Bioresource Technology Reports 26 (2024) 101858

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Unlocking sustainable solutions: Harnessing residual biomass from Colombia's non-centrifugal sugar chain for green market deployment

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ARTICLE INFO

Keywords:
Aspen Plus
Carbon footprint
Life Cycle Assessment
Jaggery
Panela

ABSTRACT

Green markets offer an alternative to bolster the economic and social dimensions of rural areas by valorizing surplus agroindustrial waste. This study aims to assess the environmental impacts of Panela, an agroindustrial crop with high relevance for the economies of Latin American and Asian countries. The Life Cycle Assessment (LCA) methodology revealed that producing 1 t of Non-centrifugal sugar results in a global warming potential of 0.262 t of CO_2-eq. Additionally, the acidification potential, freshwater eutrophication, particulate matter, and photochemical oxidant formation were found to be 0.135 kg SO_2-eq., 0.0081 kg P-eq. 0.020 kg $PM_{2.5}$-eq., and 0.043 kg NOx-eq., respectively. A nutrient balance and bagasse combustion analysis were conducted, indicating that environmental impacts were reduced by 45 %. As a result of these impact abatements, the surplus residual biomass could potentially cover 1 % of the national urea demand in a decentralized scheme, thereby reducing dependency on imports from other countries.

1. Introduction

As a result of the climate crisis that is currently faced worldwide, consumers have changed their consumption trends towards eco-branding products that are supported by a marketing approach and whose campaigns are focused on labels like “environmentally friendly”, “eco-friendly”, “low-energy consumption”, “zero emissions”, and more (Ali et al., 2023; Testa et al., 2021). It is well known that consumers pay significant prices for organic foods, “green electricity”, and other attributes that are aligned with sustainable policies such as recycling, non-toxic, biodegradable, and cruelty-free, among others (Hamilton and Zilberman, 2006). This tendency is associated with the development of green markets which seek closed-loop consumption cycles to produce valuable goods that bring benefits to the environment like reducing greenhouse gas (GHG) emissions but with higher costs (Dangelico and Vocalelli, 2017; Koul et al., 2022). The development of these green markets is aligned with the Sustainable Development Goals (SDG) established by the United Nations. Indeed, the 12th goal looks to ensure sustainable consumption and production patterns. Currently, about 485 policies have been introduced in >60 countries to warrant sustainable consumption. Under the scheme for developing green markets, green businesses, or green entrepreneurship, the quantification of the environmental footprint is important to strengthen the information about the eco-labels and certification of products to guarantee transparency for the final user. This environmental footprint is performed through the Life Cycle Assessment (LCA) methodology which is widely accepted for quantifying the environmental performance of a process and products from a holistic point of view. LCA has been widely employed for different marketable products such as proteins, dairy products, wine, fruits, electricity, and even hydrogen. For instance, Khoshnevisan et al. (2023). Carried out the environmental footprint of organic products in Denmark pointing out that calculating the environmental impact of a product is key to strengthening the European Union Green Markets. Besides, within the deployment of hydrogen technology, the development of certification schemes has been widely implemented to warrant trade among countries by establishing a suitable carbon footprint

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https://doi.org/10.1016/j.biteb.2024.101858
Received 8 February 2024; Received in revised form 18 April 2024; Accepted 6 May 2024
Available online 13 May 2024

threshold. These certification schemes have been developed for the European Union, China, and even Colombia (Liu et al., 2022; J. Moreno et al., 2022; Velazquez Abad and Dodds, 2020). Moreover, Karlsson Potter and Röös (2021) developed strategies to ensure that products in the consumer's diet are environmentally friendly. Furthermore, Peano et al. (2015) applied LCA for strawberries and berry fruits eco-branding in northern Italy, highlighting that eco-labels will boost the development of friendly agricultural systems by offsetting CO_2 emissions. It is undoubtedly that LCA is considered the standardized, structured, comprehensive tool employed for promoting green solutions towards sustainability. Hence, within the concept of green markets, LCA must be carried out as a tool to quantify the environmental impact of a product.

In Colombia, the Ministry of Environment and Sustainable Development started the strategic plan for green markets in 2003, and in 2015, the Ministry launched the National Plan of Green Business which is still being implemented. According to the Ministry, the number of green businesses in Colombia rose from 72 in 2014 to 4000 in 2022. According to the National Plan of Green Business, the green business is classified into three categories named as carbon markets, sustainable goods and services coming from natural resources, and industrial eco-products. The latter refers to those goods that are less pollutant than other products within the sector or that generate an environmental benefit. Among the Colombian sectors, the agricultural showed the highest participation in the creation of green business (30.1 %), followed by the agro-industrial sector (21.4 %), and to a low extent the waste management and valorization sector (13.4 %). Despite the low participation of the latter sector, Colombia has great potential to increase its participation since annually 71 billion agro-industrial residues are produced from 200 crops (Cuadrado-osorio et al., 2022). This residual biomass is mainly derived from crops including coffee, cacao, banana, and non-centrifugal sugar. The latter also known as *Panela* is a sweetener that contributes greatly to the economic income (Jaffe, 2015). Colombia currently produces 1.5 Mt. of non-centrifugal sugar, making it the country with the second largest production, surpassed only by India. However, Colombia is the largest consumer and Non-centrifugal sugar is a part of the diet of all Colombians (Jader et al., 2018). Therefore, this product plays an important role in economic and social development, contributing significantly to the Gross Domestic Product (GDP) and generating about 290,000 jobs which are concentrated merely in 326 municipalities in the Andean region (Gutiérrez-Mosquera et al., 2018). Currently, the production of non-centrifugal sugar is still carried out through kraft processes that lead to various environmental problems such as water, soil, and air pollution, mainly related to the lack of mechanization and low technological adoption (Ramírez Gil, 2016). Several studies have determined the carbon footprint of producing *Non-centrifugal sugar*. For instance, Castañeda-Suárez et al. (2017) calculated a carbon footprint of 0.31 kg CO_2-eq to produce 1 kg of non-centrifugal sugar, and said impact could be reduced if diesel engines are replaced by electric engines. This strategy reduces the carbon footprint to 0.30 kg CO_2-eq. Similarly, Sierra et al. (2022) assessed the LCA to produce non-centrifugal sugar in *La Hoya del Rio Suarez*, the main production site in Colombia. They pointed out that incomplete burnings are responsible for the emissions of harmful gases in the facility. Besides, they agree that switching from diesel engines to electric motors will reduce environmental impact. Tyagi et al. (2022a) conclude that inadequate combustion of fuels produces hazardous compounds such as CO and particulate matter, which can be mitigated by some technical modifications to furnaces. About 97 % of CO and particulate matter emissions and 66 % of CO_2 emissions could be reduced if the furnace is retrofitted (Tyagi et al., 2022b). Since non-centrifugal sugar is commonly produced in areas that are not connected to the power grid, fossil diesel is often used to generate electricity. Based on previous studies, the environmental impact of *Non-centrifugal sugar* production is quietly associated with bagasse combustion and the use of fossil fuels in the engine. Improvements on the furnace, will reduce carbon footprint and increase the bagasse savings. The surplus of bagasse along with other residual biomass such as residual crops (RAC) and sugarcane press-mud could be a key point for the development of new products within the non-centrifugal sugar chain supply.

Traditionally, RAC is defined as the residual crops left after the sugarcane harvesting. This residual biomass is employed for different purposes including animal feeding and fertilizing. However, in some facilities, RAC is disposed of on the land acting as nutrients for the plant, but causing some environmental issues mainly associated with aerobic decomposition and nutrient leaching. Otherwise, sugarcane press-mud is the residual waste obtained after the first clarification of the sugarcane juice. Sugarcane press-mud is widely used for animal feeding and fertilizing, but in the last decades, said residue has been employed for producing biogas, bioethanol, and even H_2 (Sanchez et al., 2020). Since *Non-centrifugal sugar* production is a kraft process and is eco-labeled as an organic product, the use of chemical fertilizers and pesticides is forbidden. Instead of using chemical fertilizers, they take advantage of the RAC and sugarcane press-mud to produce compost that could be applied to the soil. However, it is needed to determine the amount of RAC and sugarcane press-mud that is required to cover the nutrient demand for the sugarcane. The nutrient surplus has negative effects on the environment such as increasing nitrate levels in groundwater, increasing the phosphorous content, and consequently increasing the eutrophication risk (Svanbäck et al., 2019). The proper management of nutrients in the soil is key to guaranteeing soil sustainability. For instance, Velthof et al. (2020) addressed a review on the policies implemented in the Netherlands for silage maize in terms of nutrients. They pointed out that the restriction on the use of fertilizers by reducing the nitrogen and phosphorous surplus has decreased the emission of NO_3, NH_3, NO, and N_2O by at least 40 %. Besides, Ren et al., 2023 evaluated the high nutrient surplus in apple orchards concluding that the high nitrogen surplus caused nitrate accumulation and acidification. Moreover, overfertilization will raise the production cost of the agricultural products. The proper fertilization and use of residual biomass for said purpose is necessary to reduce the environmental impact and to increase the *Non-centrifugal sugar* yield (Volverás-Mambuscay et al., 2020). Up to date, nutrient requirements for non-centrifugal sugarcane have been established. For instance, the nitrogen demand is 161 kg/Ha, while the phosphorous and potassium demand is 56 and 195 kg/ha, respectively. In addition, the magnesium requirement is 204 kg/ha, whereas the calcium demand is 63 kg/ha. Other micronutrients such as manganese, sulfur, boron, copper, zinc, and iron are $<$41 kg/ha (Rodríguez Borray et al., 2020). However, an environmental assessment of traditional practices in terms of disposal of residual biomass as fertilization practices has not been explored in the literature. Therefore, this study endeavors to assess the environmental footprint of non-centrifugal sugar through Life Cycle Assessment (LCA) methodology, employing simulation tools and data collected directly from farmers. As a result of the LCA, different strategies were set to reduce the environmental impact and dwindle the use of residual biomass within the process to propose alternatives of biomass valorization and create opportunities for the deployment of green business in the *Non-centrifugal sugar* supply chain. Therefore, the research question is: how much residual biomass could be used to deploy a new green business within the non-centrifugal sugar sector?. To answer said question, we first carried out the mass and energy balance of the small facility by using Aspen Plus. This tool has been widely used to calculate the mass and energy balances for industrial processes. Afterward, the environmental impact of producing *Non-centrifugal sugar* was addressed. Then, based on the environmental results, strategies to reduce the environmental impact were carried out. Said strategies were mainly focused on the proper use of residual biomass for fertilizing and the avoiding use of fossil fuels. Lastly, we forecast the production of urea as a potential green product within the industry. Urea was selected since it could be used within the sector as fertilizer under a circular economy model. Besides, urea is considered one of the primary sources of nitrogen source for different crops (Milani et al., 2022). According to the Agricultural Colombian

Institute (ICA), Colombia produced in 2022 about 1.44 Mt., imported 1.38 Mt., and exported 0.13 Mt. of fertilizers. However, all the urea demanded by Colombia, whose actual demand is 400 kt/year, is imported from Russia, Venezuela, Trinidad and Tobago, and Ukraine. Due to the geopolitical crisis of the Russia-Ukraine war, Colombia needs to fulfill the actual demand by developing national strategies for producing urea by exploiting its resources.

2. Materials and methods

This study aims to assess the environmental impact of producing a non-centrifugal facility located in Colombia. To do so, simulation tools, interviews, and experimental methods were employed to gather the data for carrying out the life cycle assessment (LCA) that follows the standards described by ISO 14040, 14044, and 14604. In the upcoming sections, we briefly describe the methodological steps to fulfill the aforementioned goal. Fig. 1 illustrates the scenarios under scrutiny in this study. We delve into four distinct scenarios, outlined as follows: The Base scenario mirrors the conventional production of non-centrifugal sugar, where all residual biomass, including RAC, bagasse, and sugarcane press-mud, is utilized within the production process. Here, the environmental impact is gauged primarily based on the primary product. Scenario 1 spotlights the surplus of RAC, which correlates with enhancements in nutrient management derived from biomass. Scenario 2 focuses on the surplus of bagasse, linked with improvements in furnace efficiency. For Scenarios 1 and 2, the mass allocation method is employed to ascertain the environmental impact of non-centrifugal sugar. Lastly, Scenario 3 illustrates the transformation of surplus RAC and bagasse into syngas, subsequently converted into urea. This innovative approach uses syngas for electricity production, reducing reliance on diesel and external electricity during the milling stage. The remaining syngas were converted into urea. Besides, sugarcane press-mud was used as feedstock for producing bioethanol, as it was previously reported (Sanchez et al., 2020, 2019).

2.1. Base scenario

2.1.1. Data acquisition

Data was gathered from a small facility located in the municipality of Villeta (5°00′46″N, 74°28′23″W) by interviewing the facility's owners. The data obtained was employed as input information to simulate Aspen Plus® v.14 (AspenTech, MA, USA) and to build the inventory to calculate the environmental impacts through LCA.

2.1.2. Process description and simulation

The production of non-centrifugal sugar is divided into six main stages known as 1) crop stage, 2) harvest stage, 3) transport by animals, 4) milling, 5) combustion and non-centrifugal sugar production, and 6) animal feeding production, as shown in Fig. 1. An additional stage named urea production was included for the valorization of residual biomass that is not long employed in the facility. Each of these stages is briefly described in the upcoming section along with the information required to calculate the overall mass and energy balance of the process.

2.1.2.1. Crop stage. According to farmers, the total land available to cultivate non-centrifugal sugarcane is 23 ha. Non-centrifugal sugarcane reaches physiological maturity after 392 days, and it can be harvested up to 502 days after the sowing (Durán et al., 2014; Gonzáles Chavarro et al., 2018). Hence, to warrant a continuous production of non-centrifugal sugar, a portion of the cultivated sugarcane reaches

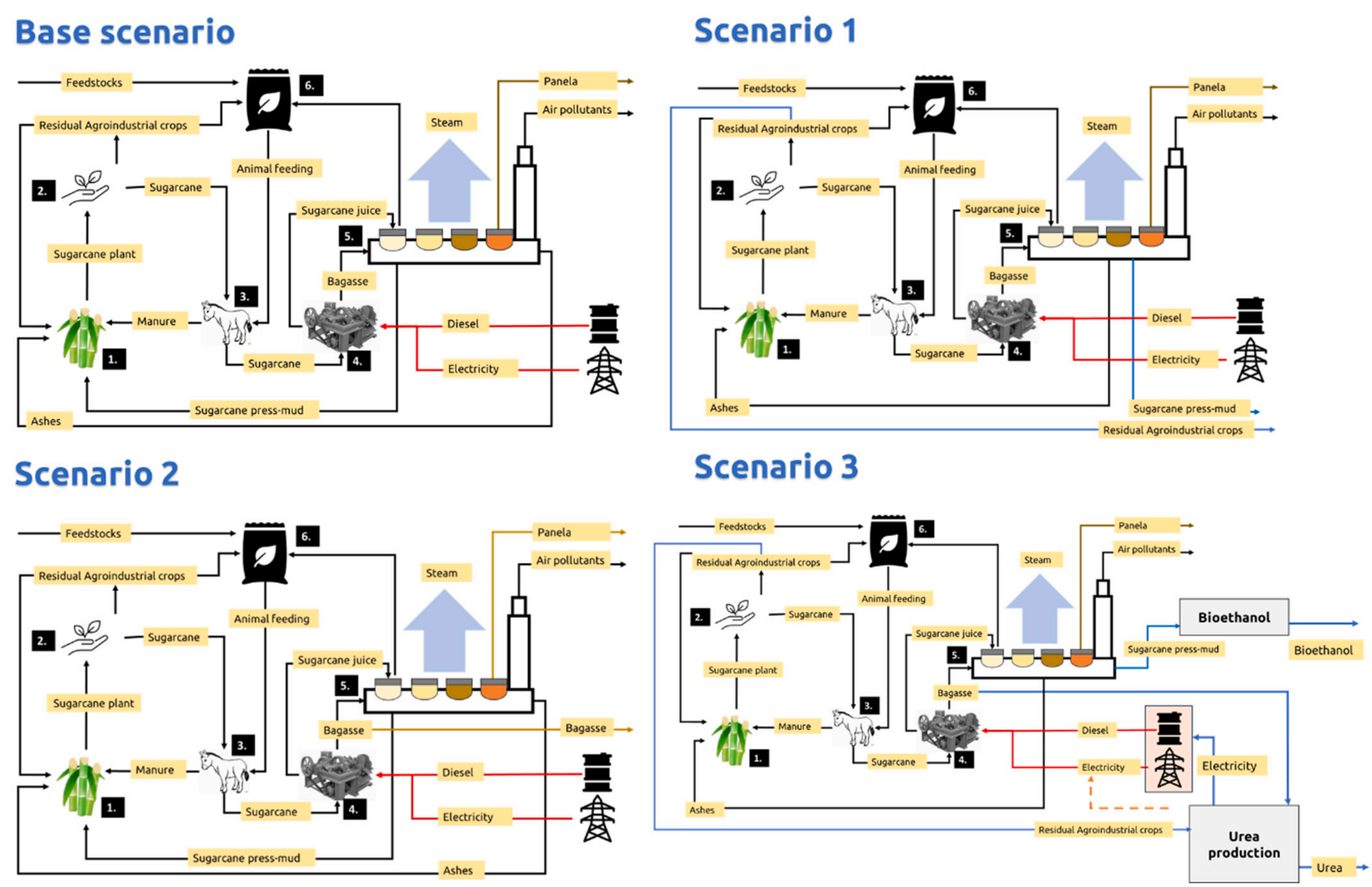

Fig. 1. Scenarios to produce non-centrifugal sugar in a small facility. The functional unit was set to produce 1 kg of *Panela* (non-centrifugal sugar). 1. Crop stage; 2. Harvest stage; 3. Transport; 4. Milling; 5. Bagasse combustion and *Non-centrifugal sugar* production. 6. Animal feeding preparation.

maturity in a specific land area whose value was calculated to be 4.27 ha**.** Based on this land area, fertilizer consumption and emissions associated with its use were forecasted, and their results are shown in the upcoming section. Life cycle inventory data was calculated according to the Intergovernmental Panel on Climate Change (IPCC) guidelines. These calculations included N_2O and NH_3 emissions due to manure and soil management. Particulate matter emission, phosphorous emissions due to fertilization and residue disposal, irrigation demand, carbon sequestration, and land use change. Detailed calculation is shown in Supplementary Material 1. Besides, emissions associated with the use of pesticides were not included in this study since they were not employed according to the interview results. Lastly, we included the burning of RAC after the harvest, we calculated their impact based on the amount of RAC disposed on the soil and the emissions factors reported by França et al. (2012), as shown in Supplementary Material (Table A.2).

2.1.2.2. Harvest stage and transport. According to the farmer's interview, the harvest of non-centrifugal sugar was manually carried out. Besides, non-centrifugal sugar is transported by mules. Since mules were included within the system boundaries, shown in Fig. 1, emissions associated with enteric fermentation and nitrogen oxides were considered, and they were calculated according to the IPCC guidelines. In addition, enteric fermentation of other animals such as swine and poultry was also considered since their manure is commonly employed as fertilizer in the crop stage.

2.1.2.3. Non-centrifugal sugar production. Once sugarcane is harvested manually by farmers, it is transported to the facility by mules. This sugarcane is milled in a *Trapiche* that is powered by diesel or electricity. According to farmers, diesel consumption is 4 gal/milling, while the monthly electricity consumption is 541 kWh. In this facility, a milling produces 3.2 t of non-centrifugal sugar. Emissions factors for diesel are shown in Table A.2 (see Supplementary Material). After milling, the bagasse is stored. This bagasse is used as heat to evaporate the sugarcane juice, which is sent to an evaporation train formed by five open pans.

In the first pan, *Guacimo* is added as a natural coagulant that allows the precipitating of soluble solids with an efficiency of 89.7 % (L. Moreno et al., 2022). *Guacimo* is burnt after usage, and its combustion was modeled in Aspen Plus. In this stage, sugarcane press mud is recovered at 45 °C. In the following pans, clarified sugarcane juice is evaporated to produce non-centrifugal sugar at 130 °C. As stated before, bagasse is sent to the combustion chamber to produce heat. The amount of heat obtained from the combustion chamber was retrieved from the simulation in Aspen Plus. Combustion of bagasse produces emissions according to Table A.2 (see Supplementary Material 1). Herein, we assumed biogenic carbon to the emissions from bagasse. Ash is also produced, and they are employed as fertilizer. However, since their composition is unknown, emissions from ashes were not considered. Non-centrifugal sugar is packed using plastic bags and lone bags. Emissions from material construction were not considered since they have a low impact compared to direct emissions (Sanchez et al., 2021a).

The above process was simulated in Aspen Plus® v.14 (AspenTech, MA, USA). Fig. 2a shows the process flowsheet of the process to produce non-centrifugal sugar in a small facility. Sugarcane, which is collected

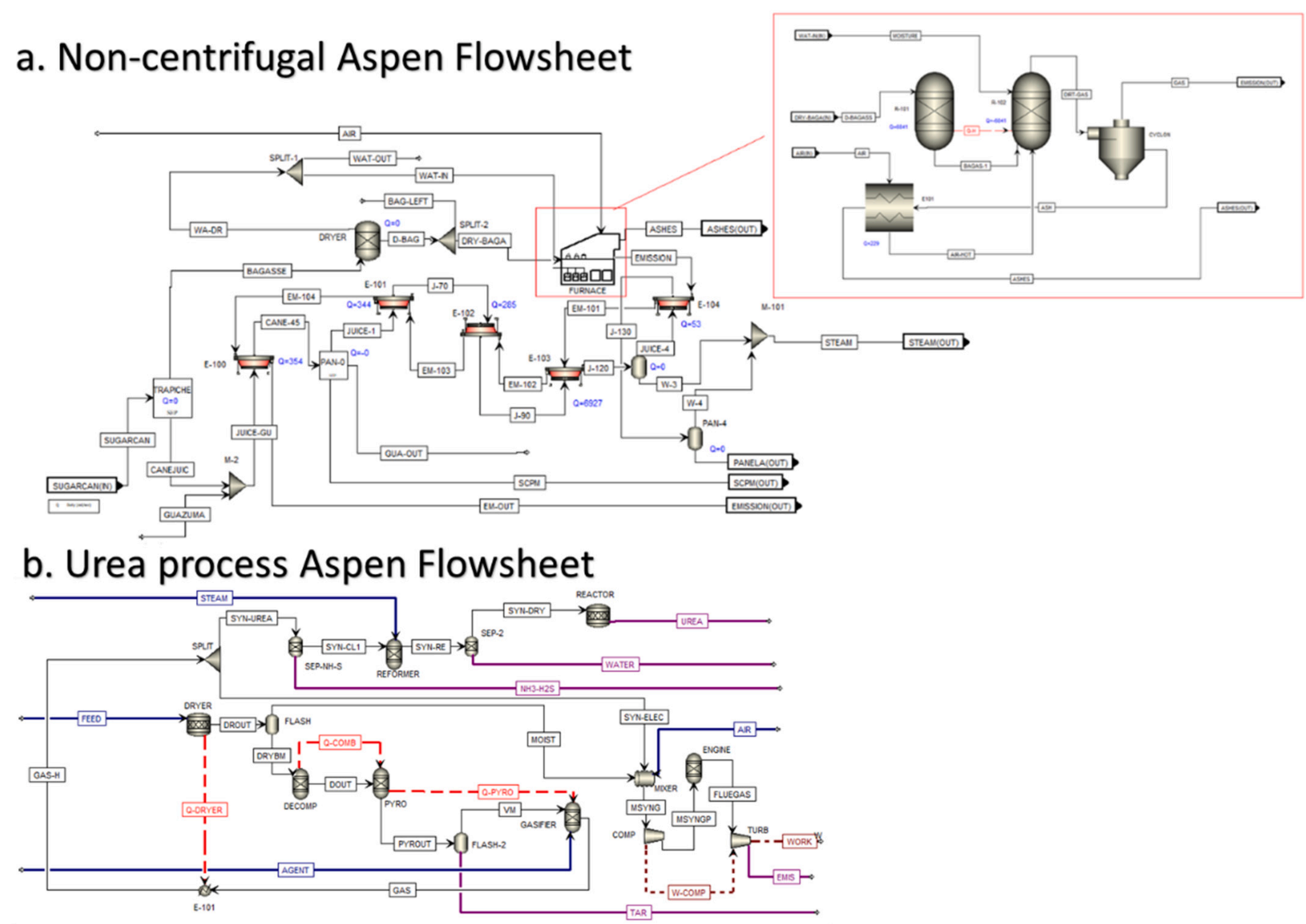

Fig. 2. a) Aspen flowsheet to produce non-centrifugal sugar in a small facility. SCPM: Sugarcane press-mud; b) Aspen flowsheet to produce urea from RAC and bagasse through gasification.

manually by farmers, is sent to the facility by mules. Sugarcane was modeled as a mixture of bagasse (30 wt%), sugarcane-press mud (4 wt %), sucrose (10 wt%), and water (56 wt%), as shown in Table 1. Sucrose and water were modeled as conventional components, while bagasse and sugarcane press mud were modeled as non-conventional components. HCOALGEN and DCOALIGT models were used to calculate the enthalpy and density of non-conventional components, respectively, by using the proximal and ultimate analysis (Sanchez et al., 2021b). The analyses are shown in Table 1**.** The composition of bagasse was retrieved from literature, and the composition of sugarcane press mud was characterized by a certified laboratory.

The harvested sugarcane is milled in a *Trapiche* to produce bagasse and sugarcane juice. The *Trapiche* was modeled using the SEP-1 subroutine, which simulates the separation of both fractions based on the fractional recovery collected from the interviews. The bagasse is then dried and sent to a furnace to produce heat. The dryer was modeled as a SEP-1 where water and bagasse fractional recovery were set based on the mass and energy balance. The combustion of sugarcane bagasse was modeled in a two-step reaction process by using an R-YIELD and R-GIBBS subroutine, as shown in Fig. 2a. The R-YIELD simulates the decomposition of bagasse in the main components (i.e., H_2, C, S, N_2, and O_2) by using FORTRAN statements through a calculator block. This stream is sent to an R-GIBBS that simulates de combustion of sugarcane bagasse to produce CO, CO_2, SO_x, NO_x, H_2O, N_2, O_2, and among others (Parascanu et al., 2020). The air is fed to cool down the ashes from the combustion chamber at 100 °C in a HEAT-X subroutine. The SEP-1 subroutine was employed to simulate the separation of ashes from the chimney gases in the combustion chamber. The heat from the chimney gases is used to heat up and evaporate the sugarcane juice in a countercurrent scheme formed by five pans (Shiralkar et al., 2014). The first pan was modeled using HEAT-X and SEP-1 subroutines. Herein, the HEAT-X simulates the heat transfer from the chimney gases to the sugarcane juice to reach 45 °C. According to the local farmers, sugarcane press mud is removed at this temperature by adding Guacimo *(Guazuma ulmifoliase),* which is a natural flocculant widely employed to produce kraft non-centrifugal sugar (Ortiz et al., 2011). The subsequent pan (i.e., E-101 and E-102 in Fig. 2a) were modeled as HEAT-X to simulate the temperature increment of the sugarcane to 90 °C. The following pan was modeled by using a HEAT-X and FLASH-2 subroutines. The HEAT-X simulates the heating of sugarcane juice from 90 to 120 °C, whereas FLASH-2 simulates the evaporation of water from the sugarcane juice to reach a sucrose concentration of 88 wt%. The last pan was also modeled with a HEAT-X and a FLASH-2, where non-centrifugal sugar is yielded with a sucrose concentration of 92 wt% at 130 °C. The steam from the last two pans is mixed in a MIX-1 subroutine to calculate the overall steam production in the facility. The Universal Quasichemical (UNIQUAC) thermodynamic package was employed to model the liquid-vapor equilibria of sucrose-water mixtures (Fukushima et al., 2019), while the Peng-Robinson thermodynamic package was used to model the gas phase during the combustion of sugarcane bagasse (Parascanu et al., 2020).

Table 1
Characterization of the sugarcane employed in the simulation.

Components	Bagasse[1]	Sugarcane press-mud[2]	Crop residue[2]	Guacimo[3]
Proximal analysis (wt%)				
Moisture	5.4	75.28	14.92	7.99
Volatile matter	84.78	83.09	63.20	80.92
Fixed carbon	11.95	10.36	8.09	17.28
Ashes	3.28	6.55	13.79	1.80
Ultimate analysis (wt%)				
Carbon	44.86	49.57	32.64	49.1
Hydrogen	5.87	7.11	4.33	5.8
Nitrogen	0.24	1.12	0.02	0
Sulfur	0.06	0.33	0.17	0
Oxygen	45.87	34.15	34.30	45.1
Lower heating Value (BTU/lb)	7740	976.6	5904	7230

[1] Data obtained from (Parascanu et al., 2020).
[2] Data obtained from certified a laboratory in Colombia.
[3] Data obtained from (Díez and Perez, 2017).

2.1.2.4. Animal feed. As described above, animals play a crucial role in the facility since the animal manure is collected and used as fertilizer. Hence, animal feeding was considered in this case. According to the interview, animal consumes 1.10 tons per year of sugarcane press mud. The animal feed composition is 66.5 % water, 3.3 % sugarcane press mud, 0.7 % salt, and 29.5 % buds and leaves. In addition, maize is used to feed poultry.

2.1.2.5. Transport of raw materials. Transportation of raw materials includes 1) diesel; 2) salt; 3) plastic bags; 4) lone bags; and 5) maize from Bogota D.C to Villeta whose distance is about 87 km plus the 5.5 km from Villeta to the facility. Initially, they are transported from Bogota D. C. to Villeta by small trucks boosted by diesel with an EURO IV standard adopted in 2015 in Colombia. The transport from Villeta to the facility is carried out by car boosted by diesel (Castillo et al., 2022). Besides, we considered a factor capacity of 50 %. It means that the transport is made in both ways, but the backway is driven with no loading. The inventory for transport is calculated according to Eq. (1) where m_{RM} is the quantity of raw materials in tons or units (i.e., plastic bags and lone bags), and d is the distance in km.

$$T(\text{Ton*km or unit*km}) = m_{RM}*d*0.5 \quad (1)$$

2.2. Alternatives scenarios

Herein, we proposed two alternative scenarios to improve the environmental impact. On one hand, the excess of nutrients in the soil might cause a negative impact, and therefore it is necessary to carry out a nutrient balance to determine whether the residual biomass fulfilled the nutrient demand of the non-centrifugal sugarcane crops. To do so, a nutrient balance was performed according to Eq. (2), where S_i is the nutrient surplus while RAC_i is the amount of nutrient *I* in the RAC, $SCPM_i$ is the amount of nutrient *I* in the sugarcane press-mud, $soil_i$ is the amount of nutrient *i* in the soil, $manure_i$ is the amount of nutrient *i* in the manure, ash_i is the amount of nutrient *i* in the ash, and $crop_i$ is the amount of nutrient *i* demanded by the non-centrifugal sugarcane crop. The nutrients "i" considered in this study were nitrogen, phosphorous, potassium, calcium, and magnesium which are regarded as the main nutrients required by the crop to grow. In Eq. (2), if $S_i > 1$, a surplus of nutrients is observed, whereas if $S_i < 1$, it is required extra fertilizers to cover the nutrient demand.

$$S_i = RAC_i + SCPM_i + Soil_i + Manure_i + Ash_i - Crop_i \quad (2)$$

On the other hand, a second scenario was evaluated by using a sensitivity analysis based on the Aspen Plus simulation shown in Fig. 2. We evaluated the effect of the outlet fuel gas temperature as a function of the consumption of bagasse. Based on the sensitivity analysis and furnace recommendations in a non-centrifugal facility, the quantity of bagasse savings was calculated. For both scenarios, by-products are yielded and consequently, valorization was considered in this study to determine the potential for producing valuable products that boost the non-centrifugal sector in Colombia.

2.3. Potential "green" products from residual biomass

Colombia has bet to the energy transition towards the decarbonization of its economy. Therefore, the deployment of products that contribute to this purpose is considered as the potential to be locally produced and consequently, boost the social and economic development of different sectors. For that reason, products such as H_2, bioethanol, biogas, and urea have risen as an alternative to decarbonization. While the former three seek to have an outstanding role in the energy transition, the latter has been considered as a potential opportunity to create a new business at the local level to be independent of other economies that are currently in geopolitical tension. Therefore, herein, we explored the potential production of urea, H_2, bioethanol, and biogas as possible products that could be obtained from non-centrifugal sugar. The potential production of said valuable products is shown in the upcoming sections.

2.3.1. Biomass gasification and urea potential

Biomass gasification was carried out in Aspen Plus based on the model proposed in the literature (Aspen Technology Inc., 2013; Haji-Hashemi et al., 2023). Fig. 2b shows the Aspen plus flowsheet for producing syngas, power, and urea. The power produced by the gasification stage will avoid the use of diesel and the power grid in the non-centrifugal sugar based on the leftovers of residual wastes from the facility which could be bagasse, residual crops, and sugarcane press-mud. In general, the feed stream which is the biomass was modeled as a non-conventional component. The HCOALGEN and DCOALGIT calculate the enthalpy and density of the non-conventional component (i.e., the biomass), respectively. The proximal and ultimate analysis shown in Table 1 was used to model the non-conventional component. The biomass is fed to a dryer (RSTOIC subroutine, $T = 105\ ^{\circ}C$, $P = 1$ atm) to adjust the moisture content to 10 %. A calculator block was used to do the said modification. The resulting stream (DROUT in Fig. 2b) is fed to an adiabatic flash unit to separate the water from the biomass. The dry biomass (DRYBM in Fig. 2b) is fed to the pyrolysis unit which is composed of two subroutines. On the one hand, a RYIELD simulates the decomposition of biomass into conventional components such as H_2, sulfur, carbon, chlorine, O_2, and N_2. On the other hand, a RGIBBS simulates the production of pyrolysis products. An energy stream from the RYIELD subroutine simulates the heat of combustion and it is connected to the RGIBBS. The pyrolysis products (PAOUT in Fig. 2b) are fed into a Flash to separate the gas, liquid, and solid products. The gas product (VM in Fig. 2b) is fed to a second RGIBBS reactor, named a gasifier, with a gasifier agent. In this case, air was used as the gasifier agent. The amount of air fed to the gasifier was calculated by using a DESIGN SPEC to warrant a temperature of 700 °C in the gasifier. The gas product that leaves the gasifier heats the dryer. Said gas is sent to a split unit. The purpose of the split unit is to divide the syngas.

A fraction of the syngas is mixed with the moisture stream and air that is sent to the engine where electrical power is produced. Simulation of the engine was simulated based on the work carried out by (Cirillo et al., 2021). Herein, the syngas is burnt to produce enough power to avoid the use of diesel within the non-centrifugal sugar facility.

The left fraction of syngas is sent to a third RGIBBS subroutine that models the steam reforming. The purpose of this simulation is to forecast the maximum amount of urea that could be produced. Hence, non-rigorous subroutines were used during the simulation. Urea production was calculated stoichiometrically assuming complete conversion of H_2. The following reactions were considered in this study.

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad (3)$$

$$2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O \quad (4)$$

2.3.2. Sugarcane press-mud valorization

Sugarcane press-mud is a liquid and viscous material obtained during the clarification of sugarcane juice. Due to its high content of carbohydrates, proteins, and lipids, sugarcane press-mud could be converted into biofuels such as bioethanol and biogas through biological pathways. The potential production of bioethanol from sugarcane press-mud was calculated based on previous studies whose value is 0.025 kg ethanol/kg sugarcane press-mud (Sanchez et al., 2021b). Said bioethanol could be also converted into H_2 through catalytic steam reforming whose overall yield is 3.0 g H_2/kg sugarcane press-mud. Furthermore, sugarcane press-mud could be also converted into biogas whose yield is 0.227 Nm^3 CH_4/kg volatile solids of sugarcane press-mud. To compare the potential of the products we calculated the economic potential based on the price market, as shown later in Section 3.5.

2.4. Life cycle assessment (LCA)

Life cycle assessment (LCA) was performed by following the guidelines of the ISO 14040 and 14044 (ISO, 2006) that encompasses four main stages: i) goal and scope definition; ii) life cycle inventory (LCI); iii) life cycle impact assessment (LCIA), and iv) interpretation. In the upcoming section, we will describe each of the LCA stages.

2.4.1. Goal and scope definition

This study aims to calculate the environmental impact of producing non-centrifugal sugar in a small facility in Colombia. The functional unit was set to 76.9 t/a of non-centrifugal sugar which is the annual production in a facility. To ease the comprehension of results, inventory was normalized to 1 ton of sugar since this is the main activity within the small facility. Fig. 1 shows the system boundaries where a cradle-to-gate approach was adopted. The system encompasses the cultivation, harvesting, and transport of sugarcane to the small facility, and its conversion into non-centrifugal sugar by coupling milling, bagasse combustion, and evaporation. Furthermore, an attributional approach was adopted since we seek to determine the main environmental hotspot within the process. As shown in Fig. 1, different products are yielded during the production of non-centrifugal sugar. These by-products are RAC, ashes, sugarcane press mud, and bagasse. According to farmers, RAC is used as fertilizer and animal feed. Ashes are also used as fertilizer. Bagasse is utilized as a fuel in the furnace to evaporate the sugarcane juice. Lastly, sugarcane press mud is used for animal feeding. All the by-products are employed within the facility. Therefore, all the environmental burdens were allocated to the production of non-centrifugal sugar.

In the alternative scenarios, RAC, bagasse, and sugarcane press-mud are mostly obtained as by-products, and therefore, multifunctionality issues must be solved. In this study, we used mass allocation to solve the multifunctionality. Furthermore, the emissions associated with the valorization of urea, bioethanol, and biogas are out of the scope of the system boundaries, and hence their impact was not considered.

2.4.2. Life cycle inventory

Life cycle inventory (LCI) is the most critical stage in LCA. In this stage, all data required to calculate the environmental impacts were gathered from farmer interviews, Aspen Plus simulation, and literature review. All information is shown in the [dataset].

2.4.3. Life cycle impact assessment

The life cycle impact assessment methodology selected for this study was ReCiPe 2016 v1.03 midpoint (H). The selected impact categories were global warming potential (GWP100), acidification potential (AP), freshwater eutrophication (FEW), particulate matter formation (PMFP), photochemical oxidant formation potential for humans (HOFP), and ecosystems (EOFP). OpenLCA v2.0.2 (GreenDelta, Germany) was used to calculate the environmental impacts. In addition, uncertainty analysis was performed by using a Montecarlo simulation with 1000 runs. To calculate the uncertainty values of the data, the pedigree matrix was employed (Ferdous et al., 2023). The role of the pedigree matrix is to convert descriptive information into a data quality value named uncertainty based on data quality indicators such as reliability, completeness, and temporal, geographical, and technological representativeness. Herein, we employed the pedigree matrix developed by Ecoinvent, as shown in Fig. S.1 (Supplementary Material S.1), to calculate the uncertainty of the data based on a lognormal distribution.

2.4.4. Carbon modelling

Herein, we modeled carbon emissions from biomass as biogenic carbon which refers to the carbon derived from biological sources that are used during crop growth but released afterward in the combustion or decomposition in a short rotating period. Therefore, this carbon is considered as neutral carbon, whose emission factor was set to 0. In other cases, CO_{2nca} has an emission factor of 1.0 when is derived from the combustion of fossil fuels.

3. Results and discussions

Environmental results for all the scenarios were calculated in terms of the global warming potential (GWP), acidification potential (AP), freshwater eutrophication (FEW), particulate matter formation (PMF), and photochemical oxidant for humans (HOFP) and ecosystems (EOFP). In the upcoming sections, we briefly showed said impacts based on the production of 1 t of non-centrifugal sugar.

3.1. Base scenario

Fig. 3a shows that producing 1 t of non-centrifugal sugar requires 10 t of fresh sugarcane, 146 kg of diesel, and 80 kWh of electricity. In addition, several by-products are obtained, such as sugarcane press mud (0.39 t), buds and leaves (2.88 t), and bagasse (3 t). In addition, the heat demand to evaporate the sugarcane juice is 12 GJ/t. The flue gas leaving the furnace is 850 °C, similar to the furnace employed in a non-centrifugal sugar facility (Jader et al., 2018). Since in the based scenario, there is a sole product named non-centrifugal sugar, we allocated the environmental burdens to said product.

Table 2 shows the environmental impact in terms of GWP, AP, FWEP, PMF, POFH, and POFE. According to Table 2, the GWP for producing 1 t of non-centrifugal sugar is 0.262 t CO_2-eq. This value is quite similar to those reported in the literature. For instance, Mendieta et al. (2021) reported a carbon footprint of 0.438 t CO_2-eq/t *Non-centrifugal sugar*, Castañeda-Suárez et al. (2017) depicted a value of 0.31 t CO_2-eq/t *Non-centrifugal sugar*, and Sierra et al. (2022) reported an impact of 0.25 t CO_2-eq./t *Non-centrifugal sugar*. In those studies, we considered biogenic carbon for the emissions obtained from the combustion of bagasse.

Fig. 4 shows the Sankey Diagram that portrays the contribution and main hotspots in terms of global warming potential for producing 1 t of non-centrifugal sugar. According to Fig. 4, the main environmental hotspots are coming from the harvest stage whose carbon footprint is 0.193 t CO_2-eq/t *Non-centrifugal sugar* and is mainly associated with direct emissions derived from the disposed of residual biomass that acts as fertilizer. In this case, direct emissions from the harvest stage contribute to almost 50 % of the total carbon footprint due to the emissions of N_2O as a result of the decomposition of nitrogen compounds present in the residual biomass. Similarly, Mendieta et al. (2021) reported that the harvest stage contributes almost to 52.5 % during non-centrifugal sugar production. The second contributor to the carbon footprint is the transport of raw materials (0.053 t CO_2-eq), followed by the use of the power grid (0.022 t CO_2-eq) to boost the mill engine and the use of diesel in the milling stage (0.020 t CO_2-eq). Based on the emission factor retrieved from Ecoinvent, diesel combustion has a carbon footprint of 0.137 kg CO_2-eq/MJ, while the Colombian power grid has a carbon footprint of 0.075 kg CO_2-eq/MJ. Moreover, the energy consumption per ton of *non-centrifugal sugar for* diesel and power grid was 146.7 and 288 MJ, respectively. Commonly, the milling stage employs diesel to power the engine instead of the grid, but in this case, diesel is used as a backup to guarantee continuous production. Previous studies conducted by Castañeda-Suárez et al. (2017) showed that changing from diesel to electricity reduces the carbon footprint by 19 %.

Concerning other environmental impacts, Table 2 also shows the AP, FWEP, PMF, POFH, and POFE. AP stands for acidification potential which is associated mainly with acid rain due to the presence of sulfur oxides, ammonia, and nitrogen oxides, while FWEP stands for the eutrophication phenomena that implies an accumulation of nutrients due to the emission of ammonia, nitrogen oxides, and phosphorus (Battista et al., 2017). Herein, we reported an AP of 0.136 t SO_2-eq/t *Non-centrifugal sugar* and FWEP of 0.0081 t P-eq/t *Non-centrifugal sugar*.

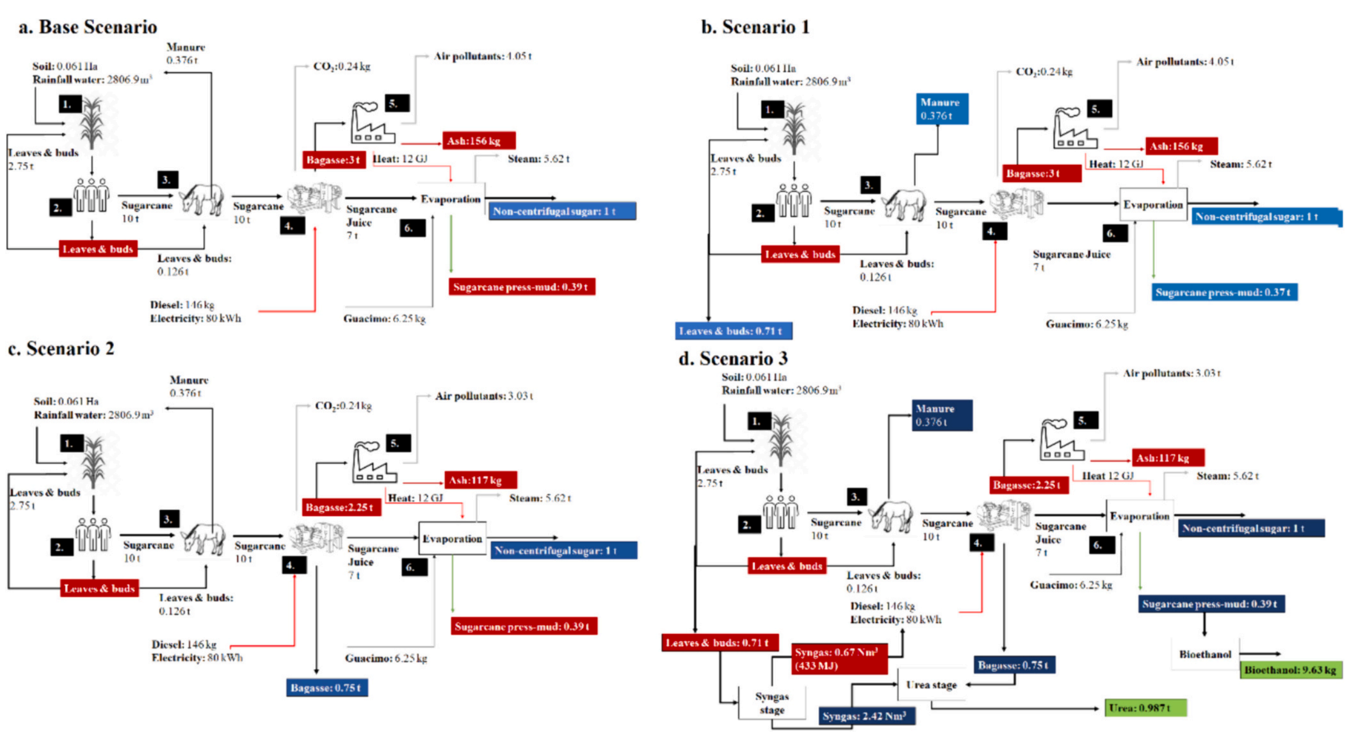

Fig. 3. Mass and energy balance result from the production of 1 t of non-centrifugal sugar for a) based scenario; b) scenario 1; c) scenario 2, and d) scenario 3. Blue squares indicate that environmental burdens were allocated to said products. Green squares indicate that said products are out of the system boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Environmental impact for the selected categories to produce 1 t of *Non-centrifugal sugar*.

Impact category	Units	Scenario	Mean	SD	5 % percentile	95 % percentile
Global Warming Potential (GWP)	t CO_2-eq	Based Scenario	0.262	0.055	0.186	0.359
		Scenario 1	0.179	0.036	0.130	0.245
		Scenario 2	0.292	0.060	0.208	0.399
		Scenario 3	0.146	0.029	0.105	0.198
Acidification potential (AP)	t SO_2-eq	Based Scenario	0.135	0.037	0.086	0.205
		Scenario 1	0.013	0.003	0.009	0.018
		Scenario 2	0.119	0.035	0.071	0.183
		Scenario 3	0.010	0.002	0.007	0.013
Freshwater eutrophication (FWEP)	t P-eq	Based Scenario	0.0081	0.0024	0.0048	0.0130
		Scenario 1	0.0053	0.0016	0.0032	0.0083
		Scenario 2	0.0072	0.0021	0.0043	0.0110
		Scenario 3	0.0038	0.0007	0.0028	0.0052
Particulate matter formation (PMF)	t $PM_{2.5}$-eq	Based Scenario	0.0200	0.0049	0.0130	0.0290
		Scenario 1	0.0047	0.0009	0.0057	0.0040
		Scenario 2	0.0170	0.0046	0.0110	0.0260
		Scenario 3	0.0029	0.0006	0.0020	0.0040
Photochemical oxidant formation – Human (POFH)	t NOx-eq	Based Scenario	0.043	0.010	0.030	0.060
		Scenario 1	0.029	0.007	0.020	0.041
		Scenario 2	0.031	0.007	0.022	0.043
		Scenario 3	0.021	0.005	0.014	0.029
Photochemical oxidant formation –Ecosystems (POFE)	t NOx-eq	Based Scenario	0.043	0.010	0.030	0.060
		Scenario 1	0.029	0.007	0.020	0.041
		Scenario 2	0.031	0.007	0.022	0.043
		Scenario 3	0.021	0.005	0.014	0.029

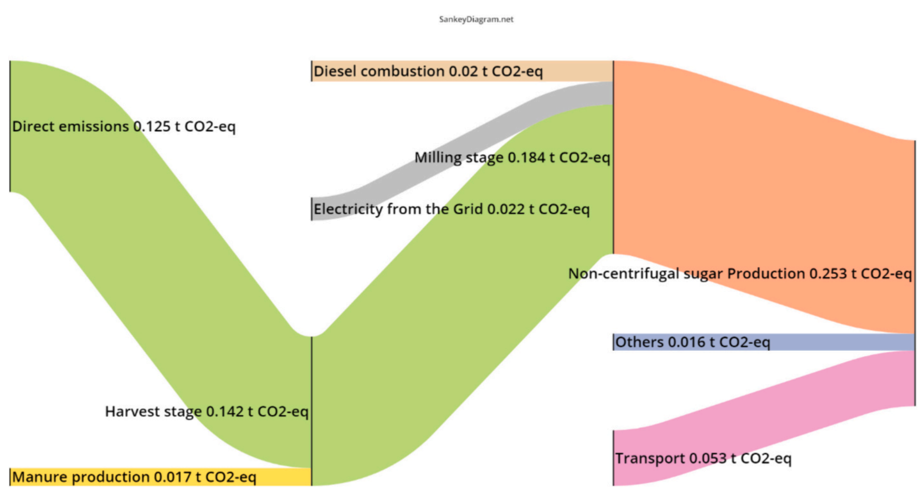

Fig. 4. Sankey diagram in terms of global warming potential (GWP100) for producing 1 t of *Non-centrifugal sugar*. Methodology impact: ReCiPe 2016, midpoint (H). Values are in t of CO_2-eq. Diagram made in https://sankeydiagram.net/

Fig. 5 shows that the harvest stage is the main responsible of AP and FWEP contributing to these impacts by at least 85 % and ascribed mainly to the use of residual biomass in the soil as fertilizer. In the case of AP, as shown in Fig. 5a, the bagasse combustion contributes to a low extent to the acidification due to the SOx emissions.

Otherwise, particulate matter is formed through the atmospheric oxidation of NO_x and SO_x causing a lot of human health problems (Franceschi et al., 2018; Hopke et al., 2020). According to Vonk et al. (2016), particulate matter is formed during soil cultivation, harvesting, cleaning, and drying in wet climates. The humidity in the municipality of Villeta is about 85 %, then producing 1 t of non-centrifugal sugar leads to 0.020 t $PM_{2.5}$-eq, as shown in Table 2**.** According to Fig. 5c, the main responsible of PMF is the harvest stage and the bagasse combustion with a contribution of 74.1 % and 23.44 %, respectively. Regarding the photochemical oxidant formation (POF) for both humans and ecosystems. POF represents the formation of smog which is harmful to both humans and ecosystems (Bauer et al., 2015). POF for humans and ecosystems was 0.043 t NOx-eq/t non-centrifugal sugar. Fig. 5d shows that the main contributor to POF is the nitrogen oxides formed during bagasse combustion, thermal decomposition of bagasse leads to the formation of NO and NO_2 which are simulated as NO_x.

According to the previous analysis, the main hotspots within the non-centrifugal sugar production stage are the harvest followed by the combustion process. Said results are quite similar to those reported in the literature. For instance, Mendieta et al. (2021) depicted that also the cultivation stage is the main contributor to climate change and acidification, while the non-centrifugal sugar processing is the main responsible for the particulate matter formation and photochemical oxidant formation. As strategies to mitigate the impacts, the use of electricity instead of diesel, and the dwindling of bagasse use in the furnace have been explored. However, the wrong management of residual biomass has not been explored. Herein, we performed a nutrient balance to enhance the environmental performance for producing non-centrifugal sugar. In the upcoming section, we explored said alternative.

3.2. Scenario 1: nutrient balance

Fig. 2 shows that this facility did not employ chemical fertilizers to

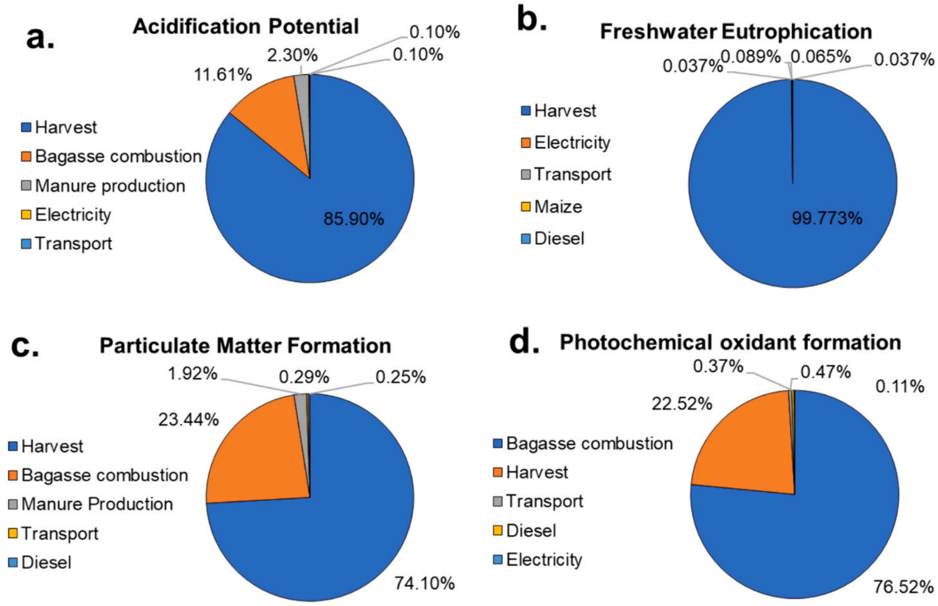

Fig. 5. Contribution analysis for other impact categories: a) Acidification potential; b) Freshwater eutrophication; c) Particulate matter formation; d) Photochemical Oxidant Formation.

cultivate non-centrifugal sugarcane or pesticides. Fertilizers are used within a facility to deliver the macronutrients (i.e., nitrogen, potassium, and phosphorous) and micronutrients (e.g., calcium, magnesium, silicon, and iron) to guarantee the proper growth of the non-centrifugal sugarcane. According to the farmers, most components are directly obtained from the soil. To validate this statement, a mass balance for the most relevant nutrients (i.e., nitrogen, phosphorous, potassium, calcium, and magnesium) was calculated. Fig. 6a shows the nutritional requirement for sugarcane growing based on experimental data retrieved from literature (Gonzáles Chavarro et al., 2018), while the nutrients available for sugarcane uptake were calculated based on the available information from the manure, residues, and soil composition.

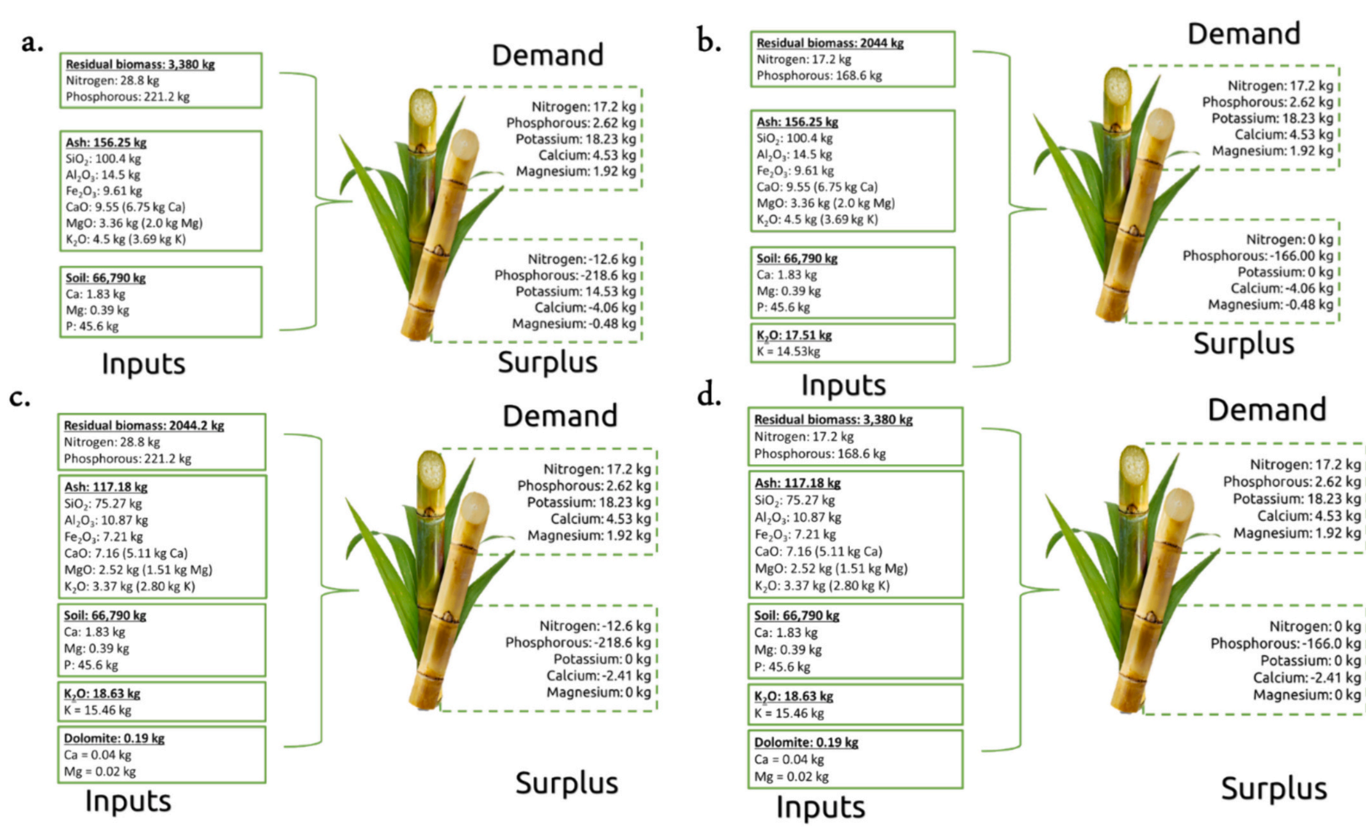

Fig. 6. a) Mass balance of nutrients during non-centrifugal sugarcane growth in the base scenario; b) mass balance of nutrients during non-centrifugal sugarcane growth in the scenario 1, and c) mass balance of nutrients during non-centrifugal sugarcane growth in the scenario 2; d) mass balance of nutrients during non-centrifugal sugarcane growth in the scenario 1.

The mass of nutrients in the soil was calculated according to the soil depth required during the sowing stage whose value was 60 cm according to farmers. In addition, we considered the nutrients present in the residual ash from bagasse combustion. According to Payá et al. (2018), the average content of SiO_2 is 63.56 ± 12.17 wt%, Al_2O_3 is 9.18 ± 5.39 wt%, Fe_2O_3 is 6.09 ± 3.11, CaO is 6.05 ± 4.78 wt%, MgO is 2.13 ± 1.77 wt%, and K_2O is 2.85 ± 1.89 wt%.

According to Fig. 6a, manure, residues, bagasse ashes, and nutrients available in the soil are enough to cover the demand for almost all of the nutrients since the surplus for almost all the nutrients is negative. This negative value indicates that more nutrients are added than those uptake by the crop. The only nutrient that is not enough is potassium whose surplus is 14.5 kg/t non-centrifugal sugar. In the case of the other nutrients, there is an excess, mainly phosphorous followed by nitrogen, calcium, and magnesium. The phosphorous and nitrogen come from the residual biomass obtained within the non-centrifugal sugar process (i.e., manure, RAC, sugarcane press-mud), while the calcium and magnesium sources are obtained mainly from the soil and the bagasse ash, being the latter the main source for these micronutrients. To overcome the environmental issues associated with the surplus of nutrients, a mass balance was carried out to determine the proper amount of residual biomass that is needed to cover the nutrient demand of the sugarcane crop.

Fig. 6b shows that the use of residual biomass dwindles by almost 40 %. According to the mass balance, only the RAC is enough to cover the nitrogen demand of the non-centrifugal sugar cane crop. However, an excess of phosphorous is still observed with a value of 218.6 kg. A phosphorous surplus is commonly observed in sugarcane fields in Brazil. Excess phosphorous is important because it tends to adsorb in the soil due to the presence of iron and aluminum compounds, and consequently, the plant uses less phosphorous for growing (Rosa et al., 2022). Concerning the calcium and magnesium surplus, the addition of bagasse ash covered the demand for these micronutrients, but there is a surplus of 4.06 kg and 0.48 for calcium and magnesium, respectively. A surplus of calcium might play a key role in the uptake of phosphorous since calcium binds to P and reduces its availability. Besides, high levels of calcium and magnesium inhibit the uptake of potassium (Meyer, 2013). The nitrogen and phosphorous addition rate (expressed as P_2O_5) was 0.030 t and 1.22 t per ton of non-centrifugal sugar. Said values are higher than those reported by Mendieta et al. (2021), who reported 0.012 t/t for nitrogen and 0.016 t/t for phosphorous, and those stated by Powar et al. (2022), whose nitrogen and phosphorous rate application were 0.022 t/t. The high application of either mineral or organic fertilizers led to a high emission rate of NO_x, nitrates, and phosphates to the atmosphere and water sources. Differences between the applications depend on the practices carried out in the non-centrifugal facilities. While some facilities use the residual biomass for animal feeding, other facilities leave the residual biomass in the facility.

Fig. 2b shows the mass balance if proper nutrient balance is carried out in the facility. Hence, based on the nutritional requirement, the annual amount of RAC required to cover the nutritional demand is 2.04 t. Hence, a surplus of 0.71 t of residual crops is obtained and could be used for other purposes that are discussed later in the manuscript. As a result of the RAC surplus, multifunctionality was solved by the allocation method. It means that environmental burdens were allocated in terms of the mass flow rate. Table 2 shows that the GWP is 0.179 t CO_2-eq/t *Non-centrifugal sugar*. It means that GWP dwindled by 32 %. Considering other impacts, Table 2 shows that AP was 0.013 t SO_2-eq/t *Non-centrifugal sugar,* the FWEP was 0.053 t P-eq/t *Non-centrifugal sugar*, the PMF was 0.047 t $PM_{2.5}$-eq/t *Non-centrifugal sugar*, and POF was 0.029 t NOx-eq/t *Non-centrifugal sugar.* In all cases, a reduction of at least 32 % of the environmental impact was observed.

Up to now, we explored the proper use of residual biomass to cover the nutrient demand of non-centrifugal sugarcane to reduce the environmental impact. However, bagasse savings could also be contributed to reducing the overall impact. In the upcoming section, we explore this alternative.

3.3. Scenario 2: bagasse savings

Improvements to the furnace of the non-centrifugal sugar could be performed to increase bagasse savings and reduce the carbon footprint associated with bagasse combustion. For instance, Jakkamputi and Mandapati (2016) showed that using solar energy could increase the bagasse savings from 0.029 to 0.24 kg/kg. Similarly, Tyagi et al. (2022a) found that a reduction of 12 % could be achieved if some technical modifications to the furnace were carried out.

Fig. 7 shows the effect of bagasse savings on the fuel gas temperature and CO_2 emissions from a thermodynamic perspective where a bagasse savings of 0.24 kg/kg could decrease the fuel gas temperature from 850 to 650 °C, and the CO_2 emissions from 1.32 to 1.00 kg CO_2/kg bagasse. Bagasse savings are associated with better combustion of the fuel and a proper furnace design. Since the main heat transfer mechanism during bagasse combustion is convection and radiation, the fluid slow circulation highly affects energy efficiency (Gutiérrez-Mosquera et al., 2018). Besides, Jader et al. (2018) showed that different furnaces will show differences in the heat losses, thermal efficiencies, and combustion temperature that will affect bagasse savings. As a result of bagasse savings, 0.75 t of bagasse is available for producing other valuables products, as shown in Fig. 2c. Concerning the environmental impact, Table 2 shows that the GWP for said scenario was 0.292 t CO_2-eq/t *Non-centrifugal sugar* whose value is slightly higher than for the based scenario (0.262 t CO_2-eq/t *Non-centrifugal sugar*). The increase in GWP was associated with the use of nutrients to keep the nutrient balance in the soil. As a result of bagasse savings, a reduction in ash production was observed. Indeed, in the based scenario ash production was 156 kg whereas in this scenario was 117 kg. Therefore, to cover the nutrient demand, K_2O and dolomite were added to the soil, as shown in Fig. 5c. The carbon footprint of adding K_2O was calculated to 0.046 t CO_2-eq, and consequently, the addition of extra nutrients raised the GWP in this scenario. Concerning other impacts, they dwindled by almost 10 % being the highest reduction observed for POF (33 %). POF is associated with NO_x emissions that are produced during bagasse combustion. The lower the bagasse burnt, the lower the NOx emissions.

Based on the above, the proper use of residual biomass to cover the nutrient demand is better than bagasse savings since the overall impact was reduced by >33 % in scenario 1 in comparison with the reduction of <30 % in scenario 2. However, combining both alternatives will result in better environmental performance, as shown in the upcoming section.

3.4. Scenario 3

Fig. 2d shows scenario 3 where proper residual biomass is used to cover the nutrient demand and bagasse savings were observed by reducing the furnace temperature. In this case, a surplus of RAC, bagasse, manure, and sugarcane press mud was observed. RAC, as a lignocellulosic material, could be upgraded to syngas through

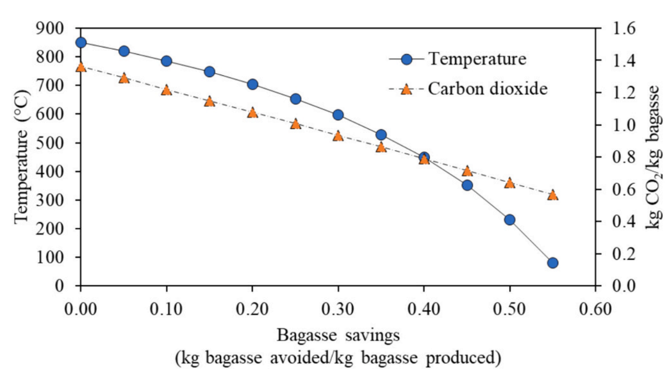

Fig. 7. Effect of bagasse savings on the furnace temperature and CO_2 emission during the production of non-centrifugal sugar.

gasification for producing electricity that avoids the use of diesel and power grid during the milling stage. Table 3 shows that the RAC available is 0.71 and could produce up to 3.09 Nm^3 of syngas with a composition of 21 mol% H_2, 39.1 mol% N_2, 17.6 mol% CO, 12.4 mol% CO_2, 9.23 mol% H_2O, and 0.15 mol% CH_4. Said syngas would produce 648 MJ of electrical energy per Nm^3 of syngas, which results in a fuel consumption of 1.29 kg/kWh whose value is lower than those reported in the literature (1.6–2.9 kg/kWh) (Martínez et al., 2020). The low fuel consumption was associated with the composition of CH_4 whose values are higher than 3.0 mol%. The low CH_4 composition is related to the Aspen Plus simulation which models the gasification by minimizing the Gibbs Free energy which is the common approach to model gasification (Ajorloo et al., 2022) and it has been proven to not properly forecast the CH_4 (Ayub et al., 2020). However, for potential calculation, minimization of Gibbs Free energy is a suitable approach for biomass gasification.

According to Table 3, the energy demand in the milling stage is 433 MJ/t. Based on the energy yield (648 MJ/Nm^3) and the energy demand (433 MJ), the amount of syngas needed to cover the energy demand is 0.673 Nm^3. Hence, only 0.15 t of RAC is required to produce enough syngas to avoid the use of diesel and power grid in the milling stage. Table 2 shows that the GWP for this scenario is 0.146 t CO_2-eq which results in a reduction of almost 45 % in comparison with the based scenario. This GWP abatement is linked to proper residual biomass use as fertilizer, bagasse savings, and diesel and power grid avoided. Regarding other impacts, the reduction of AP was 93 %, while for FWEP, PMF, and POF was 53 %, 85.5 %, and 51.2 %, respectively. The implementation of this strategy results in a surplus of different residual biomass that could be upgraded into valuable products. Fig. 2d shows that the production of 1 t of non-centrifugal sugar will produce 0.376 t of manure, 0.75 t of bagasse, 0.39 t of sugarcane press-mud, and 2.42 Nm^3 of syngas. In the following section, we focused on the possibility of creating new green markets within the non-centrifugal sugar industry.

3.5. Green markets

Green marketing has arisen as the development of new activities to help mitigate environmental issues (Dangelico and Vocalelli, 2017). Green market products are commonly derived from residual biomass. As shown in Section 3.4, there is residual biomass that could be employed as feedstock to produce valuable products. For instance, sugarcane press-mud could be upgraded either to bioethanol, biogas, and hydrogen. Concerning bagasse and RAC, they could be upgraded into syngas through gasification, and these syngas is converted into electricity and urea. Based on the literature review and Aspen Plus simulation, the potential of the aforementioned products was calculated. Table 4 shows the average yield, the price of these goods, and the potential from an economic point of view. According to Table 4, the product with the highest potential within the non-centrifugal sector is urea which has a similar revenue to its main product. Urea yield was 0.92 t urea/t biomass whose value is comparable with those reported in the literature (0.79–1.07 t urea/t biomass) (Alfian and Purwanto, 2019; Zhang et al., 2021). The urea market has gained a lot of attention in recent years due to the Geopolitical issues between Russia and Ukraine whose direct consequence is lowered fertilizer production, thus increasing urea price (Khurshid et al., 2024). Colombia imports mostly nitrogen fertilizers from Russia, Ukraine, Venezuela, and Trinidad and Tobago. Therefore, to reduce the overdependence, it is necessary to produce urea under Colombian conditions. Other products that could be manufactured within the industry such as bioethanol, hydrogen, and biogas have a low revenue and therefore, they would not have an important impact on trade markets. Possibly products such as biogas, bioethanol, hydrogen, and electricity might be used to fulfill the needs of the small farms.

Fig. 8 shows the non-centrifugal sugar production in Colombia whose current production is 1363 kt. The Andean region in Colombia comprises the departments of Santander, Boyacá, Antioquia, and Cundinamarca whose overall contribution to the non-centrifugal sugar market is 54 %. Based on the urea potential yield calculated by a simulation in Aspen Plus (0.92 t urea/bagasse), the potential production of urea from the residual biomass in Colombia would be 941,870 t which covers the urea demand whose value stands at 401,000 t. However, one of the main challenges in the chain supply of non-centrifugal industry is the access to the facilities. More of the facilities are located in the rural areas of the municipalities. Therefore, the transport of goods from and to the facility is quite complicated and only small trucks could reach the facility. Based on that limitation, we focused on the main producers whose total urea production would be 508,971 t which still covered the urea demand. However, 91 % of the total facilities for producing non-centrifugal sugar are still using kraft processes and therefore, it would not be easy to deploy urea technology in those facilities since their production is not constant. Indeed, they produce non-centrifugal sugar twice per month. The intermittency of non-centrifugal sugar production would hinder urea production and consequently limit its production. To overcome this issue, decentralization will avoid long transportation distances and also might guarantee continuous operation. This operating model in the supply chain is competitive in remote areas to reduce operational costs. Hence, an alternative to deploying urea from non-centrifugal is the creation of hubs that decentralize urea production by using residual biomass from different facilities. For instance, Villeta, the municipality under study, has 289 facilities with an average production of 20 t of non-centrifugal sugar per facility which leads to an annual production of 5780 t of non-centrifugal sugar. Based on this data, the urea potential in Villeta through the harnessing of residual biomass would be 4000 t which represents 1 % of the national demand. This small contribution could be the first step in the development of new markets within the region. Therefore, further studies must seek to evaluate the economic feasibility of the implementation of a urea plant by using the residual biomass of the non-centrifugal sugar.

Table 3
Aspen Plus simulation for RAC valorization to syngas. Values normalized to 1 t of non-centrifugal sugar.

RAC available	t	0.71
Syngas potential	Nm^3	3.09
The energy demand of the facility	MJ	433
Electricity yield from syngas	MJ/Nm^3	648
Syngas required to cover energy demand	Nm^3	0.673
Syngas Surplus	Nm^3	2.412
RAC after syngas production	t	0.56

4. Conclusions

Herein we underscore the significant environmental impacts associated with Non-centrifugal sugar production, particularly in terms of global warming potential, acidification potential, freshwater eutrophication, particulate matter formation, and photochemical oxidants formation. However, through the implementation of mitigation strategies such as nutrient balancing and the reduction of bagasse consumption, substantial abatements in environmental burdens can be achieved. This not only enhances the sustainability of Non-centrifugal sugar production but also presents opportunities for addressing national agricultural needs, such as urea demand, in a more self-reliant and decentralized manner. Embracing such strategies can contribute to the advancement of green markets and foster economic and social development in rural areas, while concurrently reducing dependency on external resources and mitigating environmental degradation.

CRediT authorship contribution statement

Nestor Sanchez: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Table 4
Potential marketable products within the non-centrifugal sugar industry.

Product	Yield per t of *Non-centrifugal sugar*		Source	Price		Potential (USD)
Non-centrifugal sugar	1.000	t	Sugarcane Juice	0.8391	USD/kg	839.1
Urea	0.691	t	Bagasse	1.22	USD/kg[1]	842.5
Electricity	434.2	kWh	RAC	0.193	USD/kWh[2]	83.81
Biogas	45	Nm^3	Sugarcane press-mud	0.053	USD/kWh[3]	24.01
Biogas	4.76	Nm^3	Manure	0.053	USD/kWh	1.54
Bioethanol	31.68	L	Sugarcane press-mud	0.521	USD/L[4]	6.44
Hydrogen	1.17	kg	Sugarcane press-mud	8.73	USD/kg[5]	10.21

1 Data obtained from: https://cvn.com.co/importacion-de-fertilizantes-en-colombia-supero-los-620-millones-de-dolares-en-2020/
2 Data obtained from: (Cañon et al., 2022).
3 Data obtained from: https://es.globalpetrolprices.com/Colombia/natural_gas_prices/
4 Data obtained from: https://fedebiocombustibles.com/statistics/#
5 Data obtained from: (Jones et al., 2020).

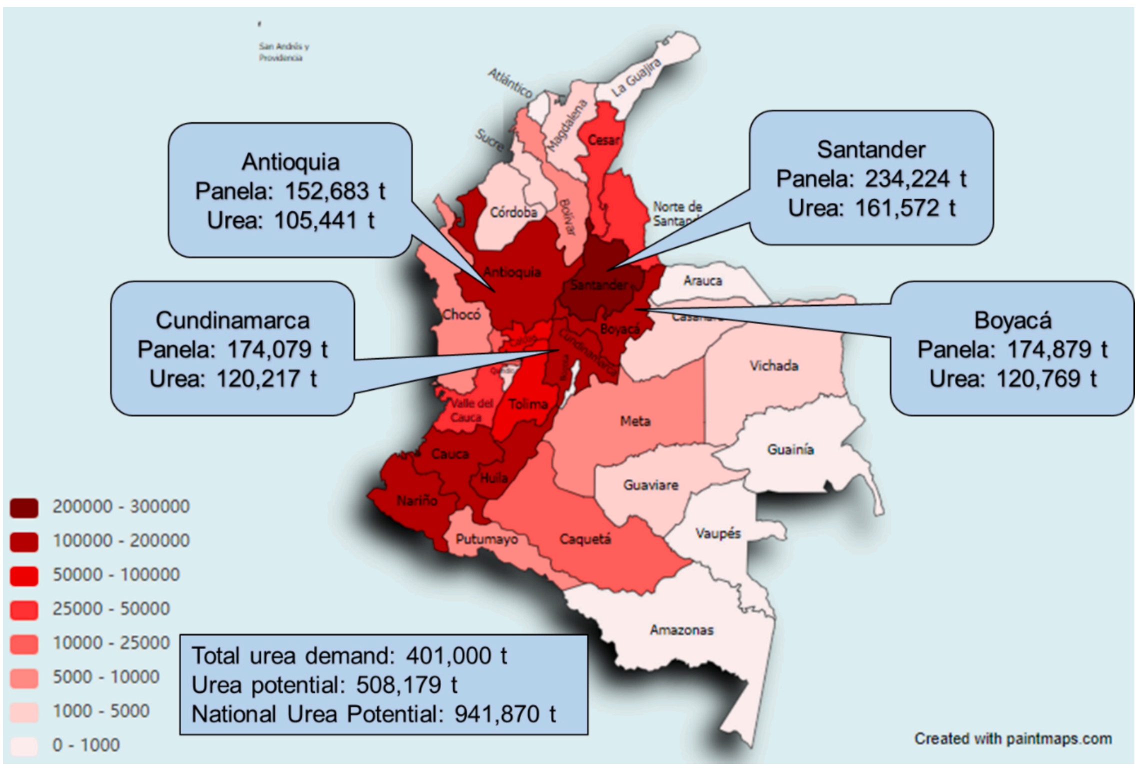

Fig. 8. Urea potential in the Colombia Market from the non-centrifugal sugar industry.

Martha Cobo: Writing – review & editing, Resources, Project administration, Investigation, Conceptualization. **David Rodríguez-Fontalvo:** Writing – review & editing, Methodology, Investigation. **Ruth Y. Ruiz-Pardo:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Anne Roedl:** Writing – review & editing, Validation, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data availability

The datasets generated during or analyzed during the current study are available in the MENDELEY repository, as follows: Sanchez, Nestor (2024), "Data for non-centrifugal sugar production", Mendeley Data, V1, doi: 10.17632/vjtjrjzdtt.1.

Acknowledgment

The authors are grateful to Universidad de La Sabana for the funding through project ING-288-2021. Besides, the authors are grateful to Lorena Guillen, CEO of Panela Don Pedro for gathering the information in the facility.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biteb.2024.101858.

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