dacosta	Highlighted the critical role of fermentation; *Saccharomyces cerevisiae* widely used.
2007	Malherbe *et al*	Effects of microbial contamination (wild yeast, acetic acid) on fermentation.
2011	Bridgers and Guigou	Identified key factors affecting fermentation: temperature, pH, substrate, nutrients, oxygen, and alcohol tolerance.
2011	Wang *et al*	Optimal fermentation: 27.7 °C, pH 5.4, inoculation 5%, ethanol efficiency 9.3%.
2013	Suwanapong	Recommended urea supplementation and pH adjustment (4.5) before yeast fermentation.
2013	Eggleston *et al*	Emphasized industrial fermentation technology; pros and cons of batch vs. continuous systems.
2015	Khalil *et al*	Mixed culture *Saccharomyces cerevisiae* + *Zymomonas mobilis*: 39.2 gL^{-1} ethanol; 58% sugar consumed, 48% converted.
2015	Bunphan *et al*	Experimental ethanol yield may differ from theoretical due to process and model variations.
2016	Partida-Sedas *et al*	Reported optimal pH range for alcoholic fermentation (5.14-5.53).
2018	Alonso-Gómez and Bello-Pérez	Sugar to alcohol conversion is a major scientific and technological advancement.
2018	Ebrahimiaqda and Ogden	Modeled theoretical maximum yield: 0.75 from M81E sorghum under optimal conditions.
2012	Fraga	Low microbial load in industrial sorghum broth; yeast separation by centrifugation.
2021	Díaz-Nava *et al*	*Pichia kudriavzevii* ITV-S42: thermotolerant, killer activity, acetic acid tolerance, furfural and HMF tolerance.
2021	Fagundes *et al*	Highlighted the need to study yeast × sorghum genotype interactions.
2023	Kumar and Singh	Emphasized controlling fermentation parameters for cost-effective production.
2024	Fentahun and Andualem	Evaluated temperature effects; studied yeast strains with thermotolerance, osmotolerance, killer activity and ethanol resistance.
2024	Kasegn *et al*	Confirmed fermentation as key for ethanol yield and cost efficiency.

Distillation and ethanol yield under insdustrail condtions

This process involves separating components with different boiling points in a liquid mixture through evaporation and condensation (Fraga, 2012) to produce hydrated alcohol with an initial 96% alcohol content, which is then further dehydrated to achieve 99.5% ethanol for fuel applications (Ishaq and Dincer, 2024). Ethanol mixed with gasoline must be dehydrated to a temperature of approximately 99.5 °C, which is called anhydrous ethanol (Silva *et al.*, 2022). In Brazil's industrial experience with sweet sorghum, a process similar to that used for sugarcane achieves an ethanol yield of up to 60 L per ton of fresh stalks, while the average production for sugarcane is 85 L per ton of fresh stalks (Fraga, 2012). Specifying that the yield is based on fresh biomass avoids ambiguity and allows for more accurate comparisons between crops. According to the review of Ameen *et al.* (2024), sweet sorghum juice can be used to make syrups, molasses, sugar, and ethanol, with fermentation efficiencies ranging from 85 to 90%. The ethanol yield is 70 to 80 L per ton of sweet sorghum juice processed. Ethanol production efficiency, defined as the ratio of actual to theoretical yield based on the sugar content of sweet sorghum juice, can reach up to 94% under optimized conditions (Aguilar and García, 2017). This metric, typically expressed on a g ethanol per g sugar basis, provides a clear measure of fermentation performance.

Purification of bioethanol

The production of anhydrous ethanol starts with fermentation, followed by distillation to obtain hydrated ethanol (Lauzurique-Guerra *et al.*, 2017). Dehydration is necessary to reduce water content for applications such as fuel (Frolkova and Raeva, 2010). Several industrial methods exist (Table 6), including chemical dehydration, vacuum distillation, azeotropic distillation (which uses a third component to break the ethanol-water azeotrope), extractive distillation, membrane separation, adsorption, and hybrid processes (Kumar *et al.*, 2010; Saini *et al.*, 2020; Taher *et al.*, 2021). Azeotropic distillation is commercially mature but energy-intensive (Table 6), prompting research into more efficient alternatives (Kumar and Singh, 2023; Botshekan *et al.*, 2022; Lorenzo-Máiz *et al.*, 2023). An azeotrope is a mixture that boils at a constant composition and cannot be separated by simple distillation based on boiling points (Saini e*t al.*, 2020).

Table 6. Industrial techniques for anhydrous ethanol production: principles, advantages, and limitations.

Technique	Principle / How it Works	Advantages	Limitations
Chemical dehydration (salts, glycols, polymers, ionic liquids)	Uses chemicals to remove water from hydrated ethanol	Simple at small scale; widely studied	Use of chemicals may require purification; environmental concerns
Vacuum distillation	Distillation under reduced pressure to lower the boiling point of water	Can operate at lower temperatures	Energy-intensive; equipment cost
Azeotropic distillation	Uses a third component to break the ethanol-water azeotrope	Mature, commercially available; scalable	High energy consumption
Extractive distillation	Uses a solvent to selectively separate water	Can improve separation efficiency	Solvent recovery required; energy cost
Membrane processes	Selective membranes separate water from ethanol	Energy-efficient; no chemical additives	Membrane fouling; scale-up challenges
Adsorption processes	Water is adsorbed onto solid materials (e.g., molecular sieves)	High purity ethanol; environmentally friendly	Cost of adsorbents; regeneration required
Diffusion distillation	Water diffuses through a barrier leaving concentrated ethanol	Simple principle	Less common; limited industrial data
Pervaporation	Ethanol passes through a membrane and evaporates	Energy-efficient; avoids solvents	Membrane durability; cost considerations
Hybrid processes	Combines two or more techniques (e.g., distillation + adsorption)	Optimizes energy use and efficiency	Complexity of operation; capital costs

CONCLUSION

Sweet sorghum represents a viable but still incipient alternative for first-generation bioethanol production in Mexico, as it shares the same processing pathway as sugarcane yet offers adaptability to diverse agroecological regions. However, technological and logistical limitations persist, particularly in sugar extraction efficiency, mechanized harvesting, and fermentation stability, which constrain large-scale adoption. To overcome these challenges, it is crucial to establish an integrative framework that connects agricultural production with industrial processing, incorporating life cycle assessment and economic feasibility to ensure sustainability. Future research should prioritize regional evaluations, the development of adapted high yield varieties, and systematic comparisons of sweet sorghum bioethanol quality with international fuel standards to strengthen its competitiveness.

Acknowledgments
Ph. D. Héctor Manuel Cortinas Escobar reviewed the English version. Project SIGI SAGARPA–INIFAP 12122419311: Varieties with high agronomic yield and high sugar content for bioethanol production. For the opportunity to collaborate in addressing a specific demand aimed at developing sustainable alternatives for the environment.

Funding. Own resources.

Conflict of interest statement. The authors declare that they have no conflict of interest.

Compliance with ethical standards. Not applicable due to the nature of the study.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request (ecl631211@gmail.com).

Author Contribution Statement (CRediT). M. E. Cisneros-López – Conceptualization, Methodology, Writing – original draft, Writing – review & editing, and Project administration. **R. D. Garza-Cedillo** – Writing – review & editing (Spanish version of the manuscript).

REFERENCES

Abbass, K., Qasim, M.Z, Song, H., Murshed, M., Mahmood, H., and Younis I., 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, 28, pp. 42539-42559. https://doi.org/10.1007/s11356-022-19718-6

Aburto, J. and Martínez-Hernández, E., 2021. Is sugarcane a convenient feedstock to provide ethanol in Mexico? *Frontiers in Energy Research*, 8.612647 https://doi.org/10.3389/fenrg.2020.612647

Aguilar, U.M.A. and Montes, G. N., 2017. Planta piloto para la producción de etanol a partir de sorgo dulce (*Sorghum bicolor* (L.) Moench). *Bolentín de la Sociedad Química de México*, 11(3), pp. 10-12.

Alejandro, A.F., García, M.R., García, S.R.C., Mora, F.J.S. and Sangerman. J.D.M., 2020. Competitividad de la producción de sorgo en el norte de Tamaulipas, México. *Revista Mexicana de Ciencias Agrícolas*, 11(1), pp. 139-50. https://doi.org/10.29312/remexca.v11i1.1914

Alhajturki, D., Aljamali, M., Kanbar, A. and Azmah, F., 2012. Potential of Some Sweet Sorghum (*Sorghum bicolor* L.) Genotypes under two water regimes for sugar and bio-ethanol production. *Sugar Technology*, 14(1), pp. 376-382. https://doi.org/10.1007/s12355-012-0181-x

Alonso-Gómez, A. and Bello-Pérez, L., 2018. Four generations of raw materials used for ethanol production. Challenges and opportunities. *Agrociencia*, 52(7), pp. 967-990.

Álvarez, C. M. and Montes G.N., 2017. Tecnología de producción de sorgo dulce [*Sorghum bicolor* (L.) Moench] como fuente para la obtención de bioetanol en el trópico subhúmedo del estado de Jalisco. INIFAP. Tecomán, Colima, México. Folleto Técnico No. 15. 21 p. https://vun.inifap.gob.mx/VUN_MEDIA/BibliotecaWeb/_media/_folletotecnico/1029_4702

Amaducci, S., Assirelli, A., Trevisan, M., Fracasso, A., Santangelo, E., Suardi, A., Giudice, A., Scarfone, A. and Pari, L., 2018. Effects of stem length and storage duration on sugar losses in sweet sorghum. *Applied Engineering in Agriculture*, 34(1), pp. 251-259. http://dx.doi.org/10.13031/aea.12498

Ameen, M., Mahmood, A., Naeem, S.A., Anjum, Z.M. and Mansoor, J. M., 2024. Sorghum's potential unleashed. A comprehensive exploration of bio-energy production strategies and innovations. *Bioresource Technology Reports*, 27, p. 101906, https://doi.org/10.1016/j.biteb.2024.101906

Andrzejewski, B., Eggleston, G. and Powell, R., 2013a. Pilot plant clarification of sweet sorghum juice and evaporation of raw and clarified juices. *Industrial Crops and Products*, 49, pp. 648-658. https://doi.org/10.1016/j.indcrop.2013.06.027

Andrzejewski, G., Eggleston, S., Lingle S. and Powell, R., 2013b. Development of a sweet sorghum juice clarification method in the manufacture of industrial feedstocks for value-added fermentation products. *Industrial Crops and Products*, 44(1), pp. 77-87. https://doi.org/10.1016/j.indcrop.2012.10.028

Appiah-Nkansah, N., Li, J., Rooney, W. and Wang, D., 2019. A review of sweet sorghum as a viable renewable bioenergy crop and its techno-economic analysis. Renewable Energy, 143, pp. 1121-1132. https://doi.org/10.1016/j.renene.2019.05.066

Argote, F.E., 2015. Evaluación de la producción de etanol a partir de melaza de caña de azúcar en Colombia. *Revista Facultad de Ingeniería*, 24(2), pp. 5-15. https://www.scielo.org.co/scielo.php?pid=S1692-35612015000200005&script=sci_arttext

Arksey, H. and O'Malley, L., 2005. Scoping studies. towards a methodological framework. *International Journal of Social Research Methodology*, 8(1), pp. 19-32. https://doi.org/10.1080/1364557032000119616

Arvizu, E.C., Rodríguez, G.C., Montes, G.N., Alemán, S.J.A., Soler Martínez, A.M.A. and Téllez. L.S., 2016. Determinación y cuantificación de azúcares totales en jarabes de sorgo dulce RB-Cañero y una variedad experimental, *Investigación y Desarrollo en Ciencia y Tecnología de Alimentos,* 1(2), pp. 679-684. http://www.fcb.uanl.mx/IDCyTA/files/volume1/2/8/119.pdf

Attchelouwa, C.K., N'guessan, F.K., Aké, F.M.D. and Djè, M.K., 2018. Molecular identification of yeast, lactic and acetic acid bacteria species during spoilage of tchapalo, a traditional sorghum beer from Côte d'Ivoire. *World*

Journal Microbiol Biotechnology, 34(11), p. 173. http://dx.doi.org/10.1007/s11274-018-2555-z

Becerra-Pérez, L.A., 2009. La industria del etanol en México. *Economía UNAM*, 6(16), pp. 82-98.

Bint-E-N., Samavi, H., Laila, D., Mrittika, B., P., K. and Mohidus, S., 2016. Analyzing physico-chemical properties of bioethanol and bioethanol blended fuels. *Journal of Nature Science and Sustainable Technology,* 11, pp. 331-339.

Botshekan, M., Moheb, A., Vatankhah, F. Karimi, K. and Shafiei, M., 2022. Energy saving alternatives for renewable ethanol production with the focus on separation/purification units. A techno-economic analysis. *Energy*, 239(Part E), p. 122363. https://doi.org/10.1016/j.energy.2021.122363

Bridgers, E.N., Chinn, M., Veal, M.W. and Stikeleather, L., 2011. Influence of juice preparations on the fermentability of sweet sorghum. *Biological Engineering Transactions*, 4, pp. 57-67. https://doi.org/10.13031/2013.38507

Bunphan, D., Jaisil, P., Sanitchon, J., Knoll, J. E. and Anderson, W. F., 2015. Estimation methods and parameter assessment for ethanol yields from total soluble solids of sweet sorghum. *Industrial Crops and Products*, 63, pp. 349-356. https://doi.org/10.1016/j.indcrop.2014.10.007

Bušić, N., Marđetko, S. Kundas, G., Morzak, H., Belskaya, M. I., Šantek, D., Komes, S., Novak and Šantek, B., 2018. Bioethanol production from renewable raw materials and its separation and purification. A Review. *Food Technology Biotechnology*, 56 (3), pp. 289-311. https://doi.org/10.17113/ftb.56.03.18.5546

Canabarro, N.I, Silva-Ortiz P., Nogueira, L.A.H., Cantarella, H., Maciel-Filho, R. and Souza, G.M., 2023 Sustainability assessment of ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala. *Renewable and Sustainable Energy Reviews*, 171, p. 113019. https://doi.org/10.1016/j.rser.2022.113019

Carrillo-Ávila, E., 2016. Evaluación agroindustrial de diez variedades de caña de azúcar (*Saccharum* spp.). *AgroProductividad*, 9(3), pp. 21-26. https://www.revista-agroproductividad.org/index.php/agroproductividad/article/view/730/597

Chapnick, J.D., 2019. The abstract and title page. *AME Medical Journal*, 4 (27), pp. 1-6 https://doi.org/10.21037/amj.2019.05.01

Chibrikov, V., Vakuliuk, P. and Sobczuk, H., 2024. Sweet sorghum juice clarification and concentration. A review. *Critical reviews in food science and nutrition,* 64(32), pp. 11850-11870. https://doi.org/10.1080/10408398.2023.2245033

Chuck-Hernández, H., Peralta-Contreras, C.M., Bando-Carranza, G., Vera-García, M., Gaxiola-Cuevas, N., Tamayo-Limon, R., Cardenas-Torres, F., Pérez-Carrillo, E. and Serna-Saldívar, S.O., 2012. Bioconversión into ethanol of decorticated red sorghum (*Sorghum bicolor* L. Moench) supplemented with its phenolic extract or spent bran. *Biotechnology Letter*, 34(1), pp. 97-102. https://doi.org/10.1007/s10529-011-0752-z

Costa, H.G., Masson, I.S., De Freita, L.A., Roviero, J.P. and Mutton, M.J.R., 2015. Reflects of clarification of sugarcane juice with moringa on inorganic compounds of sugar VH. *Revista Brasileira de Engenharia Agrícola e Ambiental – Agriambi*, 19(1), pp. 154-159. http://dx.doi.org/10.1590/1807-1929/agriambi.v19n2p154-159

Costa, E., Seixas, J., Costa, G. and Turrentine, T., 2017. Interplay between ethanol and electric vehicles as low carbon mobility options for passengers in the municipality of São Paulo. International *Journal of Sustainable Transportation*, 11(7), pp. 518-525. http://dx.doi.org/10.1080/15568318.2016.127665

CRE. Comisión Reguladora de Energía. 2017. NOM-016-CRE-2016, Especificaciones de calidad de los petrolíferos. Diario Oficial de la Federación. http://www.dof.gob.mx/nota_detalle.php?codigo=5490248&fecha=29/08/2017

Da Silva, F., Dutra, J.M., da Camara, A.S., Pinto, A. F.T., da Silva, A. and Edson, F., 2017. Row spacing, plant density, sowing and harvest times for sweet sorghum. *Pesquisa Agropecuária Tropical*, 47(4), pp. 408-415.

Danelon, F., Spolador, H.F. S. and Bergtold, S., 2023. The role of productivity and efficiency gains in the sugar-ethanol industry to reduce land expansion for sugarcane fields in Brazil. *Energy Policy*, 172(3), p. 113327. https://doi.org/10.1016/j.enpol.2022.113327

Datta, M., Saikat, A., Poshadri, P., Srinivasa, R., Reddy, C.H. and Reddy, B.V.S., 2012. Innovative use of sweet sorghum juice in the beverage industry. *International Food Research Journal,* 19(4), pp. 1361-1366.

Dávila-Gómez, J., Chuck-Hernández, C., Pérez-Carrillo, E., Rooney, W.L. and Serna-Saldívar, S.O., 2011. Evaluation of bioetanol production from five different varieties of sweet and forage sorghums (*Sorghum bicolor* (L) Moench). *Industrial Crops Production*, 33(3), pp. 611-616. https://doi.org/10.1016/j.indcrop.2010.12.022

Díaz-Nava, L., Aguilar-Uscanga, M.G., Ortiz-Muñiz, B., Montes, N., Domínguez, J. and Gomez-Rodriguez, J., 2021. Acetic Acid-Tolerant Native Yeast *Pichia kudriavzevii* ITV-S42 Isolated from Sweet Sorghum Juice for Ethanol Production. *Sugar Technology*, 24, pp. 1-9. http://dx.doi.org/10.1007/s12355-021-01040-z

Dillon, S.L., Shapter, F.M., Henry, R.J., Cordeiro, G., Izquierdo, L. and Lee, L.S., 2007. Domestication to crop improvement. genetic resources for *Sorghum* and *Saccharum* (Andropogoneae). *Annals Botany*, 100(5), pp. 975-89. https://doi.org/10.1093/aob/mcm192

Diouf, B., 2025. Modeling the used vehicle market share in the electric vehicle transition. *World Electric Vehicle Journal*, 16(1), p. 29. https://doi.org/10.3390/wevj16010029

Domínguez, J., 2016. Revisión histórica de las sequías en México de la explicación divina a la incorporación de la ciencia. *Tecnología y Ciencias del Agua*, 7(5), pp. 77-93.

Dong, J., Mengmeng, H., Jingying, F., Kun, L. and Xiaoxi, Y., 2019. Potential bioethanol production from sweet sorghum on marginal land in China. *Journal of Cleaner Production*, 220, pp. 225-234. https://doi.org/10.1016/j.jclepro.2019.01.294

Dutra, D.D, Alencar, A.R.B., Galdino, J.J., Tabosa, N.J., Menezes, R.S.C.R., de Araújo F. R.N., Primo, C.P., Piscoya, V.C and Lopes, A.J.E., 2018. First and second generation of ethanol production for five sweet sorghum cultivars during soft dough grain. *Journal Experimental Agriculture Internation*, 25(2), pp. 1-12. https://doi.org/10.9734/JEAI/2018/42742

Ebrahimiaqda, E. and Ogden, K., 2018. Evaluation and modeling of bioethanol yield efficiency from sweet sorghum juice. *BioEnergy Research*, 11, https://doi.org/10.1007/s12155-018-9909-0

Eggleston, G., Cole, M. and Andrzejewski, B., 2013. New commercially viable processing technologies for the production of sugar feedstocks from sweet sorghum (*Sorghum bicolor* (L.) Moench) for manufacture of biofuels and bioproducts. *Sugar Technology,* 15(3), pp. 232-249. https://doi.10.1007/s12355-013-0229-6

Eggleston, G., Heckemeyer, M., Cyr, E.S. and Wartelle, L., 2016. Case study. Commercialization of sweet sorghum juice clarification for large-scale syrup manufacture. *Sugar Technology*, 18(3), pp. 249-57. http://dx.doi.org/10.1007/s12355-015-0387-9

Enyew, M., Feyissa, T., Carlsson, A.S., Tesfaye, K., C. Hammenhag, C. and Geleta M., 2022. Genetic diversity and population structure of sorghum [*Sorghum bicolor* (L.) Moench] accessions as revealed by single nucleotide polymorphism markers. *Frontier Plant Science*, 12, p. 799482. https://doi.org/10.3389/fpls.2021.799482

Esparza, M., 2014. La sequía y la escasez de agua en México. Situación actual y perspectivas futuras. *Secuencia*, (89), pp. 193-219.

Espinosa-Paz, N., Montes-García, N., Martínez-Sánchez, J., Ariza-Flores, R. and Cadena-Iñiguez, P., 2019. Contenido de azúcares en variedades de sorgo (*Sorghum bicolor* L.) para etanol en el centro de Chiapas, México. *Agroproductividad*, 12(10), pp. 53-58. https://doi.org/10.32854/agrop.vi0.1481

Fagundes, T., Lombardi, G., Lopes, A.C., Fernandes, C., Lopes, L., Parrella, R., Duarte, W. and Nunes, J.A., 2021. Characterization of sweet sorghum genotypes based on agro-industrial performance and fermentation potential. *Sugar Technology*, 23(4), pp. 881-890.https://doi.org/10.1007/s12355-021-00974-8

Fentahun, M. and Andualem, B., 2024. Optimization of bioethanol production using stress-tolerant yeast strains isolated from household alcoholic beverages (Tella, Tej, and Areke) and molasses (as substrate). *F1000Research*, 13, p. 286. http://dx.doi.org/10.12688/f1000research.146910.1

Ferreira, S.A., Ferreira, O., Costa, G., Montijo, N., Mutton, M. and Mutton, M., 2016. Technological quality of sweet sorghum processed without panicles for ethanol production. *Australian Journal of Crop Science*, 10(6), 1578-1582. http://dx.doi.org/0.21475/ajcs.2016.10.11

Fraga, P., 2012. Tecnología industrial. En: A. May, F. O. M. Durães, I. A. Pereira Filho, R. E. Schaffert and R. A. P. da Costa, eds. *Sistema Embrapa de produção agroindustrial de sorgo sacarino para bioetanol:* Sete Lagos, M.G Brazil: Sistema BRS1G – Tecnologia Qualidade Embrapa*,* Embrapa Milho e Sorgo. pp. 93-106. http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/938275

Frolkova, A. and Raeva, V., 2010. Bioethanol dehydration. State of the art. *Theoretical Foundations of Chemical Engineering*, 44(4). pp. 545-556. https://doi.org/10.1134/S0040579510040342

Galicia-Juárez, M., Pecina-Quintero, V., Cisneros-López, M.E., Chávez-Villalba, G., Espinosa-Ramírez, M, Álvarez-Ojeda, M.G. and Aíl-Catzim, C.E., 2022. Effect of genotype on the production and quality of sweet sorghum juice [*Sorghum bicolor* (L.) Moench]. *AgroProductividad*, 15(7), pp. 59-67. https://doi.org/10.32854/agrop.v15i7.2335

Ghahraei, M-H., Khoshtaghaza, D. and Ahmad, D., 2008. Design and development of special cutting system for sweet sorghum harvester. *Journal Central Europe Agriculture*, 9(3), pp. 469-474.

Grandis, A., Fortirer, J.d.S., Pagliuso, D. and Buckeridge, M.S., 2024. Scientific Research on Bioethanol in Brazil. History and prospects for sustainable biofuel. *Sustainability*, 16(10), p. 4167. https://doi.org/10.3390/su16104167

Guigou, M., Lareo, C., Pérez, L., Lluberas, M. and Ferrari, M., 2011. Bioethanol production from sweet sorghum. Evaluation of post-harvest treatments on sugar extraction and fermentation. *Biomass and Bioenergy*, 35(7), pp. 3058-3062. https://doi.org/10.1016/j.biombioe.2011.04.028

Guimarães, C.E. C., Silva, M.G. and Costa, R.M., 2023. Sustainable bioethanol production from first- and second-generation feedstocks. A review. *Renewable and Sustainable Energy Reviews*, 170, pp, 113-129. https://doi.org/10.1016/j.rser.2023.113129

Gutiérrez, A., Hernández, J. and Martínez, R., 2020. Estudio comparativo de variedades de sorgo granífero en condiciones de riego en el norte de México. *Revista Mexicana de Ciencias Agrícolas,* 11(4), pp. 789-802. https://doi.org/10.29312/remexca.v11i4.2345

Harlen, W.C., 2023. Effect of using different clarifying agents and temperature on the composition of sweet sorghum syrup. *Food Science and Technology*, 58(2), pp. 123-130. https://doi.org/10.1016/j.jfst.2023.01.015

Heredia-Olea, E., Pérez-Carrillo, E. and Serna-Saldívar, S.O., 2015. Effects of extrusion pretreatment parameters on sweet sorghum bagasse enzymatic hydrolysis and its subsequent conversion into bioethanol. *Bioresource Technology*, 184, pp. 1-7. https:// https://doi.org/10.1155/2015/325905

Hernández-Cely, S. R. and Torres-Zamudio, M., 2021. Capacidades y tendencias tecnológicas en el proceso de producción de panela artesanal. Un estudio de vigilancia tecnológica. *Revista Científica Profundidad Construyendo Futuro*, 15(15), pp. 49-63. https://doi.org/10.22463/24221783.3310.

Hryhorenko, N., Husiatynska, N. and Kalenyk, O., 2021. Substantiation of a rational method of purification of sugar sorghum juice in the technology of food syrup production. *Ukrainian Food Journal*, 10(2), pp. 263–270. http://dx.doi.org/10.24263/2304-974X-2021-10-2-5

Immerzeel, D.J., Verweij, P.A., Van Der Hilst, F. and Faaij, A.P., 2014. Biodiversity impacts of bioenergy crop production. a state-of-the-art review. *GCB Bioenergy*, 6(1), pp. 183–209. https://doi.org/10.1111/gcbb.12067

IEA. International Energy Agency, 2023. World Energy Outlook 2023. https://www.iea.org/reports/world-energy-outlook-2023?language=es

Ishaq, M. and Dincer, I., 2024. Development of a new renewable energy system for clean hydrogen and ethanol production. *Energy Conversion and Management*, 306(7), p. 118304. https://doi.org/10.1016/j.enconman. 118304

Jia, F., Chawhuaymak, J., Riley, M.R., Zimmt, W. and Ogden, K.L., 2013. Efficient extraction method to collect sugar from sweet sorghum, *Journal Biological Engineering*, 7, pp.1-8. https://doi.org/10.1186/1754-1611-7-1

Jiménez-Ocampo, R. Rosales-Serna, R. and Domínguez-Martínez, P.A., 2024. Lico. a variety of sweet sorghum for forage production. *Revista Mexicana de Ciencias Agrícolas*, 15(2), pp. 1-6. https://doi.org/10.29312/remexca.v15i2.2959

Kasegn, S., Alemayehu, B. and Tesfaye, G., 2024. Optimization of fermentation parameters for enhanced ethanol yield from sweet sorghum juice. *Bioresource Technology*, 390, pp. 128-135. https://doi.org/10.1016/j.biortech.2024.128135renene.2023.02.045

Khalil, S., Abdelhafez, A. and Amer, E.A.M., 2015. Evaluation of bioethanol production from juice and bagasse of some sweet sorghum varieties. *Annals of Agricultural Science*, 60(2), pp. 317-324. https://doi.org/10.1016/j.aoas.2015.10.005

Kumar, S., Singh, N. and Prasad, R., 2010. Anhydrous ethanol. A renewable source of energy. *Renewable and Sustainable Energy Reviews*, 14(9), pp. 1830-1844. https://doi.org/10.1016/j.jclepro.2020.122357

Kumar, V., and Singh, R., 2023. Enzymatic optimization of sweet sorghum juice for industrial ethanol production. *Renewable Energy*, 210, pp. 1276-1285. https://doi.org/10.1016/j.renene.2023.02.045

Kumar R., Kurre, P., Kumar, S.B. and Nageswara, R., 2024. Multi-objective optimization for minimize cutting force and power consumption in corn stalk chopping processes. *Heliyon*, 10, p. e35373. http://dx.doi.org/10.1016/j.heliyon.2024.e35373

Kumar, V. and Sinha, A.R., 2025. Sustainable ethanol production. CO2 emission analysis and feedstock strategies through life cycle assessment. *Energy for Sustainable Development*, 88, p. 101775. https://doi.org/10.1016/j.esd.2020.101775

Lauzurique-Guerra, Y., Zumalacárregui de C.L., Pérez-Ones, O. and Molina-Rivero, G., 2017. Evaluación de técnicas de deshidratación de etanol aplicando la simulación. *DYNA*, *84*(200), pp. 185-192. https://doi.org/10.15446/dyna.v84n200.54230

Lennartsson, P.R., Erlandsson, P. and Taherzadeh, M.J., 2014. Integration of the first and second generation bioethanol processes and the importance of by-products. *Bioresource Technology*, 165. pp. 3-8. https://doi.org/10.1016/j.biortech.2014.01.127

Lingle, S. E., Tew, T. L., Rukavina, H. and Boykin, D. L., 2012. Post-harvest changes in sweet sorghum I. Brix and sugars. *Bioenergy Research*, 5(1), pp. 158-167. http://dx.doi.org/10.1007/s12155-011-9164-0

Linton, J., Miller, J., Little, R., Petrolia, D. and Coble, K., 2011. Economic feasibility of producing sweet sorghum as an ethanol feedstock in the southeastern United States. *Biomass & Bioenergy*, 35, pp. 3050-3057. http://dx.doi.org/10.1016/j.biombioe.2011.04.007

Liu, R., Zhang, H. and Wang, X., 2008. Refining bioethanol from stalk juice of sweet sorghum by fermentation with Saccharomyces cerevisiae. *Bioresource Technology*, 99(7), pp. 2571-2576. https://doi.org/10.1016/j.biortech.2007.05.027

Lopez-Cortes, O.D., Betancourt-Núñez, A., Bernal Orozco, M.F. and Vizmanos, B., 2022. Scoping reviews. una nueva forma de síntesis de la evidencia. *Investigación en Educación Médica*, 11(44), pp. 98-104. https://doi.org/10.22201/fm.20075057e.2022.44.22447

López-Sandin, I., Gutiérrez-Soto, G., Gutiérrez-Díez, A., Medina-Herrera, N., Gutiérrez-Castorena,

E. and Zavala-García, F., 2019. Evaluation of the use of energy in the production of sweet sorghum (*Sorghum bicolor* (L.) Moench) under different production systems. *Energies*, 12(9), p. 1713. https://doi.org/10.3390/en12091713

López-Sandin, G., Gutiérrez-Soto, A., Gutiérrez-Díez, N., Medina-Herrera, E., Gutiérrez-Castorena, Galicia-Juárez, M., and Zavala-García, F., 2021. Biomass and sugar production dynamics in sweet sorghum variety Roger. *Chilean Journal Agricultural Research*, 81(1), pp. 92-101. https://dx.doi.org/10.4067/S0718-58392021000100092

López-Sandin, G., Rodríguez-Jasso, R.M., Gutiérrez-Soto, G., Rosero-Chasoy, G., González-Gloria, K.D. and Ruiz, H.A., 2022. Energy assessment of second-generation (2g) bioethanol production from sweet sorghum (*Sorghum bicolor* (L.) Moench) Bagasse. *Agronomy*, 12(2), p. 3106. https://doi.org/10.3390/agronomy12123106

Luquet, D., Perrier, L., Clement-Vidal, A., Jaffuel, S., Verdeil, J-L., Roques, S., Soutiras, A.C., Baptiste, F.D., Bastianelli, D., Bonnal, L., Sartre, P., Rouan, L. and Pot, D., 2018. Genotypic covariations of traits underlying sorghum stem biomass production and quality and their regulations by water availability. Insight from studies at organ and tissue levels. *GCB Bioenergy,* 11, https://doi.org/10.1111/gcbb.12571

Malherbe, S., Bauer, F. and Du Toit, M., 2007. Understanding problem Fermentations -A Review. *South African Journal of Enology and Viticulture,* 28(1), pp. 169-186. http://dx.doi.org/10.21548/28-2-1471

Megía, P.J., Vizcaino, J.A., Calles, J.A and Carrero, A., 2021. Hydrogen production technologies from fossil fuels toward renewable sources. A mini review. *Energy Fuels Journal*, 35(20), pp. 16403-16415. https://doi.org/10.1021/acs.energyfuels.1c02501

Mejía-Kerguelén, S., Tapia-Coronado, J. J., Atencio-Solano, L. M. and Cadena-Torres, J., 2019. Producción y calidad nutricional del forraje del sorgo dulce en monocultivo e intercalado con maíz y frijol. *Pastos y Forrajes,* 42(2), pp. 124-132. https://doi.org/10.21153/pf.v42n2.133

Mendieta, M.O.A. and Escalante, H.H., 2013. Análisis experimental de la evaporación del jugo de caña de azúcar en película sobre una placa plana. *Ciencia y Tecnología Agropecuaria*, 14(2), pp. 113-127.

Mengistie, E., Bokros, N., DeBolt, S. and Mcdonald, A., 2024. Lodging variability in sorghum stalks is dependent on the biomechanical and chemical composition of the stalk rinds. *Crops*, 4, pp. 3-26. http://dx.doi.org/10.3390/crops4010002

Messmann, L., Wietschel, L., Thorenz, A. and Tuma, A., 2023. Assessing the social dimension in strategic network optimization for a sustainable development. The case of bioethanol production in the EU. *Journal of Industrial Ecology*, 27(3), pp. 760-776. https://doi.org/10.1111/jiec.13324

Mohrn, A. and Raman, S., 2013. Lessons from first generation biofuels and implications for the sustainability appraisal of second-generation biofuels. *Energy Policy*, 63(100), pp. 114–22. http://dx.doi.org/10.1016/j.enpol.2013.08.033

Montes G, N., Salinas, R.J., Jiménez, G.A y Díaz, P.G., 2010. Guía Técnica de producción de Sorgo Dulce (*Sorghum bicolor* (L.) en Tamaulipas". INIFAP. CIRNE-CERIB. Folleto Técnico No. 49. 36 p. https://www.compucampo.com/tecnicos/guiatecnica-sorgodulce-tams.pdf

Montes-García, N., Uribe-Gómez, S., Cisneros-López, M.E., Pecina-Quintero, V., Moreno-Gallegos, T. and Díaz-Franco A., 2019. RB-Pirulí. Variedad de sorgo dulce para producción de biomasa y azúcares en México. *Revista Fitotecnia Mexicana*, 42(1), pp. 75-77.

Montes, G.N., Pecina, Q.V., Williams, A.H., Hernández, M.M., Cisneros, L.M.E. and Moreno, G.T., 2021. Mejoramiento genético de sorgo en el INIFAP. *Revista Mexicana de Ciencias Agrícolas,* 25, pp. 59-62. http://dx.doi.org/10.29312/remexca.v12i25.2824

Murray S. C., Rooney, W.L., Hamblin, M.T., Mitchell, S.E. and Kresovich, S., 2009. Sweet sorghum genetic diversity and association mapping for brix and height. *The Plant Genome*, 2, pp. 48-62, https://doi.org/10.3835/plantgenome2008.10.0011

N da Silva, F., Hélio, M., Homem, B., Fernandes, T., Júnior, L., Marques, C. and Omir, M., 2014. Evaluación de la acidez en el jugo de diferentes partes del tallo de caña de azúcar, ciclo 2010/2011. *Interciencia*, 39(4), pp. 277-280.

Nazli, R., Aslankaciran, C., Yang, D., Liaqat, W., Polat, M., Çavdar, A., Tansi, V. and Baloch, F., 2024. Assessment of sweet sorghum genotypes for bioethanol production potential and bagasse combustion characteristics in a semi-arid Mediterranean climate. *Agronomy*, 14. https://doi.org/10.3390/agronomy14112626

Nghiem, N., O'Connor, J. and Hums, M., 2018. Integrated process for extraction of wax as a value-added co-product and improved ethanol production by converting both starch and cellulosic components in sorghum grains. *Fermentation,* 4(1), pp. 12. https://doi.org/10.3390/fermentation4010012

Nolasco-Hipolito, C., Carvajal-Zarrabal, O., Bujang, K., Cisneros, C., Ahumada, J., Yakub, I., García, G. M. and Gaona, O., 2023. La paradójica disponibilidad de materia prima en la producción de bioetanol. *TECNOCIENCIA Chihuahua*, 17, p. e1225. https://doi.org/10.54167/tch.v17i3.1225

Núñez, H.M., 2022. Building a bioethanol market in México. *EconoQuantum*, 19(2), pp. 21-56. https://doi.org/10.18381/eq.v19i2.7258

Olszewska-Widdrat, M., Alexandri, J.P., López-Gómez, R., Schneider, M. and Venus, J., 2019. Production and purification of l-lactic acid in lab and pilot scales using sweet sorghum juice. *Fermentation*, 5(2), p. 36. https://doi.org/10.3390/fermentation5020036

Ortiz, L. H., Salgado, G.S., Castelán, E. M. and Córdova, S.S., 2012. Perspectivas de la cosecha de la caña de azúcar cruda en México. *Revista Mexicana de Ciencias Agrícolas*, 3(spe4), pp. 767-773.

Palacios-Bereche, R., Ensinas, A., Modesto, M. and Nebra, S.A., 2014. Extraction Process in the ethanol production from sugarcane. A Comparison of Milling and Diffusion. *Chemical Engineering Transactions*, 39, pp. 1519-1524. https://doi.org/10.3303/CET1439254

Partida-Sedas, G., Montes-García, N., Carvajal-Zarrabal, O., López-Zamora, L., Gómez-Rodríguez, J. and Aguilar-Uscanga, M.G., 2016. Optimization of hydrolysis process to obtain fermentable sugars from sweet sorghum bagasse using a box-behnken design. *Sugar Technology*, 19(3), pp. 317-325. https://doi.org/10.1007/s12355-016-0461-y

Pérez-Lechuga, G., Aguilar-Velázquez, S., Cisneros-López, M. and Venegas-Martínez, F., 2019. A model for the location and scheduling of the operation of second-generation ethanol biorefineries. *Journal of Mathematics in Industry,* 9(1), pp. 2-14. http://dx.doi.org/10.1186/s13362-019-0060-0

Punia, P. and Kumar, S., 2025. A critical review on enhanced bioethanol production from sweet sorghum using nanotechnology. *Energy Nexus*, 17, p. 100339. https://doi.org/10.1016/j.nexus.2024.100339

Rao, S.S., Patil, J., Prasad, P.V.V., Reddy, D., Mishra, J. S., Akula, U., Reddy, B. and Are, A., 2013. Sweet Sorghum planting effects on stalk yield and sugar quality in semi-arid tropical environment. *Agronomy Journal,* 105(5), pp. 1458-1465. http://dx.doi.org/10.2134/agronj2013.0156

Rebollar R.E., Hernández, M.J., Rebollar, R.A., González, R.F.J., Gómez, T.G. and Rebollar Rebollar, S., 2016. Dinámica regional de la producción de sorgo en México, 1994-2012. *Revista Mexicana de Ciencias Agrícolas*, 7(3), pp. 619-630. https://doi.org/10.29312/remexca.v7i1361

Saini, S., Chandel, A.K. and Sharma, K.K., 2020. Past practices and current trends in the recovery and purification of first generation ethanol. A learning curve for lignocellulosic ethanol. *Journal of Cleaner Production*, 268, p. 122357. https://doi.org/10.1016/j.jclepro.2020.122357

SE. Secretaria de Economía., 2015. NMX-AA-174-SCFI-2015. Especificaciones y requisitos para la certificación de sustentabilidad ambiental en la producción de bioenergéticos líquidos de origen vegetal. 86 p. http://www.economia-nmx.gob.mx/normas/nmx/2010/nmx-aa-174-scfi-2015.pdf

Saleh, H., Ali, S. and Khan, M., 2022. Role of pectinases and amylases in improving juice clarity and ethanol yield. *Bioresource Technology*, 345, p. 126505. https://doi.org/10.1016/j.biortech.2022.126505

Silva, R., Mmascarenhas, M.S. and Batistote, M., 2022. Biomass. bioethanol transformation and production process. *Revista de Agricultura Neotropical*, 9(4), p. e7089. http://dx.doi.org/10.32404/rean.v9i4.7089

Srinivasa, R.P, Lizarazu, W.Z., Bellmer, D. and Monti, A., 2014. Prospect of sorghum as a biofuel feedstock. In: Y-H. Wang, H.D. Upadhyaya and Ch. Kole, eds. *Genetics, Genomics and Breeding of Sorghum*. Series on Genetics, Genomics and Breeding of Crop Plants. Boca Raton: CRC Press Taylor & Francis. pp. 303-330. http://oar.icrisat.org/id/eprint/9054

Suwanapong, S., Khongsay, N., Laopaiboon, L., Jaisil, P. and Laopaiboon, P., 2013. Dried spent yeast and its hydrolysate as nitrogen supplements for single batch and repeated-batch ethanol fermentation from sweet sorghum juice. *Energies*, 6(3), pp. 1618-1631. https://doi.org/10.3390/en6031618

Taher, H., Ali, S. and Khan, M., 2020. Role of clarification in improving bioethanol production efficiency. *Bioresource Technology*, 307, pp. 123-130. https://doi.org/10.1016/j.biortech.2020.123456

Thai, C. D., Bakir, H. and Doherty, W.O.S., 2012. Insights to the clarification of sugar cane juice expressed from sugar cane stalk and trash. *Journal Agriculture Food Chemestry*, 60(11), pp. 2916-2923. https://doi.org/10.1021/jf204998b

Turhollow, A.F., Webb, E.G. and Downing, M.E. 2010. Review of Sorghum Production Practices. Applications for Bioenergy. https://info.ornl.gov/sites/publications/files/Pub22854.pdf

Ungureanu, N., Vlăduț, V. and Biriș, S-Ș., 2022. Sustainable Valorization of waste and by-products from Sugarcane Processing. *Sustainability,* 14, p. 11089. https://doi.org/10.3390/su141711089

USDA-FAS., 2024. USDA Foreign Agricultural Service. Biofuels annual. Brazil/Mexico ethanol production data. https://apps.fas.usda.gov/gainfiles/

Vandenberghe, L., Valladares-Diestra, K., Bittencourt, G., Torres, L.A., Vieira, S., Karp, S., Sydney, E., De Carvalho, J., Thomaz-Soccol, V. and Soccol, C., 2022. Beyond sugar and ethanol. The future of sugarcane biorefineries in Brazil. *Renewable and Sustainable Energy Reviews,* 167, p. 112721. http://dx.doi.org/10.1016/j.rser.2022.112721

Vázquez, H. and Dacosta, O., 2007. Fermentación alcohólica. Una opción para la producción de energía renovable a partir de desechos agrícolas. *Ingenería Investigación y Tecnología*, 8(4), pp. 249-259.

Wang, M., Wang, J., Tan, J., Sun, J. and Mou, J-L., 2011. Optimization of ethanol fermentation from sweet sorghum juice using response surface methodology. *Energy Sources. Part A. Recovery*, 12, pp. 1139-1146. https://doi.org/10.1080/15567030903330801

Wen, Z., Chen, J., Yang, Y., Zhang, Y., Jiang, Y. and Yang, S., 2022. Pilot-scale fermentation of 300 t/a total solvents from sweet sorghum stalk juice. *Chemical Engineering Journal*, 454 (Part 4), p. 40534, https://doi.org/10.1016/j.cej.2022.140534

Williams-Alanís, H., Zavala-García, F., Arcos-Cavazos, G., Rodríguez-Vázquez, M. del C. and Olivares-Sáenz, E., 2017. Características agronómicas asociadas a la producción de bioetanol en genotipos de sorgo dulce. *Agronomía Mesoamericana*, 28(3), pp. 549-562. https://dx.doi.org/10.15517/ma.v28i3.26690

Williams-Alanís, H., Zavala-García, F., Arcos-Cavazos, G., Rodríguez-Vázquez, M. del C., Olivares-Sáenz, E. and Treviño-Ramírez, J.E., 2020. Potrillo, nuevo híbrido de sorgo dulce para la región central de Nuevo León y sur de Tamaulipas, México. *Revista Fitotecnia Mexicana*, 43(3), pp. 355-356. https://doi.org/10.35196/rfm.2020.3.355

Williams-Alanís, H., Aranda-Lara, U., Árcos-Cavazos, G., Zavala-Garcia, F., Rodríguez-Vázquez, M. de C. and Elizondo-Barrón. J. 2025. Dulcina: Nueva Variedad De Sorgo Dulce Para Tamaulipas Y Centro De Nuevo León. *Revista Mexicana De Ciencias Agrícolas,* 16 (5), p. e3413. https://doi.org/10.29312/remexca.v16i5.3413.

Wright, M., Lima, I. and Bigner, R., 2016. Stability and use of sweet sorghum bagasse. *Sugar Technology*, 19(5), pp. 1-19. http://dx.doi.org/10.1007/s12355-016-0503-5

Wu, S., Staggenborg, S., Propheter, J., Rooney, W., Yu, J. and Wang. D., 2009. Features of sweet sorghum juice and their performance in ethanol fermentation. *Industrial Crops Products*, 31(1), pp. 164-170. http://dx.doi.org/10.1016/j.indcrop.2009.10.006

Yang, Z., Li J-L., Liu L-N., Xie, Q. and Sui, N., 2020. Photosynthetic regulation under salt stress and salt-tolerance mechanism of sweet sorghum. *Frontier Plant Science*, 10, p. 1722. https://doi.org/10.3389/fpls.2019.01722

Wheatley, M.C., 2024. Advancements in Renewable Energy Technologies. A Decade in Review. *Premier Journal of Science*, 1, p. 100013. https://doi.org/10.70389/PJS.100013

Zegada-Lizarazu, W. and Monti, A., 2015. An integrated approach to harvest and storage of sweet sorghum at farm scale. *Bioenergy Research*, 8 pp. 450-458. https://doi.org/10.1007/s12155-014-9533-6