Chapter 28
Sugarcane Bioeconomy and Circularity in Latin America: Progress and Future Pathway

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28.1 Introduction

There is growing recognition of the need and urgency to base the economy on renewable resources (Bioeconomy) and for the whole process to have the lowest environmental impact possible (circular) in terms of using residues, attaining efficiency, using bioenergy, and having low GHG emissions. Sugarcane is a millennial crop that can contribute to all those aspects and, thus, be part of the plethora of resources that humanity needs to develop or enhance to solve the immense sustainability challenges. The objective of this chapter is to showcase the main products that stem from the processing of sugarcane in Latin America as well as the important advances in circularity/sustainability. In this region, several initiatives related to the circular bioeconomy are already being implemented. A notable example is the

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use of sugarcane residues, such as bagasse,[1] to generate biogas and electricity. This allows the production of clean energy that supplies the sugar mill plants themselves and provides electricity to the national grids, facilitating access to this energy for the Latin American population. This electricity cogeneration reaches an annual total of approximately 25,445 GWh (UNALA, 2024b). In addition, residues are converted into organic fertilizers, improving soil fertility and reducing the need for chemicals. Sugarcane by-products are also being used in the production of paper, bioplastics,

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[1] Dry pulpy fibrous material that remains after crushing sugarcane stalks to extract juice.

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and ethanol as a biofuel, a crucial source that reduces dependence on fossil fuels and contributes to the reduction of GHG. Regionally, around 33.5 billion liters of ethanol are produced annually (UNALA, 2024b).

Three main sections have been defined: (a) examples of progress on circularity around the main areas of environmental concern in the cultivation of sugarcane; (b) sugarcane as a raw material and as a source of bioenergy; and (c) progress and future perspectives. In the latter, a reflection on how to reach the potential of sugarcane to contribute to a circular bioeconomy is included. The text draws on cases and examples of some Latin American countries, which are a way to illustrate the main arguments. It is not, however, an assessment of the status quo of circularity in the sugarcane sector in Latin America. It will be argued that a firm starting point would be to examine the state of adoption of good practices and how those adopted can shed light on what can be done to maximize the potential of this crop not just in Latin America but in all the countries in which it is cultivated.

28.2 The Importance of Sugarcane in Latin America

The sugarcane agro-industry is a key actor for sustainable development in Latin America. It is a source of employment, economic diversification, foreign exchange, investment attraction, and innovation. Not only does it contribute to increasing exports of Latin American economies, but it also creates direct and indirect employment

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Table 28.1 Sugarcane cultivation in Latin America

Country	Hectares harvested	% of national land
Argentina	400,000	0.14%
Brazil	10,000,042	1.20%
Colombia	193,003	0.17%
Costa Rica	54,848	1.07%
Dominican Republic	32,467	0.67%
Ecuador	80,000	0.28%
El Salvador	77,827	3.70%
Guatemala	250,000	2.30%
Mexico	806,193	0.41%
Nicaragua	72,600	0.56%
Peru	84,941	0.07%

Source: UNALA (2024a)

opportunities, with potential for growth and investment attraction in related sectors. According to data from the International Sugar Organization (ISO), about 47% of sugar exports worldwide come from the region (ISO, 2023). In addition, millions of people are involved in the agro-industry's supply chain. It is estimated that the Latin American sugarcane sector generates approximately 6.4 million jobs (UNALA, 2024b). Additionally, the production of sugar and its by-products, like ethanol and electricity from sugarcane bagasse, helps diversify regional economies.

Besides economic benefits, this industry has made contributions in terms of the environment. The use of sugarcane bagasse for electricity cogeneration reduces reliance on fossil fuels and lowers GHG emissions. Furthermore, by-products of sugarcane are utilized to create other derivatives, such as ethanol, a renewable fuel that helps decrease polluting emissions. Together, Latin America produces about 30% of ethanol worldwide each year (ISO, 2023), virtually all from sugarcane. This is achieved through the utilization of 12,051,921 ha of land, accounting for 0.07–3.7% of the national territories, as detailed in Table 28.1.

There is a social component in the relevance of this agro-industry. Apart from direct and indirect jobs, there are social initiatives in place led by sugarcane companies in their area of influence. These programs range from the implementation of best practices with small and medium sugarcane suppliers, to the development of key social infrastructure, such as schools and medical clinics. Some of these projects are implemented in partnership with national and local governments. In other cases, there are social programs implemented with fully private participation, showing the commitment of Latin America's sugarcane agro-industry to neighboring communities.

28.3 Sugarcane as a Sustainable Crop and Progress on Circularity

Sugarcane cultivation, as with any human activity, can have negative impacts on the environment in areas such as water use and pollution, air quality, deforestation, and soil degradation. However, there are numerous ways in which environmental impacts can be substantially reduced. This industry has examples in all components of circularity: resource use efficiency, use of biological options, reuse of liquid and solid waste, renewable energy through biomass use, and even natural resources restoration in its area of influence. In this section, the main mechanisms in Latin America to optimize the use of resources and pollution control are presented. We argue that the sugarcane agro-industry has several examples of circularity and that it is headed towards a sustainable future. This is not to say it does not affect the environment, but rather that there is great potential when adopting existing practices by all producers on the continent. Only some specific cases will be mentioned and cited though there are more in the region.

28.3.1 Water Management

Agriculture is the biggest water user in the world with an estimated 70% use of all water withdrawals globally (FAO, 2021; World Water Assessment Programme, 2009) though there are variations between different continents. While North America and Europe use around 50% of water withdrawn for agriculture (with industry being their biggest user), the percentage in Africa, Oceania, Asia, and Latin America varies from 70 to 90% (FAO, 2021).

Sugarcane has a small water footprint compared to other crops (Mekonnen & Hoekstra, 2014), but since it is one of the main crops worldwide, it is also an important water user. Its impact on the environment depends on how it is used as well as on the treatment of wastewater. Advances have taken place, as the following examples of sustainability through water management will suggest.

The volume of water used for sugarcane cultivation varies between countries. The water footprint indicates the volume used per unit of production (i.e., m^3 of water per ton of sugarcane). Hoekstra et al. (2011) proposed three components of the water footprint, namely: blue water footprint, which is that withdrawn from surface and ground sources and applied as irrigation; the green water footprint, which is that covered with rainfall; and the gray water footprint, which refers to the volume of water needed to dilute the most abundant pollutant. Table 28.2 shows the water footprint estimated for different countries across Latin America and how they compare to global values. These important differences are related to location and their rainfall levels, crop yield differences related to management, and irrigation technology.

Table 28.2 Water footprint of sugarcane in Latin American countries compared to the global mean (m^3/ton)

Country/region	Green water footprint	Blue water footprint	Gray water footprint	Total water footprint	Source
Mexico				274	Garay Jacome et al. (2022)
Peru		134	8	142	Mekonnen & Hoekstra (2011) in Scarpare et al. (2016)
Brazil	79	28	14	121	Scarpare et al. (2016)
Guatemala	94	19	6	119	ICC (2024a) (2023
El Salvador	105	10	3	118	ICC (2024a)
World average	139	57	13	209	Mekonnen and Hoekstra (2014)

There have been advances in irrigation efficiency in Latin America. Technology has played a major role and efficiency values vary from 30 to 40% in the case of inundation or furrow irrigation, to more than 90% in drip irrigation (Torres Aguas, 1995). As producers shift to those irrigation technologies, their water use declines. Technology and science have also played a role in better water use through the estimation of crop water demand according to temperature, rainfall, soil type, and wind speed at the local level. There are software programs, such as Cengiriego in Guatemala (CENGICAÑA, 2018) and Gerenciamento Integrado de Riscos Hídricos e Ambientais (GIRHA) in Brazil, that indicate the right amount of irrigation sheets for plots daily. Weather stations and soil humidity sensors are used to feed information into the software. In Colombia, by using the Water Balance Estimation tool to measure and control water consumption in the fields, the sugar agro-industry has managed to reduce its water consumption in sugarcane production by 50% (UNALA, 2025). A third defining factor in efficiency is irrigation canals.

The impact of water use in the industrial processing of sugarcane can be reduced considerably. The first step is to reduce general use, which can be done with the use of technology to clean sugarcane before crushing it without using water. In the case of São Paulo, water demand decreased by 85% from the 90s to 2024, as seen in Fig. 28.1 (Governo do Estado de São Paulo, 2024). The second general step is to reuse water in the different processes. Cooling systems are widely used in countries like Argentina, Brazil, Colombia, El Salvador, Guatemala, Mexico, and Peru. Water treatment plants are also used to remove certain components so that water can be further re-used in other processes. For example, Leales Sugar Mill's (Argentina) commitment to sustainability in sugar, alcohol, and energy production has estimated a total 35% reduction in water consumption per ton of cane milled since Leales Mill was acquired by *CIA. Inversora Industrial S.A.*—CIISA in January 2010 (ComunicarSe, 2013).

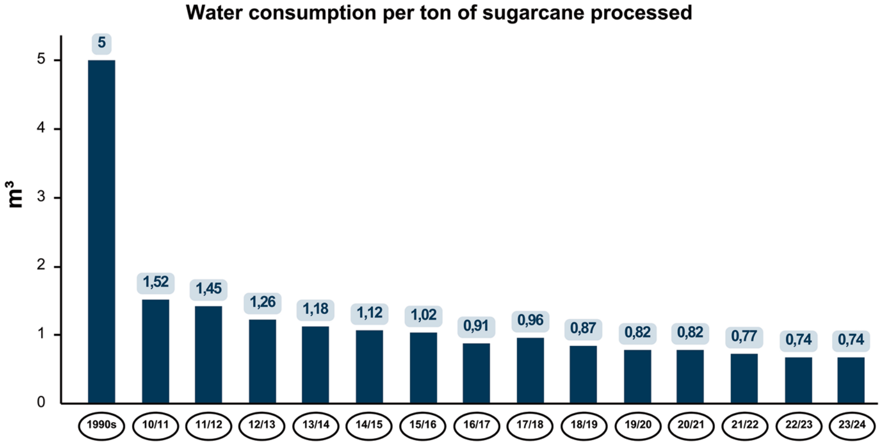

Fig. 28.1 Water consumption per ton of sugarcane processed in São Paulo (m^3/ton) per milling year. Source: Governo do Estado de São Paulo (2024)

The third main action is to use wastewater for fertigation,[2] so that it is not discharged into rivers. It does, however, require treatment before it is used for that purpose. The benefits for the environment are more than twofold. On the one hand, water demand reduction entails less pressure on water sources, and in some companies (ICC, 2023), the industrial component in the water footprint of sugar comprises around one percent. On the other hand, wastewater treatment and its use for fertigation prevents pollution in rivers.

Between 1990 and 2023, in the state of São Paulo alone, the sugar-energy sector reduced absolute water demand by approximately 60%, while sugarcane production increased by about 150% during the same period. This result was achieved through a series of investments, notably the closing of industrial water circuits, the elimination of burning as a pre-harvest agricultural method—thereby ending the need to wash the sugarcane before processing—and fertigation using vinasse (Governo do Estado de São Paulo, 2024). Grupo CASSA, the biggest sugar producer in El Salvador, reported a 71.6% reduction of industrial water use in the period 2015–18, and 97% of water recycling (Grupo CASSA, 2018).

There are several examples of the contributions of the sugarcane companies to integrated water resource management, including some outside their chain of production. They are related to watershed management and include forest protection and restoration, soil conservation, disaster risk reduction, and scientific data generation (weather and river flow). Specific cases are the Water for Life and Sustainability Fund in Colombia (Moreno, 2016) and the Integrated Watershed Management program of the Climate Change Research Institute in Guatemala (ICC, 2024a). *Compañía Azucarera Salvadoreña*—CASSA Group in El Salvador has also funded

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[2] Fertigation is the application of fertilizers through irrigation system and is the most advanced and efficient practice of fertilization (Kant & Kafkafi, 2013).

and managed initiatives directed toward communities in their surroundings (ICC, 2024a, 2024b).

A water governance case involving the sugarcane agro-industry of Guatemala was highlighted in the latest report of the Intergovernmental Panel on Climate Change -IPCC- (Castellanos et al., 2023). Following a water crisis associated with the very intense El Niño event that took place from November 2014 to May 2016 (CIIFEN, 2016; NOAA, 2019), dialogue roundtables were established and managed to recover two main rivers in the Pacific lowlands (Gobernación de Escuintla et al., 2017). Local agreements involving a diverse set of stakeholders have been key for effective water management despite the lack of water authorities and legislation. Similar actions have been key for flood risk management too, which was also mentioned in the IPCC report.

28.3.2 Biofertilizers and the Use of Sugarcane Residues as Compost

Sugarcane is a crop with a high biomass production capacity, associated with its long growth cycle, leading to high requirements for both water and nutrients. The application of chemically synthesized fertilizers has, historically, been necessary to sustain profitable production. However, the large-scale application of fertilizers entails economic and environmental costs, since both its production and application generate large quantities of GHG and other impacts on soil and water (Romero et al., 2009).

Biofertilization is currently the most promising alternative to reduce or eliminate chemical fertilization without affecting sugarcane productivity. Biofertilizers are biological products containing living microorganisms, such as fungi and bacteria, that promote plant growth through various mechanisms, including biological nitrogen fixation, phytohormones and siderophores production, phosphorus solubilization, induction of defense mechanisms, among others. Those used in sugarcane consist of plant growth promoting bacteria (PGPB) belonging to *Pseudomonas*, *Gluconacetobacter*, *Azotobacter*, *Burkholderia*, *Herbaspirillum*, and *Azospirillum* genera, which can enhance plant nutrition and growth mainly through biological nitrogen fixation and phosphorus solubilization. However, thanks to advances in agricultural biotechnology, new genera and species of PGPB associated with sugarcane and novel growth promotion mechanisms are constantly being discovered, working synergistically (Zahid et al., 2015).

Biofertilizers have demonstrated significant potential to reduce the needs of fertilizers and enhance sugarcane productivity across Latin America. Brazil leads the development and massive application of fertilizers to sugarcane plantations. Bioinputs based on *Azospirillum brasilense*, which provides up to 70% of the plant's nitrogen needs, have permitted production of up to 100 tons/ha/year with low doses of nitrogen (50–60 kg/ha/year) and with no evidence of depletion of this element in the soil (Rivera-Urbalejo et al., 2017; Velasco-Velasco 2014). The sugarcane agro-industries of Argentina, Brazil, Colombia, Dominican Republic, Ecuador, Guatemala, Mexico, Nicaragua, and Peru have implemented biofertilizers to their production processes.

In Tucumán, Argentina, the adoption of biofertilizers has become a widespread practice among the productive sector during recent years. Currently, over 65% of the sugarcane fields in the province are fertilized annually with these bioproducts, significantly reducing the use of chemical fertilizers in the agronomic management of the crop (Leggio Neme et al., 2023). Nevertheless, further research and extension of these technologies are needed to integrate them into conventional management practices and move towards a sustainable production system.

In Costa Rica, promising results were observed in Carrillo County, Guanacaste, where a biofertilizer mixture, including *Azotobacter chroococcum* and several strains of *Bacillus*, combined with half the normal nitrogen dose, achieved yields comparable to those obtained with full nitrogen application. The Department of Research and Extension of Sugarcane (DIECA) of the *Liga Agrícola Industrial de la Caña de Azúcar* (LAICA) has played a pivotal role in advancing this research in the crop. Through rigorous bioprospecting and greenhouse trials, promising bacterial strains have been identified for improving sugarcane growth under reduced fertilization regimes of up to 50%. These trials have validated that certain bio inputs can maintain high productivity while significantly reducing the use of synthetic fertilizers (DIECA, 2023). This research underscores the viability of biofertilizers in enhancing the growth and productivity of sugarcane, combined with the mitigation of externalities to soil, water, and environment.

Compost from Mill Muds and Other Solid Residues from Sugarcane

In the sugarcane agro-industry, organic residues are used, such as mill muds (also called filter cake), ash from the washing of chimney gases, bagasse, and sugarcane trash, in mixtures that proportionally can also absorb a certain percentage of the vinasse produced (Sotomayor et al., 2019). The final product can be used as an organic amendment in agricultural fields, providing nutrients such as potassium in important quantities or nitrogen and phosphorus in smaller quantities, depending on the proportions of raw material used in the process.

In São Paulo, CETESB—Environmental Company of the State of São Paulo recognized the agronomic benefits of using organic residues, such as filter cake and ash, by publishing a regulation with general guidelines for their use (Directorate Decision No. 126/2021/P, dated December 16, 2021). These guidelines establish the technical procedure for the application of residues generated in ethanol and sugar production plants and for the licensing of waste mixing yards.

In the case of Argentina, the Obispo Colombres Agro-industrial Experimental Station provides technical assistance to sugar-alcohol companies for the analysis of raw materials, formulation of compost heaps, physicochemical control of the process, evaluation of its stability at the end of the process and evaluations so that its dosage on arable or non-arable land is carried out with the best possible use. Efficient compost application practices would allow, on the other hand, at least partial substitution of the use of fossil fertilizers on arable land.

Vinasse

Vinasse is a liquid by-product of ethanol production rich in minerals and organic matter. It is used as a fertilizer applied directly in liquid form (diluting it first with water) or in solid form after going through a process of treatment, often adding other nutrients. For every liter of ethanol produced, about 12 L of vinasse are generated, making it a sustainable solution for nutrient replenishment (Silva et al., 2014)

Vinasse holds significant potential for energy production. It is composed mainly of potassium (3340–4600 mg/L K_2O) and sulfur (3700–3730 mg/L SO_4); however, significant amounts of phosphorus (9–200 mg/L P_2O_5), carbon (8700–12,100 mg/L C), nitrogen (480–710 mg/L N), calcium (1330–4570 mg/L C), and magnesium (580–700 mg/L MgO) can also be found (Pinto in Barbosa Cortez et al., 2020). Vinasse can be converted into biogas, biomethane, and bioenergy through biodigestion, a process that maintains its fertilizing properties while producing clean energy and water, aligning with the biorefinery model (de Carvalho et al., 2023). An example of this is Magdalena, one of four ethanol producers in Guatemala that built the biggest biodigesters in the country to extract methane from vinasse for use in electricity generation (Alvarado, 2023).

Currently, Brazil already has numerous biofertilizer factories using vinasse, attached to sugarcane processing plants, with increasing investments in the production of biogas and biomethane as well. Major industry groups already operate industrial plants, such as Raizen, Cocal, and Tereos, with installed capacity ranging from 5 to 21 MW of electricity and more than 25,000 Nm^3/day of biomethane per plant. New projects are also announced annually, such as those by the São Martinho Group, further consolidating another renewable energy production route from sugarcane. Vinasse is also being used as a fertilizer in the sugarcane growing process in Argentina, Colombia, Dominican Republic, Guatemala, Mexico, Nicaragua, Panama, and Peru.

28.3.3 Biological Pest Control and Disease Prevention

Biological control is based on regulating pests through natural agents such as predators, parasitoids, and pathogens, which is considered ecologically and economically sound (Gangwar, 2017). The implementation of these methods began in Costa Rica in the 1980s with the support of the Liga Agrícola Industrial de la Caña de Azúcar (LAICA), which established programs to control the common stalk borer (*Diatraea* spp.) and the spittlebug (*Aeneolamia* spp., *Prosapia* spp.) using parasitoids and entomopathogenic fungi, respectively (Rodríguez-Morales & Chaves-Solera, 2020).

LAICA's Biological Control Programs have been led by the Department of Research and Extension of sugarcane (DIECA) and have allowed the coverage of extensive cultivation areas, benefiting both large mills and independent producers, with the releasing of 809.93 million parasitoids and the application of 498,375 kg of entomopathogenic fungi between 1984 and 2020 (Rodríguez-Morales & Chaves-Solera, 2020). National average control over the sugarcane borer (*Diatraea* spp.) after 40 years of constant releasing of the parasitoid *Cotesia flavipes* has been established at 30.2%, considering only one application; but, in areas where two applications have been made, the control reached 60%. In addition, different natural enemies contribute to control at the border with another 10%; that's the case of tachinid fly (*Billaea claripalpis*) and braconid wasps (*Alabagrus* sp. and *Agathis* sp.). On the other hand, control level by *Metarhizium anisopliae* over the spittle bug (*Aeneolamia* spp., *Prosapia* spp.) in a period of 15 years reached 57.4%, with a maximum of 87.1% in 1996.

This approach has significantly reduced the use of chemical pesticides, preserved several natural enemies, which contribute to 10% control for the border (mainly tachinid and braconid parasitoids), and promoted a sustainable practice aligned with the principles of bioeconomy, which seeks to reduce reliance on fossil resources and foster more sustainable agricultural practices. In Guatemala, adoption has been widespread through research capacity building and investments by CENGICAÑA and the sugar producing companies since the 1990s (CENGICAÑA, 2014).

Biological control programs have not only improved pest management but also contributed to the environmental and economic sustainability of sugarcane cultivation in most Latin America countries. However, without proper risk management and monitoring, these programs may have unforeseen consequences, such as invasive potential and the spread of diseases.

28.3.4 Greenhouse Gas Emissions (GHG) and the Carbon Footprint of Sugarcane

One of the most used indicators associated with life cycle analysis is the carbon footprint. This measures the total GHGs released into the atmosphere, both directly and indirectly, due to human activities. In 2019, it was estimated that 22% of all GHG emissions came from agriculture, forestry, and other land uses, though with more uncertainty than in other sectors due to the high share and uncertainty of CO_2-LULUCF emissions (Shukla et al., 2023).

The carbon footprint of cane sugar is between 0.24 and 0.76 ton CO_2e/ton sugar (CEFS, 2012; de Figueiredo et al., 2010; García et al., 2016; ICC, 2023). It is estimated using the IPCC guidelines, which define the main components in the whole lifecycle: land use change, fossil fuel use in transportation and agricultural activities, fossil fuel use for irrigation pumps, preharvest and postharvest burning of sugarcane, electricity use (self-generated or purchased from the national grid), nitrogen-based fertilization, and methane from wastewater treatment facilities (IPCC, 2006). In the case of Guatemala (ICC, 2023), 66% of the carbon emissions correspond to processes in the field, whereas transportation of cane accounts for 9% and the industrial process for the remaining 25%.

In Argentina, the agricultural, livestock, and forestry sector is responsible for 37% of reported emissions and faces the challenge of adapting to climate change while ensuring food security. Among productive activities, the sugar-alcohol agro-industry is of significant economic and social relevance in northwestern Argentina, with Tucumán province having a net harvestable area for the 2024 crop of 294,470 ha. A study to estimate GHG emissions was conducted based on two agricultural systems, on using calcium ammonium nitrate (CAN) as an n-based fertilizer and another using urea. Total GHG emissions using CAN were 28.8 kg CO_2eq/ton cane, and 36.1 kg CO_2eq/ton cane when using urea. Emissions per unit area were 1848 kg CO_2eq/ha with CAN, while with urea they totaled 2317 kg CO_2eq/ha. In Guatemala, emissions per hectare were estimated at 3900 kg (ICC, 2024a, 2024b) and 3002 for El Salvador (ICC, 2023).

Studies in some countries have shown that fossil fuel use is the main source of emissions in the sugar production process, followed by N-based fertilization and pre-harvest burning. Fossil fuels, mainly diesel, are used for agricultural activities, transportation of cane and sugar, and for irrigation pumps. Another factor that can vary and determine emissions is the source of electricity for internal uses. In sugarcane growing countries, it is a widespread practice to generate their own electricity using bagasse and, thus, their carbon footprint is much lower than in those countries where they use other sources, especially non-renewable ones. Mitigation strategies and plans need to tackle the main sources of emissions mentioned above before considering external projects. In terms of emissions, what is valuable in the sugarcane sector is the generation of bioelectricity and biofuels, which will be explained later in the chapter.

At the country level, an initiative in Costa Rica is worth highlighting. Under the concept of Nationally Appropriate Mitigation Action (NAMA), part of the Paris Agreement and the UN Convention on Climate Change, it is a public–private partnership to reduce GHG and promote sustainable practices. It includes capacity building for sustainability; establishing mitigation targets for the chain of production; implementing good practices and technological actions to improve productivity, reduce costs, increase profits and reduce environmental impacts; and generating a differentiated product, the "low emission sugar" (LAICA, 2023).

28.4 Sugarcane as a Raw Material and as a Source of Renewable Energy

Sugarcane can contribute greatly to the bioeconomy for two main reasons. In the first place, a vast number of products can be manufactured from all parts and by-products of sugarcane, from the juice, bagasse, sugar, molasses, mill muds, vinasse, and trash. The products span from food, beverages, pharmaceutical uses, fertilizers, animal feed, fuels, bioplastics, packaging, cosmetics, and more, as Fig. 28.2 shows.

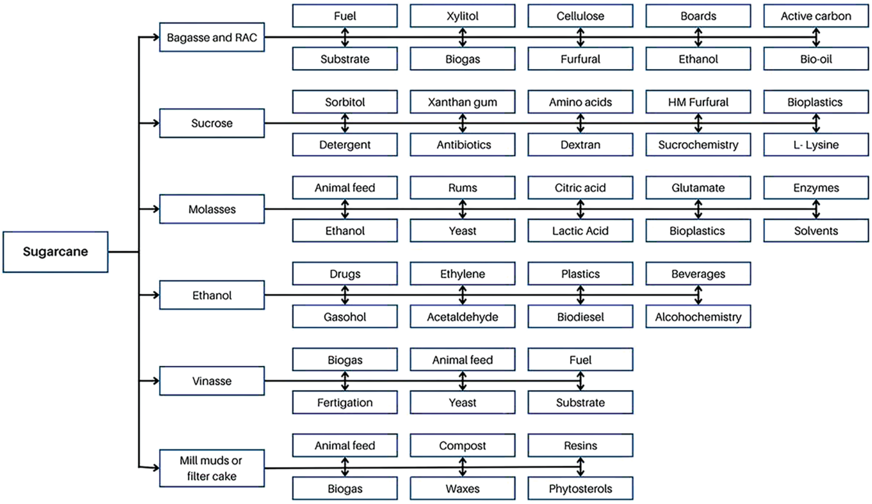

Fig. 28.2 Main products from sugarcane and its derivatives. Modified from Aguilar Rivera (2009)

Most importantly, many of those products are produced from oil derivatives at present, so sugarcane presents an opportunity to replace them. Secondly, it contributes to bioenergy generation through electricity from bagasse (mainly), and through ethanol, which is used to replace a certain percentage of gasoline in many countries, though it can be used as the only fuel in some cars. The main products and uses of sugarcane as a raw material will be presented next. Again, only a few examples are included for the purpose of illustrating progress to date and future potential.

28.4.1 Bioelectricity

Bagasse is a fibrous material that is composed of the external part of the cane. The mean composition of washed–dried bagasse is cellulose (45–55%), hemicellulose (20–25%), lignin (18–24%), and ash (1–4%) (Payá et al., 2018). Sugarcane bagasse, with its high energy potential, has proven to be an important renewable energy source, by turning what would otherwise be waste into a valuable resource, the sugarcane industry drives sustainable development and fosters a circular economy within the sector.

The process of energy generation from bagasse involves burning the material to produce steam, which powers turbines that generate electricity. This cogeneration method is highly efficient, as it simultaneously produces electricity and heat for industrial use (CENGICAÑA, 2014). Not only is this process clean—since the carbon released is offset by the carbon absorbed by growing sugarcane—but it also significantly reduces waste and emissions.

The environmental benefits of producing electricity from sugarcane bagasse are remarkable. Unlike fossil-based energy sources, sugarcane absorbs CO_2 during its growth in the field, effectively sequestering carbon rather than releasing it, as is the case with fuels like coal or natural gas, which contribute to GHG emissions. In fact, electricity production from sugarcane bagasse in Guatemala alone helps prevent the emission of around 4 million tons of CO_2e annually into the atmosphere (Salazar et al., 2023), highlighting just how significant its environmental impact can be.

In Argentina, in 2009 the facilities that allowed for the first time in the country the sale of surplus electrical energy to the national grid by a sugar mill were completed, with a 4 MW power surplus. In 2024, that figure rose to 50 MW delivered to the national grid by six sugar mills, with projects and investments in the process to keep increasing the energy delivered by both the mills that already deliver energy and those that do not yet.

Sugarcane bagasse-based electricity production also plays a crucial role in Latin American economies. Not only does it represent an opportunity for sugar mills to be self-sufficient in terms of energy, but it also means the possibility of diversifying their product portfolio. Besides creating jobs in rural areas, this activity also saves foreign exchange for the countries where this activity is developed, by avoiding the need to import coal or other sources of energy. This, in turn, also means that economies become more energy independent, making them less exposed to the risks posed by importing energy from other countries. It also helps to keep the spot price of energy more stable, benefiting both households and companies that need electricity to produce.

For decades, many sugar companies in Latin America have made important investments in bagasse-based electricity production. By doing so, they have successfully lessened their dependence on fossil fuels, contributing to having cleaner energy matrixes throughout the region. Electricity from bagasse is produced by the sugarcane agro-industries in countries such as Argentina, Brazil, Colombia, Costa Rica, the Dominican Republic, Ecuador, El Salvador, Guatemala, Mexico, Nicaragua, Panama, and Peru.

Even though electricity generated from sugarcane bagasse has many perks, it also faces several challenges. One of its main challenges is its availability. Aside from the production in Colombia and Peru, where sugarcane is harvested all year round, bagasse availability is limited to the 6-month harvest period. This means sugarcane producers need to buy other sources of energy to meet their energy contract commitments to the national matrixes. However, new technologies could enhance efficiency and biomass storage, which could increase the time that sugarcane mills are able to offer energy throughout the year.

The Guatemalan sugarcane agro-industry has invested more than US $800 million since the 1990s in bagasse-based electricity production. This investment has positioned the sector as a key player in the national energy grid, supplying up to 30% of the country's electricity demand during the harvest season (November to May). This contribution is crucial, as it complements hydropower plants—the largest generators in the grid—during the dry season when their operations are limited. The continuous efforts of the agro-industry help ensure energy stability and sustainability, showcasing its pivotal role in Guatemala's renewable energy landscape, and making remarkable contributions to the accomplishments of some of the United Nations' Sustainable Development Goals (SDGs), such as SDG 7 (Energy) and SDG 12 (Responsible Consumption).

Besides bagasse, sugarcane trash can be used for electricity generation. The gradual elimination of sugarcane field burning and the growing advance of green harvesting have made more biomass available for energy use in boilers. Sugarcane trash, composed mainly of sugarcane leaves and stalks, represents about 20% by weight of the harvest. In the case of Tucumán (Argentina), 151 kg of dry matter per ton of sugarcane milled is the estimate of trash. Assessments have shown its good quality as fuel, similar to that of bagasse. The energy characterization considered as standard for the sugarcane trash from Tucumán has a lower calorific value of 10,495.07 kJ/kg, moisture 15%, and ash content 11.39% (Feijóo et al., 2015).

In the case of Brazil, recent data compiled in the National Energy Balance (BEN), conducted by the Energy Research Company (EPE) under the coordination of the Ministry of Mines and Energy (MME) of Brazil, show that sugarcane continues to be the leading renewable source in Brazil's energy matrix, accounting for 16.9% of the total (Empresa de Pesquisa Energética, 2024).

Sugarcane biomass-based electricity production plays a major role in advancing towards economies that depend less on fossil fuels, supporting the sustainable development of Latin America. It brings about several environmental advantages, namely: reducing emissions, sequestering carbon, and complementing other sources of renewable energy. With the right incentives, policies, and resources for regular investments, sugarcane bagasse-based electricity could reach a higher standard, driving greener economies throughout the region (Fig. 28.3).

28.4.2 Ethanol

The transport sector around the world depends almost entirely on fossil fuels. It is crucial to decarbonize this sector while internal combustion engines are still in use and the adoption of electric vehicles continues to grow. Ethanol can be produced from many raw materials, like grains, sugars, or cellulose. Today, more than 70 countries produce and use ethanol, but carbon intensity is gaining importance in all life cycle analyses. According to the European Union Renewable Energy Directive (RED II), the GHG calculations depend on the feedstock production, processing, and distribution activities. According to the RED II calculations, sugarcane ethanol has a default value of 28.6 g CO_2e/MJ, ethanol from sugar beet in the range of 22.5–50.2 g CO_2e/MJ (it depends on the type of energy used to produce), and corn ethanol has default values from 30.3 to 56.8 g CO_2e/MJ. The industry and sustainable standards are becoming increasingly stringent, making sugarcane globally one of the crops with the lowest default GHG values.

Figure 28.4 illustrates the global warming potential of biofuels in gCO_2e/MJ, a metric that quantifies GHG emissions during all phases of biofuel production and

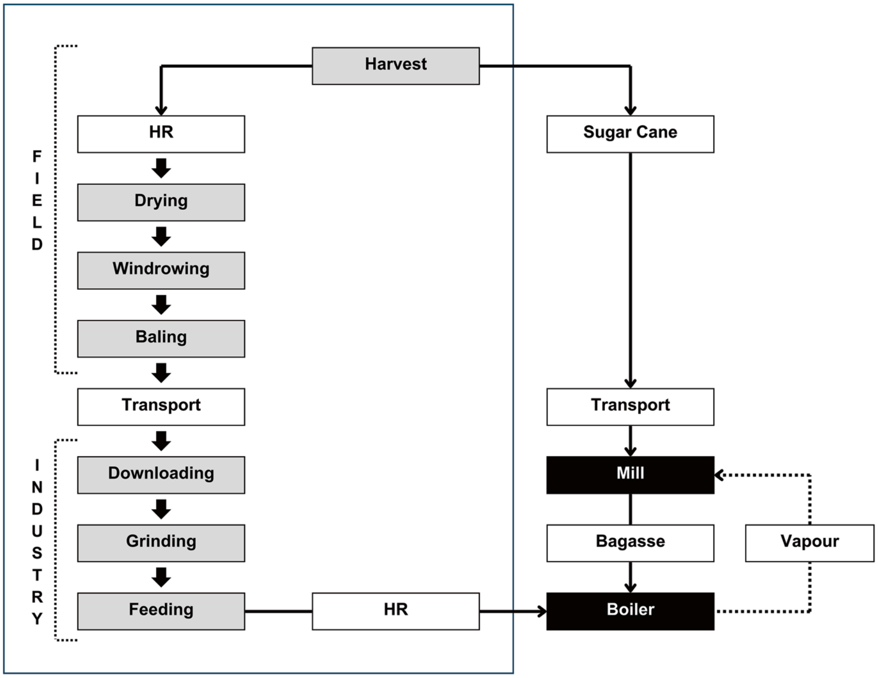

Fig. 28.3 Operational flowchart for sugarcane harvest residue (HR) collection system. The system under study is delimited by the rectangle. Source: modified from Golato et al. (2017)

use for a certain energy quantity that can be obtained from the use of that biofuel. These values are compared to the global warming potential of their fossil fuel equivalents, represented by the dashed line.

Brazil has more than four decades of producing and using ethanol in the gasoline from sugarcane. In Latin America, there are other countries that produce from this sustainable biomass, namely: Argentina, Bolivia, Colombia, Ecuador, Paraguay, Peru, and Uruguay. These countries have a blending program with gasoline. On the other hand, Costa Rica, the Dominican Republic, Guatemala, Mexico, Nicaragua, and Panama are ethanol producers, but they still do not have blending programs.

Ethanol from sugarcane in Argentina is produced in 16 distilleries, attached to sugar mills located in the northwest of the country, using molasses from the sugar production process and occasionally a percentage of direct cane juice as feedstock.

Research conducted using the Life Cycle Assessment (LCA) approach (Garolera De Nucci et al., 2017) showed a noticeable improvement with the addition of bioethanol to fossil fuel. Considering gasoline and a hypothetical case of 100% ethanol (E100) in an engine, 0.735 kg CO_2eq/MJ and 0.442 kg CO_2eq/MJ are generated with gasoline and E100, respectively. This explains that climate change impact is higher for fossil fuel than for biofuel. This demonstrates a 40% reduction in emissions, meaning that gasoline emits approximately 67% more CO_2 than bioethanol.

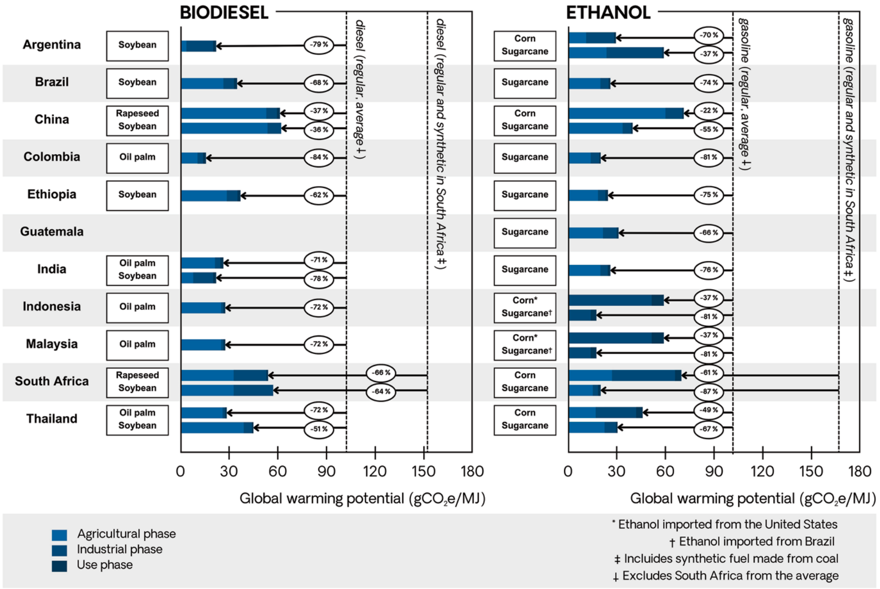

Fig. 28.4 Global warming potential of biofuels compared to fossil fuels in different countries. Source: Modified from Leal Silva et al. (2024)

This work contributes to the ongoing development of regional comparisons of the environmental profiles of gasoline-ethanol blends.

In the case of Brazil, the exploration of ethanol as a fuel began in the early twentieth century. In 1925, a Ford Model T traveled 230 km using hydrated ethyl alcohol (70% alcohol, 30% water). The motivation was primarily economic, aimed at reducing the country's dependence on imported gasoline. Over the following decades, regulations were established requiring the blending of alcohol with gasoline, such as the decrees of 1931 and 1938. However, a major turning point came in 1975 with the launch of the National Alcohol Program (Proálcool), which was developed in response to the 1973 oil crisis that severely impacted the global economy (Castro, 2017).

Proálcool was designed to create a domestic alternative to oil, relying on the sugarcane sector, which was already growing due to strong sugar exports. The program gained further traction when the first ethanol-powered vehicle was introduced by the national automotive industry in 1979. From that point on, the Brazilian government actively supported the production and consumption of ethanol as a fuel.

Ethanol offers clear advantages over fossil fuels. As a renewable biofuel, it can reduce greenhouse gas emissions by up to 90% during combustion, making it a key tool in mitigating climate change. The development of Proálcool and the broader adoption of ethanol in Brazil demonstrate how public policy can drive innovation and sustainability in the energy sector.

In 2017, Brazil introduced RenovaBio, a policy aimed at expanding biofuel use in its energy matrix. The program seeks to reduce GHG emissions, promote the decarbonization of transportation, and align with global climate commitments made at the Paris Agreement.

A study published in *Nature Communications* highlighted the positive public health effects of ethanol use by showing a correlation between fuel choice (ethanol or gasoline) and the number of nanoparticles in São Paulo's air. Researchers found a 30% increase in the concentration of particles smaller than 50 nm in diameter when gasoline, instead of ethanol, was used in flex-fuel vehicles, indicating that ethanol use reduces nanoparticle emissions (Salvo et al., 2017).

Similarly, a 2013 study by the University of São Paulo concluded that the exclusive use of pure gasoline in Brazil's eight largest metropolitan regions would result in 1384 additional deaths and over 9000 respiratory illness cases annually, adding about R$ 430 million in healthcare costs. The same study estimated that expanding hydrated ethanol use between 2015 and 2030 could prevent more than 6000 respiratory-related deaths, corresponding to a savings of $894.8 million for the healthcare system (Ferrini, 2020). Similar findings were found for São Paulo in a later report (Ministerio de Minas e Energia, 2021).

It is evident that ethanol fuel plays a crucial role in the new global energy transition scenario. Ethanol is a quick and commercially scalable solution for reducing emissions across various modes of transportation. Public policies, such as those implemented in Brazil, are necessary to ensure the replacement of fossil fuels. Biofuels can enhance energy security and mitigate climate change. However, if not properly managed, they can also lead to biodiversity loss, water resource depletion, air and water pollution, among other impacts.

28.4.3 Other Products

There are several other products that are being produced in Latin America and that have great potential for expansion. One of them is paper produced from bagasse in Argentina, Colombia, and Peru. Yeast is another one, and cane and beet molasses are the main raw materials for its production. They provide all the sugars for yeast to develop, the energy, and some of the necessary nitrogen (Lallemand, 2001). Some of the most promising by-products are mentioned next.

Bioplastics

Sucrose, bagasse, molasses, and ethanol can be used to produce bioplastics (Aguilar et al., 2019; Aguilar Rivera, 2009). According to Suarez et al. (2023), the bioplastics industry has grown exponentially in the past years, and it is expected to triple by 2026.

Different bioplastics are produced, but bio-polyethylene presents an interesting opportunity since its fossil counterpart is one of the most used materials worldwide (Suarez et al., 2023). It has the same properties as conventional polyethylene, but it is renewable and reduces the carbon footprint. Various companies are already marketing these products on a global scale, providing packaging for major brands (Belloli, 2010).

Lignocellulosic biomass is the basis for many biopolymers, which are available for various applications (de Resende & da Costa, 2020). Cellulose, hemicellulose, and lignin, including those from sugarcane bagasse, are some of the most currently used.

Biodegradable Packaging

There is a growing need for sustainable packaging materials at present due mainly to land and ocean pollution, especially by plastic materials, which take hundreds of years to decompose. Also, the extraction and manufacturing processes of common materials contribute to greenhouse gas emissions (Hussain et al., 2024).

Sugarcane has emerged as a promising raw material for the production of sustainable packaging, primarily through two by-products: sugarcane bagasse and bioplastics. Sugarcane bagasse can be transformed into biodegradable packaging through compression and molding processes. These packages are eco-friendly alternatives to traditional plastic, offering faster decomposition and a smaller environmental impact (Stroescu et al., 2024). Compostable packaging materials from sugarcane (and cornstarch) were first introduced in the 1990s (Hussain et al., 2024).

The use of sugarcane-based materials in packaging manufacturing is gaining relevance in sectors such as food, cosmetics, and cleaning products, as demand for more sustainable solutions grows. This innovation contributes to the circular economy by reducing plastic waste and the consumption of fossil fuels. Significant investments have been made in Argentina, Colombia, Mexico, and Peru to produce packaging with sugarcane as feedstock.

CO_2 for Carbonated Drinks

The raw material used is the CO_2 generated during the alcoholic fermentation process of molasses or honey derived from sugar production in distilleries annexed to sugar mills. During this process, the sugars present are converted into ethanol and carbon dioxide (CO_2) by the action of microorganisms, mainly yeasts. The "raw" CO_2, which is a mixture of gases containing CO_2, ethanol, N_2 and O_2, is captured and then purified through a series of processes to obtain only food-grade carbon dioxide, which is used to produce carbonated water and as an input for the food and chemical industries, among others, for various uses (Sianca, 2009).

Theoretically, for every 100 kg of ethanol produced, 95.6 kg of CO_2 are produced. Its production has a great environmental impact, as it eliminates the gases emitted into the environment, reducing GHGs by replacing the CO_2 obtained from fossil fuels. There is demand for this product in the world market (Sianca, 2009).

Biochar

The research conducted by DIECA in Costa Rica explores the conversion of sugarcane trash into biochar and its preliminary experimental impact on crop productivity. Biochar produced by pyrolysis of different "*bio-wastes*," including biomass from agro-industrial activity, has shown promise in improving soils' physicochemical properties, including structure, water retention, and cation exchange capacity

(Kameyama et al., 2017; MEFT/GIZ, 2020; Snohomish Conservation District, 2018). The massive use of biochar in agriculture would permit a significant reduction in the amounts of chemical fertilizers applied and favor carbon sequestration in soils contributing to Climate Change mitigation (FAO, 2019; MEFT/GIZ, 2020; Moyer et al., 2020). Initial results indicate that biochar significantly increases carbon content and organic matter in acidic soils (mainly Ultisols), improving their pH and nutrient retention capacity (Núñez-Chacón, 2023).

28.5 Future Pathway

As has been shown here, there are many ways in which sugarcane has contributed to the bioeconomy, and there has also been progress in circularity in Latin American countries, and there are abundant possibilities for the future. Nonetheless, as not all good practices are the norm, there is immense potential in their widespread adoption. In this section, lessons will be shared and ways that need to be addressed for the potential to be reached.

28.5.1 Environmental Impact and Circularity

There are four main environmental impacts that are of concern in the sugarcane growing areas, namely: water use, pre-harvest burning, agrochemical use, and deforestation. They have been a source of conflict and accusations by several stakeholders. If the sugarcane agro-industry is to be a key player in a circular bioeconomy, those concerns need to be addressed. Fortunately, there has been progress in several countries and regions around those concerns, and their lessons should be used as a basis for widespread adoption of good practices.

Investment is necessary. From research to capacity building to the purchase of equipment, funding is needed. Sugarcane growers and manufacturing companies have funded most of what has been done in Latin America, but available funding and fluctuations in the international prices of sugar and ethanol, especially, limit investment in some years (of low prices). Governments can support certain programs for small farmers and mitigate the potential impact of certain changes in processes. This was the case with the mechanization of harvesting in the state of São Paulo, Brazil, where thousands of cane cutters were going to lose their jobs.

Other elements include:

- Measuring and monitoring are key.
- There are technical limitations. For example, a mechanized harvest that is needed to avoid pre-harvest burning cannot be carried out everywhere.
- External factors need to be considered: for example, cane burning by third parties.
- Research is critical and investment from private and public sources should be provided, as well as collaboration between research centers in the continent.

- Capacity building (training) and change management are necessary.

Besides the four main environmental concerns listed above, soil degradation should also be tackled. Aspects that need to be considered are soil erosion (through rainfall), soil fertility, and physical properties. Again, there is progress in Latin America with a shift to the concept of "living soil" (*suelo vivo*) being adopted by three companies in Guatemala (Pantaleon, Magdalena, and Santa Ana). In this regard, there is also potential in looking at agricultural soils as a carbon sink, subject to carbon markets. It is necessary to continue advancing the development and application of biofertilizers, taking advantage of all available technological resources.

To address all potential environmental impacts from sugarcane and all its products and by-products, the Life Cycle Assessment (LCA) is the ideal tool to assess the sustainability of a process, product, or activity. It was used in Tucumán, Argentina, where the bioethanol environmental profile was determined by analyzing the potential environmental impacts (global warming, biodiversity loss, water scarcity, fossil resource depletion, eutrophication, among others) associated with the entire production process. This analysis accounted for resource consumption and emissions generated throughout the life cycle, from the agricultural to the industrial stage, using 1 MJ of anhydrous ethanol as the functional unit and employing the ReCiPe Midpoint impact assessment method (Garolera De Nucci, 2016; Garolera de Nucci et al., 2019).

28.5.2 Potential for New Products from Sugarcane

The experience thus far in Latin America has been that using residues and by-products from sugarcane processing can be an important part of economic sustainability. The environmental benefits were probably "lucky side effects" at the beginning, but critically important, nonetheless. The potential to use all parts of sugarcane has been pinpointed for decades, and developed countries have taken advantage of it, thus buying raw sugar and molasses, for example, as raw materials. Figure 28.2 shows the potential use of the main products and by-products of sugarcane. The use of each of the products has further options. Paturau (1982), for example, long ago indicated that through three processes (fermentation, synthesis, and degradation), sucrose itself could derive into 33 products. Not only could Latin American countries produce many of the existing products in developed countries themselves, but they could produce higher value products from the materials that are not exported (i.e., bagasse, residues in the field, molasses and vinasse). According to the experience in the region, what is needed to advance is:

- Funding, especially for initial investment.
- Large-scale production
- Human talent, including specialized labor
- Research and development

28.6 Conclusion

Sugarcane is a strategic crop for a circular bioeconomy in Latin America. The different examples and cases illustrated the diversity of uses of this plant and all its derivatives, many of them replacing what are at present fossil fuel-based materials. Because of the history of sugarcane cultivation (and nearly all crops), there are concerns about the sustainability and circularity of its production system. Progress in that regard was also shown through examples in several countries. The cases, although not explained in detail, showed that vision, investment, and capacity building from (private) producers have been key to progress. However, the role of governments through legislation, policies, and programs has been essential for the advancement of some areas, such as the use of ethanol to replace gasoline. Even though the focus of the chapter was on environmental, in many cases the main motivation for growers and companies was economic sustainability. The environmental benefits, nonetheless, were as important. This chapter did not look at the social aspects, though some could be inferred, especially through reducing environmental impacts. Possibly the main one is the improvement of water quality in some rivers by tackling pollution from mill wastewater as well as from solid cane residues.

Several elements are needed to reach the full potential of sugarcane in a circular bioeconomy. For companies to be willing to invest, they need legal certainty, long-term contracts, and incentives. Clear regulations and long-term stability are needed from governments. Research and development are also key. Lastly, the growers and companies that process sugarcane need to be aware of their surroundings, including neighboring communities, the watersheds in which they operate, and even the global stage. This sector has the potential to lead the way for other crops and to be a proactive member of Latin America for a sustainable future.

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