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Bioindicators for the Sustainability of Sugar Agro-Industry

Noé Aguilar-Rivera[1]

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Abstract The worldwide sugar industry presents a productive inertia and a fragile sustainability due to there are marginal advances in the productivity, productive diversification, and reduction of the environmental impact in cane crop fields, sugar factories, distilleries, and non-centrifuged sugar production. The complexity of sustainability evaluation in sugar industry is highlighted by the incorporation of many criteria including both quantitative and qualitative issues, measured by different units or at least the development of standards for benchmarking. The key to successful sustainability will ultimately depend on the progress in sugarcane productivity without increasing the cultivated area and decreases the environmental impacts without the lack of coordination between public policies, stakeholders, and markets which would have benefits and wellness on social, economic, and environmental aspects. The aim of this research was to carry out a review about the sustainability frameworks, indicators, constraints, and barrier to transit the sugar industry to sustainability. The results present opportunities and strengths of sugar industry related to 2030 agenda for sustainable development and circular economy as an useful guidance to formulate strategies to maximizing the potential of the sugar industry to a sustainable biofactory.

Keywords Sugar industry · Frameworks · Sustainability · Agenda 2030 · Circular economy

✉ Noé Aguilar-Rivera
naguilar@uv.mx

[1] Facultad de Ciencias Biológicas y Agropecuarias, Universidad Veracruzana, Córdoba, Veracruz, México

Introduction

Sugarcane is a crop grown in tropical and sub-tropical regions highly efficient in converting sunlight, CO_2, water, and nutrients mainly nitrogen giving the highest yields of carbohydrates per hectare into biomass and simple carbohydrates as sucrose. It is potentially and economically profitable raw material to produce food, feed, biofuel, bioproducts, and highly specialized commodities. Along with supplying over 80% of the world's sugar in more than 100 different countries around the world. Brazil is the world's largest producer of sugarcane (40% of world production). The rest of sugar producing countries are India, Thailand, China, Pakistan, and Mexico. Although it is an agribusiness with several constraints as overproduction, a crop highly sensitive to environmental changes as drought, climate change and recently the COVID-19 impact, negative image of sugar as potential risk of diseases as diabetes and obesity, the unstable and volatile sugar market as commodity, the high rate of adoption of High Fructose Corn Syrup (HFCS), and other non-caloric high intensity sweeteners (HIS) and Stevia (*stevia rebaudiana*) in the food industry, coupled with a demand for high-technology goods commercial value among others issues and low sustainability in cane and sucrose production mainly in developing countries due to environmental, political and socioeconomic factors (Voora et al. 2020; Leal and Teodoro 2020).

However, sugarcane as biofactory can make a significant contribution to help solve the great problems of sustainable development worldwide, such as poverty reduction, technological innovation, climate change, green energy, and water scarcity, among others. For this, it is necessary to move agribusiness and stakeholders toward new paradigms of the XXI century such as sustainability, economy and circular bioeconomy, new parameters of competitiveness, productive diversification, Industry 4.0, Agriculture 5.0, sucrochemical, ethanolchemical, lignochemical, in biorefineries, among others, based on the regional and national analysis of the parameters that it requires transforming within the technological, cultural, socioeconomic, political, etc., issues with adequate and reliable methodological frameworks for the systemic, holistic, and transdisciplinary evaluation of the current and potential sustainability of sugar industry.

Constraints and Barrier to Sugar Industry Sustainability

The environmental, economic, and social implications of conventional sugar industry are the first step toward a more sustainable transition to adopt a sustainable production without focusing only on the final part of the supply chain (domestic or foreign sugar consumer). The second step is the valorization of wastes and by-products, by identifying the most productive option with novel, emerging or artisanal technologies considering geographical, economic, political, and social context (evaluation of circularity). However, the sugarcane agroindustry sustainability at most countries with high and low productive is only measured with economic and technological indicators of productivity (Fig. 1).

Often, the metrics and indicators of sugar industry present contradiction in both form and content, which contributes to confusion and misunderstanding with stakeholders.

Nevertheless, the most investigated research area, at the traditional linear industrial economy in sugarcane agroindustry, is the cane agriculture, which is the focus of the agronomic research. This result underlines the fact that the combined effort of the sugar agroindustry stakeholders is devoted to deeply exploiting the environmental and engineering mechanical aspects in sugar mills, distilleries and biorefineries rather than focusing on impacts of agricultural practices considering SDG 12 (Responsible Consumption and Production) although, in addition, the aspects of health and social benefits are strongly considered in sustainability evaluations. Besides, the themes as conversion and diversification and are not fully exploited yet, and this is clear by the fact that most of the possible use of cane and by-products from a technological point of view and feasibility are still economically or politically not addressed correctly. Sugarcane agroindustry is based on pattern of growth or linear model based on the assumption that resources are abundant, available, easy to source, and cheap to dispatch but there is fear that the sugar from cane cannot be consumed endlessly then the search of concept more general 'win–win' framing of sustainability is indeed raised as successful at encouraging sustainability efforts of businesses (Fig. 2).

Many studies have demonstrated since 1970 the potential of a biorefinery model/approach for the sugar industry (mixed production of sugars, ethanol, and power cogeneration). However, few multidisciplinary approaches have focused on a regional level through the integration of production indicators, socioeconomic, and environmental factors to determine areas that have the potential to supply cane, depending on edaphoclimatic land potential and resources and capacities of sugarcane farms, without increasing the actual acreage to produce sugar, ethanol, electricity, bioproducts, and other derivatives in a biorefinery (Lora et al. 2014a; b).

Nevertheless, three products are offered by the sugar mills: sugar, alcohol (hydrated and anhydrous), and energy, the reuse of waste such as vinasse, cane trash, and filter mud are marginal. Cane trash is burned, only in some countries like Brazil cane harvest is prohibited by public policies, so the growers must rethink a more suitable destination to prevent erosion, and the rest will be incorporated into the biomass process, animal feed, or bioproducts. However, few studies have explored the adoption of the circular economy and agenda 2030 proposal of sustainability indicators in the loop sugarcane, sugar mill, non-centrifuged sugar, distillery, and bioproducts to notice the necessity of a systemic change and circularity, and the variety of these definitions reveals that the sustainability concept has different meanings for different stakeholders.

At the farm level, sugarcane farmers have faced two major issues: low sugarcane yields and low quality of sugarcane production. These issues are caused by improper production practices, such as overuse of agrochemicals and cane trash burning. Three reasons for the persistence of the burning issue were identified: (1) labor shortages; (2) hired labor choosing to burn sugarcane leaf before harvest to increase profits; and (3) the short duration of the milling season (4 months).

In relation to the above, issues such as biodiversity loss, climate change, resource depletion, water scarcity, population growth, minimization of waste, increase in economic returns, the redesign of products, the choice of materials, reduction in price volatility, and increased job growth are challenges for sugar industry as an agri-food sector (Hamam et al. 2021).

El Chami et al. (2020) and Khaire et al. (2021) reported that sustainability of the sugar industry and especially the sugarcane field, requires the participation of all the stakeholders taking a holistic approach and adopting new emerging frameworks considering topics such as: i) any country, region, or scale; ii) increase in sugarcane productivity and expansion of sugarcane production; iii)

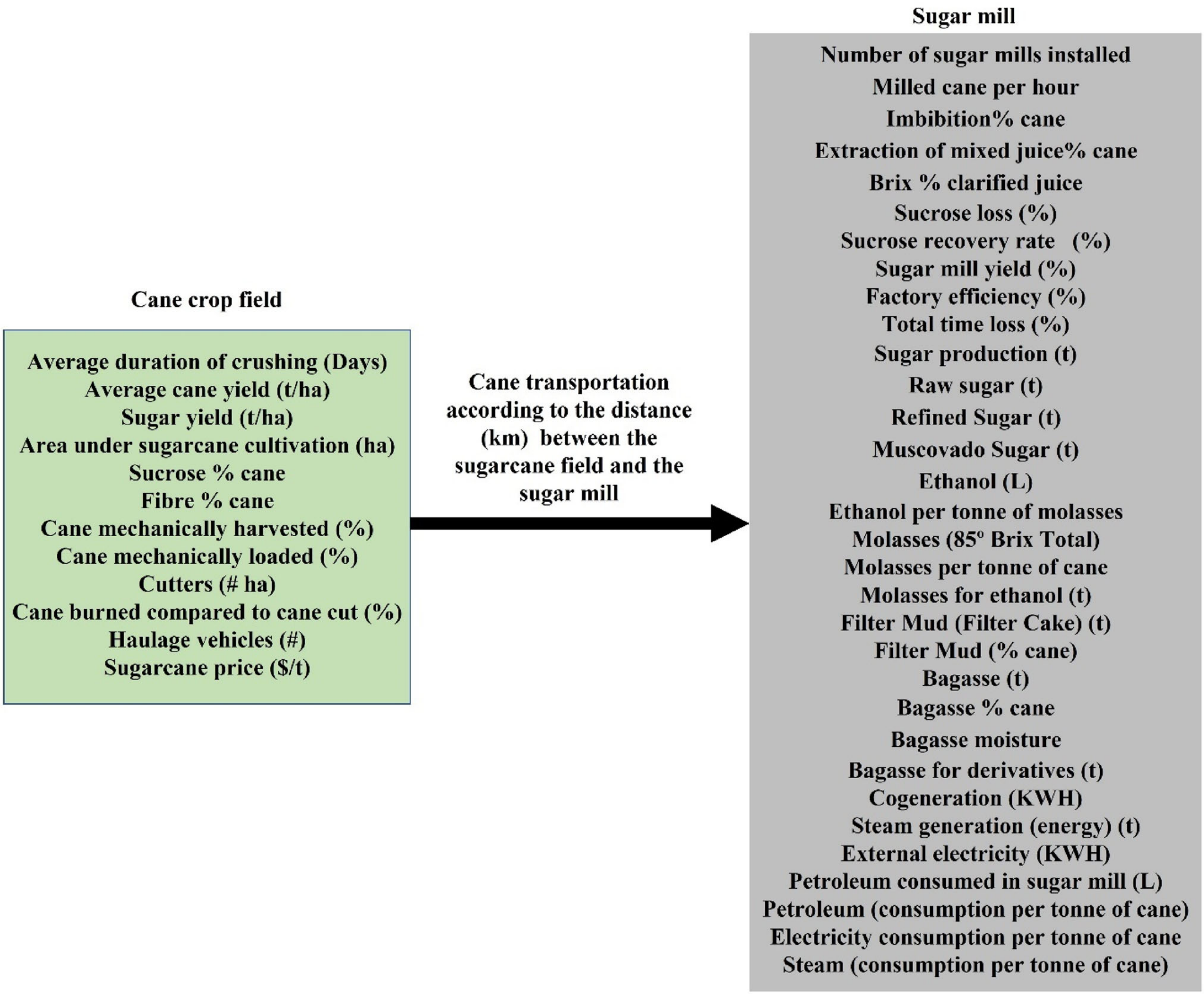
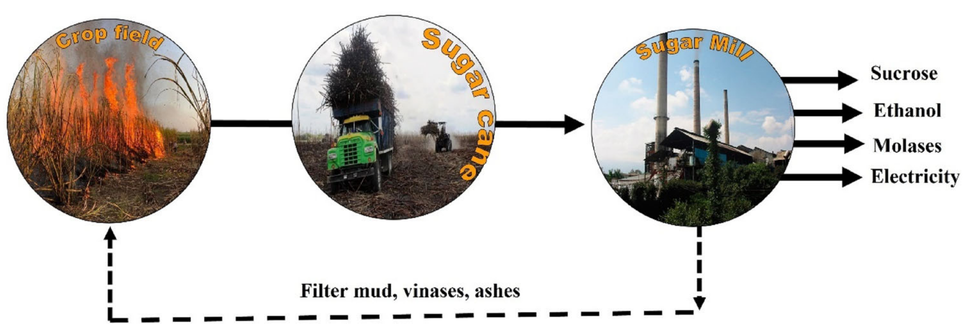


Fig. 1 Conventional indicators of sugar industry sustainability

Fig. 2 Linear production model of the sugar industry



comparing benefits and / or impacts on ecosystem outcomes; iv) methods of experiments and / or modeling and software; v) studies that consider benefits / impacts on water, land and air resources, biodiversity, wildlife, environment, food, health, income, and other social aspects—e.g., labor rights, child labor; v) health of the soil, sugar cane fields and workers, soil chemical properties, soil biological properties, soil physical properties, water resources, air quality, human well-being, impacts on health, impacts on farmers' income, labor conditions, biodiversity.

Transition of Sugar Industry to Sustainability

Palmeros-Parada et al. (2021) concluded that sustainability can be defined or evaluated through the identification of relevant issues or indicators in the socioeconomic and environmental interaction of the industry, crop fields, population, public policies, etc., to measure the level of sustainability which is based on stakeholder engagements but mainly within the application of established framework of the 2030 sustainable development agenda and its indicators, goals, and objectives.

Indicators for evaluating sustainability are selected considering the availability of data and measurement feasibility, framework, reliability and associated uncertainty, and relevance. For sugar industry, there are some sustainability certification schemes and indicator sets that have been developed by various authors (Aguilar-Rivera 2019) and companies such as Bonsucro. However, in most sugar countries they are not applied due to numerous complex factors. Therefore, to evaluate sustainability at the local context is necessary to interact indicators such as soil condition and climate, commercial acceptability, energy security, investment security, soil sustainability, climate change, efficiency, profitability, social development with an analytic framework (Fig. 3).

In relation to the Bonsucro standard known as the Bonsucro Production Standard was set up in 2008 by a group of stakeholders to support the sugarcane sector in improving its sustainability performance and to provide farm and mill operators with a reference tool that defines the sustainable conditions to produce sugarcane and sugarcane-derived products. It is a metric-based performance standard that provides operators with a set of measurable sustainability objectives with a set of real production data to measure the performance across the three pillars of sustainability: environmental responsibility, economic return (efficiency), and social wellbeing (Viart et al. 2016).

However, Thitithawonwong et al. (2019) identified that the factors that impact the adoption of the standard are.

- Gender of farmer
- Number of years in a formal education
- Experience in sugarcane production
- Number of members of household working full time on farm
- Sugarcane farm size
- Value of agricultural assets
- Farmer's perception of the indicators of the Bonsucro Standard for sugarcane production
- Percentage of sugarcane income to total household income
- Distance from farm to sugar mill

The most significant were the sugarcane farmers' gender, experience in sugarcane production; educational level; farm household labor; farmers' perception of the Bonsucro Standard; and distance from a crop field to a sugar mill.

In relation to the above, Alcázar et al. (2020) mentioned producing environmentally responsible food, feed, biofuel, and bioproducts from sugarcane is a challenge, because sustainable practices are not encouraged either due to a complex interaction between farmers, unions, owner of sugar mills, market-demanding consumers of healthier bioproducts with less chemical inputs, conserve natural resources, biodiversity, and ecosystem services and lack of support from governmental institutions, For example, the elimination of the cane burning and the alternating creation of agribusiness based on trash.

Therefore, it is pertinent to incorporate innovative methodologies that demonstrate the sustainability of farming practices with several indicators to assess:

Indicator Social

1. Satisfaction of family needs
2. Permanence of employees
3. Working conditions

Economic

4. Economic feasibilities
5. Economic risks
6. Diversification of products and services

Ecological

7. Pollution and energy consumption
8. Rational uses of natural resources
9. Adoption of agroecological techniques

Political

10. Internal accounting
11. Legal
12. Empowerment of employees
13. Technological and scientific
14. Research and education
15. Ability to change or innovation

Cultural

16. Perception of intangible benefits of employees
17. Training and generation of knowledge in employees

The review of Traldi (2021) concluded that in the evaluations of sustainability standards; the economic indicators are the most frequently evaluated, and only 20% of studies analyze economic, social, and environmental indicators simultaneously.

Therefore, there are many indicators, methodological frameworks, and theoretical positions for the evaluation of the sustainability of the sugar industry, however, the choice

Fig. 3 Opportunities for the sugar industry with the agenda 2030 of sustainable development

Fig. 3 continued

of method, indicators, and interpretation will depend on the geographic and temporal context, data quality and availability, method of aggregation, normalization, standardization, etc. (Fig. 4).

Circular Economy in the Sugar Industry

Circular economy (CE) involves goals such as narrower, slower, and closed end-of-pipe technologies, energy and material loops, through sharing, reduction, reuse, recycling and recovery in the production, distribution, and consumption processes. The transition from a linear economy to a CE requires effort to manage complex changes, as well as improvements in unsustainable process technologies, non-renewable resources, costs, products, and reliable strategies based on sustainability indicators. Therefore, it is an area of great opportunity for the transition to sustainability of the conventional sugar industry. (Geissdoerfer et al. 2017).

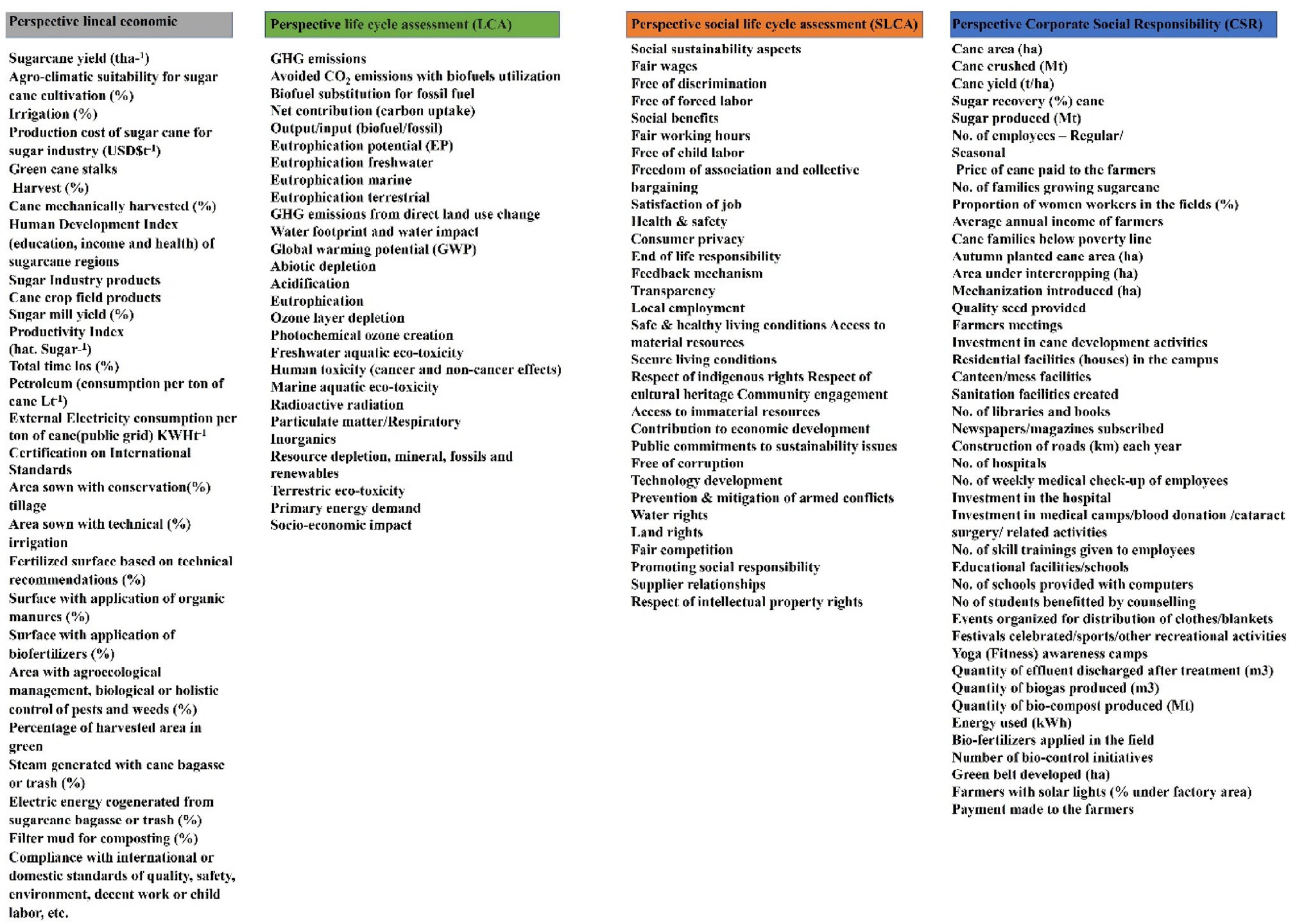
The review of Navare et al. (2021) provides an initial understanding of the opportunities provided by the circular economy (CE) as a solution to the current need to reduce the environmental impacts of the conventional sugar industry and their relation to sustainability.

The use of biotic resources as sugarcane is not necessarily circular and sustainable. Therefore, a critical evaluation of the biological cycles is essential in the context of CE, which is currently lacking. Therefore, the circularity of biological cycles and their subsequent processing should be analyzed to avoid overexploitation of natural resources and further degradation of ecosystems. Therefore, according Navare et al. (2021) thorough CE monitoring of the biological cycles should assess (1) sustainable sourcing (2) cascading use of materials (3) the extent to which nutrients effectively re-enter the biological cycles and (4) the environmental impact of sourcing biotic resources and carbon fluxes using economic and environmental indicators, to identify the key elements to optimize their economic performance and a lower environmental impact.

Kirchherr et al. (2017) proposed a connection of CE with the sustainable development: "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies,consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by.

novel business models and responsible consumers".

Chiaraluce et al. (2021) concluded the circular economy is a concept that represents a novel economic model, where



Perspective lineal economic

Sugarcane yield (tha-^{1})
Agro-climatic suitability for sugar cane cultivation (%)
Irrigation (%)
Production cost of sugar cane for sugar industry (USD$t^{-1})
Green cane stalks Harvest (%)
Cane mechanically harvested (%)
Human Development Index (education, income and health) of sugarcane regions
Sugar Industry products
Cane crop field products
Sugar mill yield (%)
Productivity Index (hat. Sugar-^{1})
Total time los (%)
Petroleum (consumption per ton of cane Lt^{-1})
External Electricity consumption per ton of cane(public grid) KWHt^{-1}
Certification on International Standards
Area sown with conservation(%) tillage
Area sown with technical (%) irrigation
Fertilized surface based on technical recommendations (%)
Surface with application of organic manures (%)
Surface with application of biofertilizers (%)
Area with agroecological management, biological or holistic control of pests and weeds (%)
Percentage of harvested area in green
Steam generated with cane bagasse or trash (%)
Electric energy cogenerated from sugarcane bagasse or trash (%)
Filter mud for composting (%)
Compliance with international or domestic standards of quality, safety, environment, decent work or child labor, etc.

Perspective life cycle assessment (LCA)

GHG emissions
Avoided CO_2 emissions with biofuels utilization
Biofuel substitution for fossil fuel
Net contribution (carbon uptake)
Output/input (biofuel/fossil)
Eutrophication potential (EP)
Eutrophication freshwater
Eutrophication marine
Eutrophication terrestrial
GHG emissions from direct land use change
Water footprint and water impact
Global warming potential (GWP)
Abiotic depletion
Acidification
Eutrophication
Ozone layer depletion
Photochemical ozone creation
Freshwater aquatic eco-toxicity
Human toxicity (cancer and non-cancer effects)
Marine aquatic eco-toxicity
Radioactive radiation
Particulate matter/Respiratory
Inorganics
Resource depletion, mineral, fossils and renewables
Terrestric eco-toxicity
Primary energy demand
Socio-economic impact

Perspective social life cycle assessment (SLCA)

Social sustainability aspects
Fair wages
Free of discrimination
Free of forced labor
Social benefits
Fair working hours
Free of child labor
Freedom of association and collective bargaining
Satisfaction of job
Health & safety
Consumer privacy
End of life responsibility
Feedback mechanism
Transparency
Local employment
Safe & healthy living conditions Access to material resources
Secure living conditions
Respect of indigenous rights Respect of cultural heritage Community engagement
Access to immaterial resources
Contribution to economic development
Public commitments to sustainability issues
Free of corruption
Technology development
Prevention & mitigation of armed conflicts
Water rights
Land rights
Fair competition
Promoting social responsibility
Supplier relationships
Respect of intellectual property rights

Perspective Corporate Social Responsibility (CSR)

Cane area (ha)
Cane crushed (Mt)
Cane yield (t/ha)
Sugar recovery (%) cane
Sugar produced (Mt)
No. of employees – Regular/ Seasonal
Price of cane paid to the farmers
No. of families growing sugarcane
Proportion of women workers in the fields (%)
Average annual income of farmers
Cane families below poverty line
Autumn planted cane area (ha)
Area under intercropping (ha)
Mechanization introduced (ha)
Quality seed provided
Farmers meetings
Investment in cane development activities
Residential facilities (houses) in the campus
Canteen/mess facilities
Sanitation facilities created
No. of libraries and books
Newspapers/magazines subscribed
Construction of roads (km) each year
No. of hospitals
No. of weekly medical check-up of employees
Investment in the hospital
Investment in medical camps/blood donation /cataract surgery/ related activities
No. of skill trainings given to employees
Educational facilities/schools
No. of schools provided with computers
No of students benefitted by counselling
Events organized for distribution of clothes/blankets
Festivals celebrated/sports/other recreational activities
Yoga (Fitness) awareness camps
Quantity of effluent discharged after treatment (m3)
Quantity of biogas produced (m3)
Quantity of bio-compost produced (Mt)
Energy used (kWh)
Bio-fertilizers applied in the field
Number of bio-control initiatives
Green belt developed (ha)
Farmers with solar lights (% under factory area)
Payment made to the farmers

Fig. 4 Indicators of the sustainability of the sugar industry according to various methodological frameworks (Data from Prasara et al. 2019; Solomon et al. 2019; Silalertruksa et al. 2017; Gheewala et al. 2016) the old linear "make-use-dispose" wants to be replaced initially by a circular approach based on the "3R" principles "reduction-reuse-recycling".

CE requires the satisfaction of some principles: (1) preserve natural capital and renewable resources, (2) enhance resource yields by recycling materials, and ensuring that energy is produced from renewables and (3) make sure that all resources are utilized to generate value reducing negative externalities. Therefore, the 3Rs "Reduce, Reuse, and Recycle" are the core principles (Pourahmadi et al. 2016).

Borrello et al. (2020) commented that circular economy (CE) has emerged as a paradigm, highlighting multiple paths and targets to attain sustainable development, and to propose ways to create value for costumers, societies, and other stakeholders. However, CE has a direct relationship by including concepts and principles from interdisciplinary form such as cradle-to-cradle, industrial ecology, cleaner production, biomimicry, laws of ecology, performance economy, blue economy, regenerative design, permaculture, the natural step, natural capitalism, industrial metabolism, symbiosis, biorefineries and eco parks, socio-technical change; sustainability transition; multilevel perspective; recycling; upcycling; downcycling; servitization; circular business model among many others.

Reike et al. (2018) defined CE as an economic system that takes the reusability of products and materials and the conservation of natural resources as starting point. It also strives for value creation for people, nature, and the economy in each part of the system that is, a need for balance among the three dimensions.

Padilla-Rivera et al. (2020) mentioned that social aspects are relevant in CE since they can give an overview on how strategies and actions impact or benefit society; moreover, social aspects can bring a better understanding of circular economy with the evaluation of indicators. For example, the most cited socio-economic indicators related to CE are employment, health and safety, and participation; however, there are some thematic areas and aspects for social dimension within CE: 1. employment, 2. labor/management relations, 3. occupational health and safety, 4. training and education, 5. diversity and equal opportunity, 6. fair distribution of income, 7. quality and well-being, 8. investment, 9. non-discrimination, 10. freedom of association and collection bargaining, 11. child labor, 12. forced or compulsory labor, 13. security practices, 14. human rights mechanisms, 15. social inclusion (equity), 16. social networks, 17. social cohesion, 18. participation and local democracy, 19. anti-corruption, 20. public policy, 21. compliance, 22. supplier assessment for impacts on society, 23. cultural traditions, 24. tourism and recreation, 25. local communities (sense of community and belonging), 26. customer health and safety, 27. product and service labelling, 28. marketing communications, 29. costumer privacy, 30. compliance, 31. anti-competitive behavior, etc. The Social Life Cycle Assessment (SLCA) can be used as tool to evaluate and integrate these and other indicators to include social aspects within a life cycle perspective, to complement environmental and economic dimension of CE. These social issues are inherently linked with circular economy and must be included for the evaluation of sustainability indicators.

Corona et al. (2019) argued that different strategies have been proposed to move from a linear economy to a CE: sustainable and eco-design, energy and material efficiency measures, strategies defined within the three-R's waste hierarchy reduce-reuse-recycle. The impacts or benefits generated by these circular strategies are often measured using circularity metrics.

These approaches at the conventional sugar industry frequently overlook the characteristics of the circular loops and the multi-dimensional sustainability:

1. Reducing input of resources, especially scarce ones (agrochemicals, water for irrigation, fossil fuels, chemical specialties)
2. Reducing emission levels (pollutants and GHG emissions from excess of nitrogen fertilizers, manure or filter mud without compost, use of heavy fuel oil for steam generation in sugar factory)
3. Reducing material losses/waste (steam and water leakage and sucrose losses)
4. Increasing input of renewable and recycled resources (trash in boiler, recovery of water from the cane itself)
5. Maximizing the utility and durability of products (interleaved crops, rotating, green fertilizers, maintenance strategies, equipment renovation and process control)
6. Creating local jobs at all skill level (mainly when replacing manual cut by mechanized harvest)
7. Value added creation and distribution (organic cane production, organic sugar and various qualities and presentations on the market, organic spirits)
8. Increase social wellbeing (improve the corporate social responsibility (CSR) of sugar industry)

However, the major challenges of current circularity metrics relate to (1) difficulties in measuring the CE goals in all the sustainability dimensions, (2) evaluating the scarcity of used materials, and (3) underrepresenting the complexities of multiple cycles (multifunctionality) and the consequences of material downcycling.

CE as a sustainability framework is based at the triple-P (People, Planet, Prosperity) as an analytical basis to analyze existing 10-R imperative exchanges beyond resource supply and waste generation, to evaluate the social and environmental processes:

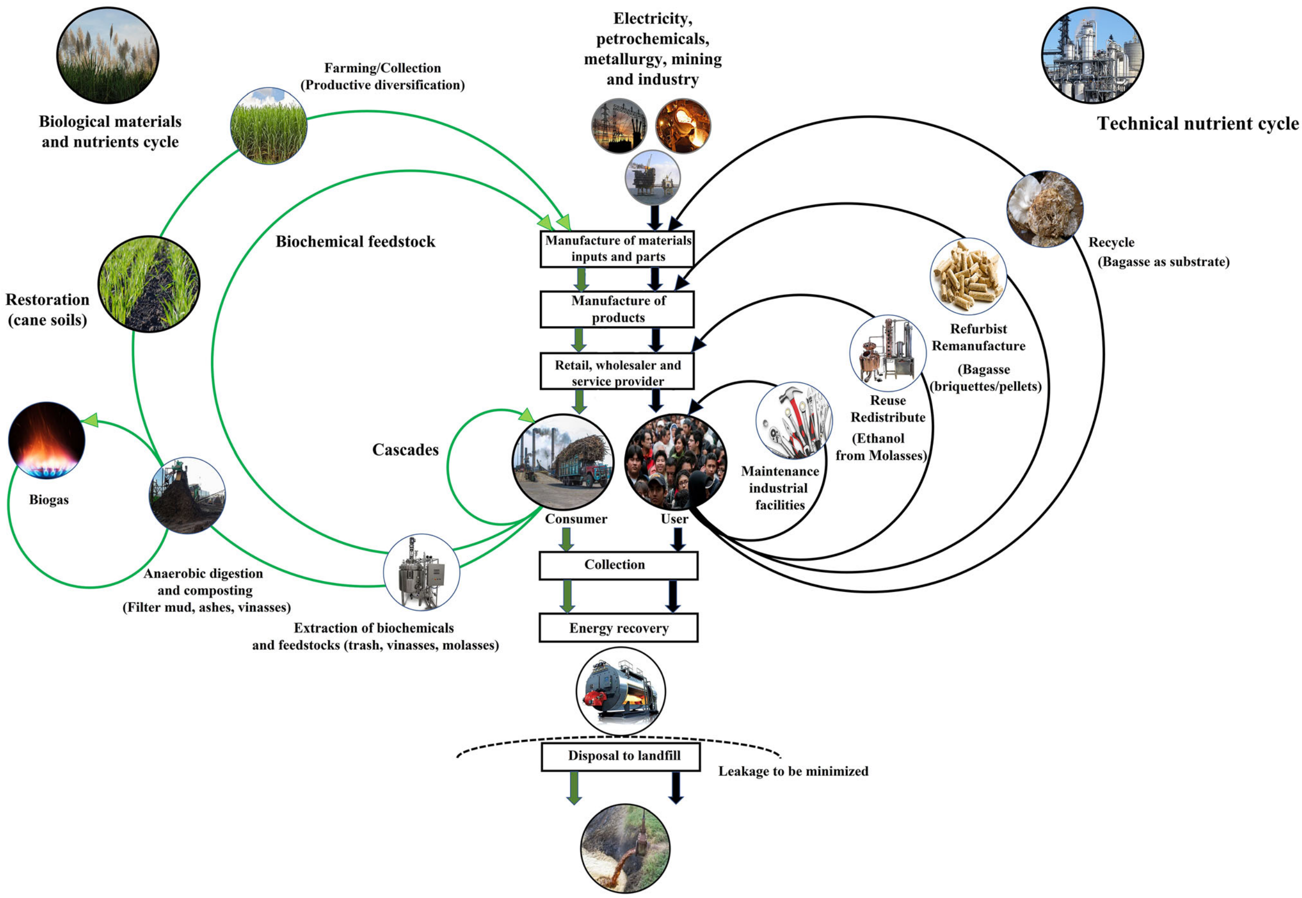


Fig. 5 Closed loop and circular economy model for sugarcane agro industry sustainability

1. R0 Refuse (diversify sucrose in quality and presentations to the market as granular, solid and liquid)
2. R1 Reduce (increase the use of regional byproducts for fertilization and recovery of cane soil)
3. R2 Resell, Reuse (increase the use of filter mud, vinasse and molasses within sugar mill)
4. R3 Repair (Avoid by correct repair and maintenance steam leakage, water, sucrose loss and optimization of inputs)
5. R4 Refurbish Referring (increase the production of non-centrifugated sugar with new options such as the organic granulate and combine its production with ecotourism and bioproducts as spirits, syrup, handmade paper from sugarcane, etc.)
6. R5 Remanufacture (combined trash and filter mud composting for soil recovery and reduce chemical fertilizers)
7. R6 Re-purpose (use sucrose not sold to markets in the production of liquid sugar or sucrochemistry)
8. R7 Recycling (employ bagasse to produce briquettes and pellets with energetic purposes facilitating storage and transportation)
9. R8 Recovery (use of trash in livestock feed, energy production or composting to recover nutrients, fiber, and chemical components)
10. R9 Rethink (use of cane stalks, trash, sucrose, bagasse, filter mud, molasses, vinasse, ashes, etc., in biorefineries for food, feed, biofuels, biochemical, biomaterial, pharmaceutics, bioplastic, etc., incorporating new approaches and emerging technologies within Industry 4.0 and Agriculture 5.0)

R-imperatives are applied to different stakeholders in the lifecycle. For example, concerning the sugar industry, sugarcane products and use, with R0 → 6 relating to the product (sugar, ethanol, electricity, non-centrifuged sugar) and R7 → 8 relating to the materials (cane, wastes and byproducts as molasses, vinasses, filter mud, trash, bagasse) (Refuse (R0), Reduce (R1), Resell (R2), Repair (R3), and Recycling (R7) are applicable for consumers (sugar intake, per capita sugar consumption, food and beverage, chemical, biotechnology, pharmaceutical industries). While Resell (R2), Repair (R3), Refurbish (R4), Remanufacture (R5), Recycling (R7), Recover (R8), and Re-mine (R9) for producers and growers, businesses and retailers and R-imperatives $0 \rightarrow 7$ are applicable within this original ‘closed-loop’ value chain of several products of cane and sucrose and byproducts (compost, livestock, energy, biofuels diversification in sugar mills and biorefineries) (Reike et al. 2018; Campbell-Johnston et al. 2020) (Fig. 5).

Many actions derived from the application of sustainability frameworks can be taken to improve sustainability according to the main conclusions of García-Bustamante et al. (2018) for sugar industry are to increase product diversification in crops fields, processing, and markets, improve access to credit, increase irrigation efficiency, improve raw material quality, reduce production costs, eliminate fossil fuel use, make fertilizer, and manure application more efficient and reduce the burning harvest. Future work must focus on developing more and better indicators, particularly for the social dimension, as well as building new models for indicator integration and weighting as the use of reliable and robust sustainability approaches as Life cycle assessment (LCA), Life Cycle Sustainability Assessment (LCSA), Social Life Cycle Assessment (SLCA), circular economy, and the Sustainability Development Goals (SDG) among others.

Regarding the barriers derived from public policies for the transition to a circular economy, the worldwide sugar industry is distributed mainly in developing countries where key aspects for sustainability are the lack of trained human capital in the development and application of specific technologies for each cane region, for example precision agriculture, the lack of sufficient economic and financial resources for investment in infrastructure, basic services and research, the deficiency of political agreements between stakeholders and decision-makers, owners of cane fields, sugar mills, distilleries, unions, researchers to address issues such as education, research and training, land tenure, development of varieties, sustainable crop management, biofuel ethanol in transport, decent work, environmental impacts, productive diversification among many others to establish a competitive environment (Jesus et al. 2021; Leal and Teodoro 2020).

Conclusions

The analysis of sustainability of sugar industry is highly related paradigms, such as competitiveness, productivity, profitability, productive diversification, and its relationship nature-society. The current sugar industry and related agribusiness, urgently requires methodological framework to evaluate sustainability indicators because the actual approaches are based on evaluations of linear economy models and productive indicators of stakeholders without considering social and environmental impacts. In this review, it was shown that methodological frameworks such as the 2030 agenda for sustainable development, circular economy and others represent an opportunity to evaluate sustainability with the integration of indicators and allow the sugar industry to become a cluster of sustainable regional development.

References

Aguilar-Rivera, N. 2019. A framework for the analysis of socioeconomic and geographic sugarcane agro industry sustainability. *Socio-Economic Planning Sciences* 66: 149–160.

Alcázar, P., I. Espejel, M. Reyes-Orta, and M.C. Arredondo-García. 2020. Retrospective assessment as a tool for the management of sustainability in diversified farms. *Agroecology and Sustainable Food Systems* 44 (1): 30–53.

Borrello, M., S. Pascucci, and L. Cembalo. 2020. Three propositions to unify circular economy research: A review. *Sustainability* 12 (10): 4069.

Campbell-Johnston, K., W.J. Vermeulen, D. Reike, and S. Brullot. 2020. The circular economy and cascading: Towards a framework. *Resources, Conservation & Recycling: X* 7: 100038.

Chiaraluce, G., D. Bentivoglio, and A. Finco. 2021. Circular economy for a sustainable agri-food supply chain: A review for current trends and future pathways. *Sustainability* 13 (16): 9294.

Corona, B., L. Shen, D. Reike, J.R. Carreón, and E. Worrell. 2019. Towards sustainable development through the circular economy: A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling* 151: 104498.

El Chami, D., A. Daccache, and M. El Moujabber. 2020. What are the impacts of sugarcane production on ecosystem services and human well-being? A review. *Annals of Agricultural Sciences* 65 (2): 188–199.

García-Bustamante, C.A., N. Aguilar-Rivera, M. Zepeda-Pirrón, and C. Armendáriz-Arnez. 2018. Development of indicators for the sustainability of the sugar industry. *Environmental & Socio-Economic Studies* 6 (4): 22–38.

Geissdoerfer, M., P. Savaget, N.M.P. Bocken, and E.J. Hultink. 2017. The circular economy—A new sustainability paradigm? *Journal of Cleaner Production* 143: 757–768.

Gheewala, S.H., T. Silalertruksa, P. Pongpat, A.J. Prasara, T. Prapaspongsa, and Jakrawatana N. 2016. Sustainability assessment of sugarcane biorefineries to enhance the competitiveness of the Thai sugar industry. In *Proceedings of the International Society of Sugar Cane Technologists* 29: 791–798.

Hamam, M., G. Chinnici, G. Di Vita, G. Pappalardo, B. Pecorino, G. Maesano, and M. D’Amico. 2021. Circular economy models in agro-food systems: A review. *Sustainability* 13 (6): 3453.

Jesus, G.M.K., D. Jugend, L.A.B. Paes, R.M. Siqueira, and M.A. Leandrin. 2021. Barriers to the adoption of the circular economy in the Brazilian sugarcane ethanol sector. *Clean Technologies and Environmental Policy*. https://doi.org/10.1007/s10098-021-02129-5.

Khaire, K.C., V.S. Moholkar, and A. Goyal. 2021. Bioconversion of sugarcane tops to bioethanol and other value-added products: An overview. *Materials Science for Energy Technologies* 4: 54–68.

Kirchherr, J., D. Reike, and M. Hekkert. 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* 127: 221–232.

Leal, M.R.L.V., and J.C. Teodoro. 2020. A global view of bioproducts: The sugarcane perspective. *Sugar Journal* 82 (12): 16–20.

Lora, E.E.S., M.H. Rocha, J.C.P. Escobar, O.J. Venturini, M.L.G. Renó, and O.O. Almazán. 2014a. The sugar and alcohol industry in the biofuels and cogeneration era: A paradigm change (part I). *Zuckerind (sugar Ind)* 139 (1): 28–36.

Lora, E.E.S., M.H. Rocha, J.C.P. Escobar, O.J. Venturini, M.L.G. Renó, and O.O. Almazán. 2014b. The sugar and alcohol industry in the biofuels and cogeneration era: A paradigm change (part II). *Zuckerind (sugar Ind)* 139 (2): 97–104.

Navare, K., B. Muys, K.C. Vrancken, and K. Van Acker. 2021. Circular economy monitoring—How to make it apt for biological cycles? Resources. *Conservation and Recycling* 170: 105563.

Padilla-Rivera, A., S. Russo-Garrido, and N. Merveille. 2020. Addressing the social aspects of a circular economy: A systematic literature review. *Sustainability* 12 (19): 7912.

Palmeros-Parada, M., W. van der Putten, L.A. van der Wielen, P. Osseweijer, M. van Loosdrecht, F. Pashaei Kamali, and J.A. Posada. 2021. OSiD: Opening the conceptual design of biobased processes to a context-sensitive sustainability analysis. *Biofuels, Bioproducts and Biorefining* 15: 961–972.

Pourahmadi, A., T. Ebadi, and M. Nikazar. 2016. Development a conceptual framework for industrial and hazardous wastes rating systems. *Civil Engineering Journal* 2 (4): 140–149.

Prasara, A.J., S.H. Gheewala, T. Silalertruksa, P. Pongpat, and W. Sawaengsak. 2019. Environmental and social life cycle assessment to enhance sustainability of sugarcane-based products in Thailand. *Clean Technologies and Environmental Policy* 21 (7): 1447–1458.

Reike, D., W.J.V. Vermeulen, and S. Witjes. 2018. The circular economy: New or refurbished as CE 3.0?—Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling* 135: 246–264.

Silalertruksa, T., P. Pongpat, and S.H. Gheewala. 2017. Life cycle assessment for enhancing environmental sustainability of sugarcane biorefinery in Thailand. *Journal of Cleaner Production* 140: 906–913.

Solomon, S., G.P. Rao, M. Swapna, A. Kumar, and R.C. Singhal. 2019. Corporate social responsibility initiatives and their impact on sugar-mill performance: A case study of the Seksaria Biswan Sugar Factory, India. *Proceedings of the International Society of Sugar Cane Technologists* 30: 377–383.

Thitithawonwong, A., T. Athipanyakul, and C. Potchanasin. 2019. Factors affecting the adoption of the Bonsucro Standard amongst Thai sugarcane farmers. In *Proceedings of the International Society of Sugar Cane Technologists* 30: 806–815.

Traldi, R. 2021. Progress and pitfalls: A systematic review of the evidence for agricultural sustainability standards. *Ecological Indicators* 125: 107490.

Viart, N., R. Seixas, and S. Slavinski. 2016. Evaluation of the Bonsucro calculator as a sustainability performance benchmarking tool in the sugarcane sector. In *Proceedings of the International Society of Sugar Cane Technologists* 29: 371–378.

Voora, V., S. Bermúdez, and C. Larrea. 2020. *Global Market Report: Sugar*. International Institute for Sustainable Development. Accessed 26 November 2021. https://www.jstor.org/stable/pdf/resrep22026.pdf.