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SUCRE

2020

BRA/10/G31
SUCRE
Sugarcane Renewable Electricity

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Project BRA/10/G31

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Sugarcane Renewable Electricity

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Published by:

Sugarcane Renewable Electricity (SUCRE) Project
Brazilian Biorenewables National Laboratory (LNBR)
Brazilian Center for Research in Energy and Materials (CNPEM)

1st edition
Campinas, SP, Brazil
2020

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FOREWORD BY LNBR/CNPEM DIRECTOR

This report summarizes the findings of Project BRA/10/G31 – Sugarcane Renewable Electricity – SUCRE aimed at mitigating greenhouse gas emissions from sustainable biomass utilization for electricity generation in Brazil. The SUCRE results, obtained in partnership with sugarcane mills, contained an in-depth technical feasibility analysis of sugarcane straw-based electricity generation, considering economic, environmental and societal impacts. The expected outcome of SUCRE is an increase in production and commercialization of sugarcane straw-based electricity, thereby displacing electricity generated from fossil-fuels.

The Project was funded by the Global Environment Facility – GEF and implemented by the United Nations Development Programme – UNDP in coordination with the Brazilian Ministry of Science and Technology Innovations and Communications – MCTIC. The executing partner, Centro Nacional de Pesquisa em Energia e Materiais – CNPEM, conducted the Project from 2015 to 2020 through one of its four National Laboratories, Laboratório Nacional de Biorrenováveis - LNBR, formely known as Laboratório Nacional de Ciência e Tecnologia do Bioetanol – CTBE.

Results presented in this report include evaluations of existing technologies and processes aimed at improving equipment and operations based on previously made investments by partner mills. Since dedicated boilers for burning straw are very costly, SUCRE focused on feasibility options for increasing straw utilization in existing boilers. An evaluation of three straw recovery routes indicated that, irrespective of the straw collection system, recovered biomass contained high mineral impurity contents. Thus, attention was devoted to biomass quality, by seeking ways to reduce its mineral impurity contents and to identify adequate straw particle size distribution to enable efficient collection, processing and burning. In addition, SUCRE provided suggestions for improvements in the legal and regulatory framework for electricity commercialization.

The SUCRE legacy website contains an open-access tool for a preliminary assessment of straw-based electricity production and sale, guidelines for sustainable straw recovery based on conservation practices and sugarcane productivity and a tutorial on how to estimate sustainable straw removal. A key lesson learned was the importance of continuous outreach and dissemination efforts that, in about three years, led to increased engagement of the sugar-energy sector. By then, partial SUCRE results were being used as inputs for assessing existing mill operations.

In summary, we expect for the next decade that SUCRE will be perceived as a major contributor to sustainable biomass-based electricity generation in Brazil and that it will have positively impacted other sugarcane growing countries.

Eduardo do Couto e Silva
LNBR/CNPEM Director

ACKNOWLEDGEMENTS

LNBR/CNPEM would like to express our gratitude for the following institutions that contributed to the successful implementation of SUCRE

- Global Environment Facility (GEF)
- United Nations Development Programme (UNDP)
- Agência Brasileira de Cooperação (ABC)
- Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC)
- Ministério de Minas e Energia (MME)
- União da Indústria de Cana-de-açúcar (UNICA)
- Cerradinho Bioenergia S.A.
- Ferrari Agroindústria S/A
- GranBio
- Pedra Agroindustrial S/A
- Raízen Energia S.A.
- São Martinho S/A
- Usina Açucareira Ester S.A.
- Usina Alta Mogiana S.A. - Açúcar e Álcool
- Usina Caeté S/A
- Usina de Açúcar Santa Terezinha Ltda
- Usina Granelli Ltda
- Usina Santa Isabel S/A
- Usina São José da Estiva S/A Açúcar e Álcool
- Usina São Luiz S/A
- Zilor Energia e Alimentos
- Associação Brasileira de Distribuidores de Energia Elétrica (ABRADEE)
- Centre de Coopération Internationale en Recherche Agronomique pour le Développement (Cirad)
- Centro de Investigación de la Caña de Azúcar (Cenicaña)
- Centro Guatemalteco de Investigación y Capacitación de la Caña de Azucar (Cengicaña)
- Estación Experimental Agroindustrial Obispo Colombres (EEAOC)
- Grupo de Motomecanização (GMEC)
- Instituto Agronômico de Campinas (IAC)
- International Society of Sugar Cane Technologists (ISSCT)
- Universidade de São Paulo (USP)
- Universidade Estadual de Campinas (UNICAMP)
- Agrícola BPZ
- Agroquatro-S Experimentação e Consultoria Agronômica Aplicada
- CTC - Centro de Tecnologia Canavieira S.A.
- Dedini S/A Indústrias de Base
- Excelência Energética Consultoria Empresarial Ltda.
- Herbae - Consultoria e Projetos Agrícolas Ltda.
- HPB Engenharia e Equipamentos Ltda.
- Tama Brasil Indústria de Soluções em Embalagens Agrícolas Ltda.
- U.P.P. - Usinagem Industriais Ltda.

ACRONYMS

- **AB1F1S** - Ascending Blowing - 1 Fan - 1 Stage
- **AB2F1S** - Ascending Blowing - 2 Fans - 1 Stage
- **ABINEE** - Brazilian Electrical and Electronics Industry Association
- **ABIOGÁS** - Brazilian Biogas Association
- **ABRACEEL** - Brazilian Energy Traders Association
- **ANP** - Brazilian National Agency of Petroleum, Natural Gas and Biofuels
- **ASTM** - American Society for Testing and Materials
- **ATALAC** - Association of Sugar Technicians in Latin America and the Caribbean
- **B** - Sugarcane bagasse
- **BBEST** - Brazilian Bioenergy Science and Technology Conference
- **BD** - Bulk Density
- **BDAgro** - Agricultural Experiment Database
- **BDGeo** - Geographic Database
- **BNDES** - Brazilian Development Bank
- **BPS** - Bale Processing System
- **BS** - Bagasse and Straw mixture
- **C** - carbon
- **C1, C2, C3** - Configuration 1, Configuration 2, Configuration 3
- **Ca** - calcium
- **CAPEX** - Capital Expenditure
- **CEC** - Cation Exchange Capacity
- **CEISE Br** - Centro Nacional das Indústrias do Setor Sucroenergético e Biocombustíveis
- **CEPEA** - Centro de Estudos Avançados em Economia Aplicada
- **CFD** - Computational Fluid Dynamics
- **Cl** - chlorine
- **CMO** - Marginal Operating Cost
- **CNPEM** - Brazilian Center for Research in Energy and Materials
- **COGEN** - Associação da Indústria de Cogeração de Energia
- **Conab** - National Company of Food Supply
- **CSLL** - Social contribution on net income
- **CTC** - Sugarcane Technology Center
- **db** - dry basis
- **DB2F1S** - Descending Blowing – 2 Fans – 1 Stage
- **DB2F2S** - Descending Blowing – 2 Fans – 2 Stages
- **DC** - Distribution Center
- **DCS** - Dry Cleaning System
- **DEM** - Discrete Element Method
- **DIN** - Deutsches Institut für Normung
- **EBC** - Brazilian Communication Corporation
- **EF** - Emission Factor
- **EPE** - Energy Research Office
- **ESTEC** - Expected Short-Term Economic Cost
- **EUBCE** - European Biomass Conference and Exhibition
- **FAPESP** - São Paulo Research Foundation
- **FCE** - Free Contracting Environment
- **fiber%cane** – fiber content in sugarcane (g/100g, wb)
- **GEF** - Global Environment Facility
- **GHG** - Greenhouse Gas
- **GIS** - Geotechnologies
- **GL** - billion liter
- **Gt** - billion ton
- **GW** – 10^9 W
- **H** - hydrogen
- **H+Al** - soil potential acidity
- **ha** – hectare (10,000 m^2)
- **HHV** - Higher Heating Value
- **HR** - High Removal
- **ICB** - Expected Cost Benefit Index
- **ID** - Information Dissemination
- **IEM** - Inorganic Extraneous Matter
- **IPCC** - Intergovernmental Panel on Climate Change
- **IRPJ** - Income tax
- **IRR** - Internal Rate of Return
- **ISSCT** - International Society of Sugar Cane Technologists

- **K** - potassium
- **kg** - kilogram
- **kW** - kilowatt (1000 W)
- **kWh** - kilowatt hour
- **L** - liter
- **LCA** - Life Cycle Assessment
- **LHV** - Lower Heating Value
- **LIMS** - Laboratory Information Management System
- **LNBR** - Brazilian Biorenewables National Laboratory
- **LR** - Low Removal
- **LUC** - Land Use Change
- **M** - Mill
- **M&E** - Monitoring and Evaluation
- **MaP** - Macroporosity
- **MAPA** - Brazilian Ministry of Agriculture, Livestock and Food Supply
- **MBC** - Microbial Biomass Carbon
- **MCTIC** - Ministry of Science, Technology, Innovations and Communications
- **Mg** - Magnesium (also Mg = 1 Metric Ton)
- **MI** - Mineral impurities
- **MiP** - Microporosity
- **ML** - million liter
- **MME** - Ministry of Mines and Energy
- **Mt** - million ton
- **MW** - 10^6 W
- **MWD** - Mean Weight Diameter
- **N** - nitrogen
- **n.d.** - Not detected
- **Na** - sodium
- **NEPA** - Nucleus of Studies and Research of Food
- **NG** - Natural Gas
- **NPV** - Net Present Value
- **NR** - No Removal
- **OPEX** - Operational Expenditure
- **P** - phosphorus
- **PAC** - Project Advisory Committee
- **Pb** - lead
- **PECEGE** - Continuing Education Program in Economics and Agribusiness Management (Programa de Educação Continuada em Economia e Gestão de Agronegócios, in Portuguese)
- **pH** - hydrogenionic potential
- **pol%cane** – sucrose content in sugarcane (g/100g, wb)
- **PROINFA** - Programa de Incentivo às Fontes Alternativas
- **R** - Restricted
- **RCE** - Regulated Contracting Environment
- **ROC** - Rotating Octagonal Cylinder
- **S** - Sulfur
- **Sa** - Sample
- **SAZ** - Sugarcane Agroecological Zoning
- **SC** - Spontaneous Combustion
- **SDG** - Sustainable Development Goals
- **Sm** - Straw Fraction in Mixture
- **SOC** - Soil Organic Carbon
- **SOM** – Soil Organic Matter
- **SRP** - Soil Resistance to Penetration
- **STAB** - Sociedade dos Técnicos Açucareiros e Alcooleiros do Brasil
- **SUCRE** - Sugarcane Renewable Electricity
- **t** - metric ton
- **TC** - metric ton of cane stalks
- **TCT** - Technical Coordination Team
- **TECNICAÑA** - Colombian Association of Sugarcane Technicians
- **TR** - Total Removal
- **TW** - 10^{12} W
- **U** - Unsuitable
- **UDOP** - National Union of Bioenergy
- **UNDP** - United Nations Development Programme
- **UNICA** - Brazilian Sugarcane Industry Association
- **VSB** - Virtual Sugarcane Biorefinery
- **W** - Watt
- **wb** - wet basis
- **yr** - year
- **Zn** - zinc

1. PREFACE

Author: *Manoel Regis Lima Verde Leal*

To understand the motivation and structure of the SUCRE Project it is worthwhile reviewing the recent history of Brazilian Sugar-Energy and Electric Energy sectors, considering their context, their synergies and how they have been interlaced.

THE BRAZILIAN SUGAR-ENERGY SECTOR

The Brazilian sugar-energy sector evolved rapidly during the first decade of the twentieth first century, after 15 years of stagnation and motivated by the fast increase in oil prices and the growing success of the country as a sugar exporter. From 2000 to 2010, sugarcane, sugar and ethanol production increased by 364 Mt (142%), 21.8 Mt (135%) and 16.8 billion L (159%), respectively. These quantities leveled out after 2010 (*Table 1*), with oscillations attributed to changes in weather conditions and sugar and ethanol market demands.

Product	2000/01	2005/06	2010/11	2015/16	2017/18	2018/19
Sugarcane (Mt)	256.8	385.1	620.4	666.8	641.0	620.8
Sugar (Mt)	16.2	25.8	38.0	33.8	38.6	29.0
Ethanol (Gl)	10.6	15.8	27.4	30.2	27.9	33.1

Sources: MAPA (2015) and Conab (2019)

Table 1: Sugarcane, sugar and ethanol production (2000-2019).

The 2008 world financial crisis occurred when the sector had high debt levels due to investments of its expanding years. As a consequence, after 2010, there was deterioration of good management practices and reduction of sugarcane yields and quality, that contributed to deepen the effects of the crisis in the sector that lasts until today. On the positive side, we can point out that this great expansion of the sugar-energy sector brought modernization and efficiency gains to the industrial sector and, due to smart policies from the Brazilian Development Bank (BNDES), the new mills (and old ones who were retrofitted) adopted efficient high pressure boilers and turbogenerators (BNDES, 2011). Nowadays the core of the problems resides in the agricultural area of mills leading to low sugarcane yield and quality. According to the Sugarcane Technology Center (CTC, 2011) the percentage of sucrose in cane (pol%cane) decreased from 14.0-14.5% to 13.0-13.5% and the percentage of fiber (fiber%cane) increased approximately 0.9% from 1988 to 2010, probably due to the accelerated rate of introduction of mechanical harvesting of sugarcane in the Center-South region.

One important characteristic of Brazilian sugar-energy sector is its production flexibility. Since the second half of 1970s it has been producing different proportions of ethanol and sugar depending on market demands. For some time, this flexibility allowed, in most mills, to alternate production of sugar and ethanol between 40% and 60% for either product. Lately, this range has expanded, and some mills were able to use up to 100% of the sugars to ethanol production. This flexibility increases the resilience of the sector to volatility in international sugar and oil prices, which frequently brings the sugar prices to levels below the production costs. This happened from 2017/2018 to 2018/2019 harvesting seasons when the production of sugar/ethanol went from 37.8 Mt/27.2 GL to 29.0 Mt/33.1 GL, leading to a reduction of sugar of 8.8 Mt and to an increase of ethanol of 5.9 GL, that may have prevented the collapse of the international sugar market. This variation was possible changing the percentage of sugarcane directed to sugar production from 45.9% to 34.9 % (Conab, 2019).

During this expansion environmental laws were enacted to prohibit preharvest burning of the sugarcane and there was shortage of labor in the new cultivated areas. As a result, there was an accelerated growth of sugarcane mechanized harvesting without burning, hereafter green cane harvesting practice, which contributed to aggravate the problems of soil compaction, ratoon damage and higher harvest cane losses at the mills. The green cane harvesting practice results in large amounts of sugarcane straw left on the ground, with clear benefits to the sugarcane fields, such as, increase in soil organic matter (SOM), protection against erosion, some weed control, nutrient recycling and others. On the other hand, the straw mulch increases the risk of accidental fires, inhibit sprouting in colder regions and favors proliferation of pests. On the industrial side of the mill, green cane harvesting increased the amount of extraneous matter processed together with the sugarcane milled in the industry, leading to sugar losses due to bagasse carryover, reducing the throughput of the milling tandem or diffuser due to additional fiber, and decreasing the quality of the juice and, possibly, of final sugars as demonstrate by Kent et al. (2010) in Australia. It is worthwhile mentioning that the huge amount of agricultural residues – straw – that is available creates the opportunity to use it as raw material for production of cellulosic ethanol (second generation) and additional electricity production, making it a natural extension to bagasse, already in full use.

In summary, (1) Brazil can rapidly expand sugarcane production, as well as sugar and ethanol (in just 10 years the sugarcane production increased from 257 Mt to 620 Mt, or 363 Mt, that is approximately the size of an average annual crop of India, the second largest producer in the world); (2) the country can vary the production of ethanol and sugar in significant amounts, which can positively affect the international sugar market.

It is important to point out that the Brazilian sugar-energy sector has reached a high level of efficiency in the conversion of the sugars in the sugarcane into sugar and ethanol. Data provided by Conab (2019) allow to estimate that the average industrial efficiency is around 85%, a very high value considering inevitable losses in the juice extraction and fermentation processes. However, the efficiency of converting the primary energy of sugarcane in the fields to final products in the mills (sugar, ethanol and electricity) barely reaches 30%, 32% in the best mills (Leal et al, 2012). The main reason is the low attention paid to the fibers of sugarcane: bagasse is inefficiently consumed in most mills (with high levels of process steam consumption and use of inefficient boilers for burning) while straw is left on the ground for agronomic benefits and because there is no commercial use for it. Currently, only few mills recover straw to generate surplus electricity and this is normally done using small quantities of straw, typically around 10% of the biomass fed into the mill boilers.

THE BRAZILIAN ELECTRIC ENERGY SECTOR

In 1995 the Brazilian electric energy sector was subjected to privatization. This resulted in decrease of government participation in a significant way, especially in generation, distribution and commercialization of new energy, while the transmission sector remained the only one with strong government participation.

Inadequate planning and a drought in 2001 forced the Brazilian government to stablish an approximate reduction of 20% in the electric energy consumption in the country. The Government also created a program to increase thermal power generation with natural gas (NG), coal and fuel oil to reduce the high dependency on hydro power (75% in 2002). As an additional effort to diversify the Brazilian electric power generation, a Program to Incentivize Alternative Sources of Electric Energy (PROINFA) was created on 26 April 2002 with differentiated tariffs for 3,300 MW of total installed capacity of renewable sources equally divided among wind, small hydro and biomass power plants.

In 2004 the new Regulatory Framework of the Electric Sector was established. This led to two main electric energy contracting environments: Regulated Contracting Environment (RCE) and Free Contracting Environment (FCE). In the former, the electric energy contracting process is based on auctions organized by the Government while in the latter the contracting is decided by direct negotiation between generator and consumer. Since 2017, there has been discussions about changes in the Regulatory Framework aiming to modernize it and to attempt to solve problems that plague the present system.

Despite the effort of the Brazilian government to reduce participation of hydroelectricity in the electricity supply matrix (636 TWh total in 2018) this is yet, and by far, the main contributing source representing 66.6% of the total supply, followed by 14.2% of fossil thermal power plants (mainly natural gas – NG), 8.5% of biomass and 7.6% of wind power (EPE, 2019). This matrix of electricity generation maintains the contribution of renewable sources at 83.3% of the electricity supply in the country. Due to the increase of the intermittent renewables (wind and solar) in the electric matrix, in conjunction with the reduction in size of the reservoirs of the new hydro plants, more backup power will be required, mainly during the dry season, which creates new opportunities for dispatchable sources such as natural gas and biomass. In this respect, biomass is in direct competition with natural gas.

BIOELECTRICITY FROM SUGARCANE

The sugar-energy sector is an energy intensive sector. It demands large amounts of thermal energy in the form of low-pressure process steam and a smaller amount, but still significant, of electro-mechanical energy, which is required to drive several large equipment such as cane preparation shredders, juice extraction milling tandem, boiler exhaust fans and pumps. Fortunately, bagasse, the byproduct from the juice extraction process, is more than enough to provide fuel for the energy system of the mills that operates in the very efficient cogeneration mode, although mostly with inefficient boilers and turbogenerators in the older mills. In the mid-1990s, Brazilian sugarcane mills reached self-sufficiency in electricity, and the most efficient ones began to generate surplus electricity for sale. The surplus power injected in the Brazilian National Grid by the sugar-energy sector grew from 8.8 TWh in 2010 to 21.5 TWh in 2018, representing 2.1% and 4.6% of the national electricity consumption, respectively. If the electricity generated for self-consumption is included, the participation of sugarcane electricity increases to 8.3% (UNICA, 2019). The authorized installed capacity in the mills was 11,424 MW, corresponding to 77% of total biomass authorized capacity. In 2017, there were 200 mills selling electricity (54%) out of the 369 mills in operation. The electricity generation and consumption, the average number of total generation, self-consumption and surplus electricity in 2017 were 55.6, 22.2 and 33.4 kWh per ton of cane processed by the mill (kWh/tc), respectively (UNICA, 2018). Considering that only about 54% of the mills in operation currently sell electricity and that they are near the technical limit using only bagasse, new improvements in energy efficiency in the mills and/or an additional fuel will be required to expand electricity generation. When considering supplementary fuel to bagasse, sugarcane straw appears to be a natural candidate. It is produced not too far from the generating plants, seems similar to bagasse and its production is normally controlled by the mill. Extending the power generation by the mills also offers the possibility to generate part of the surplus electricity during the cane harvesting off-season improving the quality of the electricity in terms of dispatchability and power factor and making better use of the installed equipment (boiler and TG's). It seems also a good alternative for the increasing number of mills that are annexing corn ethanol distilleries and need to import electricity or to generate the energy needed using fossil fuels or wood chips.

In summary, it may seem obvious that to recover straw to increase power generation is a good economic alternative for existing and future mills. However, the present use of sugarcane straw for surplus power generation in the mills is frustratingly small, when considering the number of mills involved and the percentage of the available straw currently used. There has been more than two decades of interest in straw. Nevertheless, since the initial experimental studies to recover and use straw (Ripoli, 1991; Hassuani et al, 2005) there has been a high level of optimism, but expectations have not been met for this potential new fuel.

THE SUCRE PROJECT

The SUCRE Project (Project BRA/10/G31) was conceived by CTC, as a follow-up of a similar project (BRA/96/G31) that studied the use of sugarcane residues to generate power with advanced technologies (Hassuani et al., 2005). SUCRE intended to make viable the use of straw in conventional systems in the mills using steam cycle. The project was approved by GEF at the end of 2010, but a few months later CTC became a for profit organization and no longer eligible to receive GEF grants. UNDP searched for another Executing Partner and selected LNBR (then CTBE)/CNPEM. The Project is aimed at promoting renewable power generation by the sugar-energy sector by increasing the use of sugarcane straw to supplement bagasse in the existing mills. To accomplish that, one must identify and provide ways to overcome barriers that are hampering a widespread use of straw by mills. This is organized in the following outcomes:

1

Technology for sugarcane straw collection and conversion for electricity generation made operational for commercial use.

2

The economic viability of sugarcane straw collection and utilization for electricity generation demonstrated in commercial sugar mills.

3

The effects of straw collection on the cultivation and harvesting cycle addressed to ensure environmental integrity and long-term sustainability.

4

Sugarcane straw utilized across the sugarcane sector with private investment taking benefit from lessons learned.

5

An adequate Legal and Regulatory Framework in place to promote sustainable use of sugarcane straw for electricity generation and sales to the grid.

In addition, there are two additional non-technical outcomes: O6 - Project monitoring, learning, adaptive feedback and evaluation, implemented by UNDP; and O7 - Project Management, executed by LNBR/CNPEM.

The main goal of the SUCRE is to reduce the greenhouse (GHG) emissions through the increase of renewable electricity in the Brazilian National Grid.

To that end, it was paramount to assess after many years of tentative use of sugarcane straw as a supplement to bagasse to increase surplus electricity generation, why this has not been largely adopted. One identified barriers that were hampering the process such as, lack of reliable information in technical, economic, environmental and social areas, problems in the legal and regulatory framework of the electric sector and the most sensitive areas for sustainable sugarcane straw collection and use for power generation.

After this first evaluation, studies and evaluations were concentrated in the Center-South Region of Brazil where more than 90% of the sugarcane is produced, where mechanized harvesting has reached 96%. The SUCRE Project Outcomes are detailed below:

I. REMOVAL: identify how much straw are there in the cane fields, what are the impacts of straw mulch on the soil health and sugarcane yields and what is the minimum amount of straw that must remain on the ground to maintain soil health and sugarcane yields.

What makes these questions more challenging to answer is that they depend on the local soil and climate conditions, sugarcane varieties, age and renovation of cane field, time of harvest, and management of tilling operations. Besides, the straw mulch has impacts on sugarcane yields, nutrient recycling, soil texture, soil carbon stock, soil erosion, soil biology, soil GHG emissions, pest infestation, weed control, among others. Another important impact of the straw mulch is on the water balance (infiltration, evaporation and runoff). Despite all difficulties, SUCRE made a broad set of evaluations of these impacts. It started by a comprehensive literature review to identify the existing knowledge and gaps on each topic, to orient experimental testing, taking into account that, whenever possible, SUCRE results would be compared with those form other experiments, if differences in methodologies could be reconciled. In total, there were 32 field experiments design to cover all aspects previously mentioned. SUCRE investigated different amounts of straw left on the ground, ranging from zero to 15 ton/ha of straw, on a dry basis (db). The experimental sites encompassed a wide variation of soil types, climate conditions and cane varieties and tests were conducted for a full sugarcane cycle, normally around five cuts in Brazil.

The methodology and main results are presented in a summarized way with reference to technical articles and reports.

The main product of this Removal is a set of ***Guidelines for Strategic Straw Recovery*** to improve the sustainability of the process. The methodology to prepare straw recovery maps by the mills, based on their specific cane fields and management practices, and following the Guidelines, can be made available to any interested mill.

II. RECOVERY: the question here is how can straw be recovered, transported, stored, processed and burned in the bagasse boilers? The studies include mass, energy and GHG emissions balances, economic evaluations and straw quality parameters especially the ash content (mineral impurities plus biomass constituent ashes) along the value chain.

This was implemented by partnering with four mills already experienced in straw collection and use. There were three different recovery routes: (1) Hay Harvester (Mill A), (2) Baling (Mill B and Mill C) and (3) Integral Harvesting (Mill C and Mill D). For the latter, straw is transported to the mill entrained in the cane billets increasing the vegetal impurity index in the load. This is achieved by reducing the rotation speed of the harvester primary extractor to reduce the cleaning effect and allow more straw to be loaded with the cane. The straw arrives at the mills with high level of mineral impurities in all routes and with a coarse particle size distribution, so it must be processed in the factory before it can be mixed with bagasse and fed into the boilers. For the Hay Harvester route, there is no straw processing at the factory. To improve the performance of Route 3 SUCRE developed a fourth route, a variation of Route 3, with a straw shredder installed in the outlet of the harvester primary extractor to reduce the size of the straw pieces and to increase the density of the cane/straw load, with a high vegetal impurity content. Besides increasing the cane load density, it was expected that it would increase the efficiency of the Dry Cleaning System (DCS) installed at the factory, to separate the straw from the cane billets and reduce the amount of fiber of the cane milled.

Analysis of Routes 2, 3 and 4 based on simulations considered a typical cane field (50,000 ha of cultivated area, 77 tc/ha average cane yield) and a collection of 100,000 tons of straw per year (dry basis, db) assuming three different recovery rates (2, 3 and 4 ton of straw per hectare, db). Recovery costs, energy consumption and GHG emissions were estimated for all cases and the main parameters impacting the results were assessed. Computational fluid dynamics (CFD) was shown to be a powerful a tool to improve the performance of the existing DCSs and the straw shredder.

In the early stages of the Project, a literature review on the use of straw as a boiler fuel for power generation suggested that it was considered equal, and sometimes better, compared to bagasse. Standard analyses for solid fuels (Proximate Analysis, Ultimate Analysis, Higher and Lower Heating Values, Ultimate Mineral Analysis), according recognized international standards (ASTM and DIN), indicated similar values for both bagasse and straw (Hassuani et al., 2005). Higher amounts of potassium (K), chlorine (Cl) and sulfur (S) in straw, compared with bagasse, was acknowledge in

(Hassuani et al., 2005), but given the low concentrations of these three elements there was reduced interest in them. Since samples were collected in the standing sugarcane before harvesting, in that reference, the ash concentrations were similar to bagasse. When straw collection began with the purpose of supplementing bagasse as fuel, one noticed that the ash content in straw samples was considerably higher than that in bagasse and high erosion in some parts and components of the boilers were observed and associated with straw use blended with bagasse. As the straw fraction in the biomass fed into the boilers increased, problems of choking in the boiler fuel feeding valves became more frequent. For the four SUCRE partner mills of Batch 1, where straw collection and use technologies were tested, one identified the following characteristics: Mill A (Route 1 – Hay Harvester) did not process straw at the factory; Mill B (Route 2) used only a straw shredder; Mill C (Routes 2 and 3) used a complete straw processing system with rotary screen type sieve for reduction of mineral impurities (MI) and a shedder; and Mill D (Route 3) employed a complete system consisting of rotary screen and shedder. With the deficiencies noticed in all four partner mills, the SUCRE team sought well-designed systems in other mills that could be considered as reference for the existing technologies. The tests in the four partner mills (Batch 1) and in other mills with different designs were summarized with an intent to identify limitations of existing technologies and main bottlenecks. SUCRE performed boiler tests in partner mills that operated with different designs and different percentage of straw in the biomass fed into boilers. Results showed elevated levels of erosion, corrosion, deposits and slagging. The results of these tests are also presented in this report.

III. **ENVIRONMENTAL IMPACTS:** the main environmental impacts of sugarcane production expansion and straw recovery evaluated in SUCRE were those resulting from land use change (LUC), straw removal and sugarcane management changes. GHG emissions, water balance, deforestation and soil health are the main ecosystem services under focus.

The impacts of straw removal on soil health and GHG emissions were studied in the **REMOVAL** activities and the results were further explored in **RECOVERY**. These were used in the simulation of the straw power generation in the Batch 2 partner mills (eight mills), where different alternatives were evaluated.

This report also discusses environmental and social impacts related to sugarcane straw collection and use and the associated land use change (LUC). This evaluation benefited from several studies of the effects of the LUC associated to past and future sugarcane expansion regarding water resources, deforestation, GHG emissions and social effects.

The evaluation of two alternatives, for each of the two of the eight Batch 2 mills selected, are discussed considering economic feasibility and GHG emissions.

IV. DISSEMINATION OF INFORMATION: consists of the application of lessons learned in the other project outcomes to demonstrate technical and economic viability of straw collection and use, to increase power generation. An example of this activity is presented here, as two case studies for two of the partner mills of Batch 2. In addition, the SUCRE team decided to expand the concept of Dissemination of Information to reach the sugar-energy sector in Brazil, and abroad. Central to this process was the Project Website created to facilitate access to SUCRE information and products. SUCRE also developed and implemented three databases to assure easy storage and traceability of a large amount of data, which includes results from laboratory analyses, field tests, project simulations, among others:

- **e-LN LIMS:** is a laboratory platform customized to organize and store all data generated by the analytical laboratories,

- **Agricultural Experiment Database (BDAgro):** all data generated in the field experiments,

- **Geographic Database (BDGeo):** georeferenced information to integrate field and spatial data.

Project results were presented to the general and specialized public interested in sugarcane straw, through workshops, seminars and congresses, articles in technical journals, newsletters, booklets, videos and flyers. Each set of tests executed in partner mills generated at least one technical report that was sent to the respective mill for review.

SUCRE also released a calculator, which is a virtual simulation open-access tool on the Project's website (https://lnbr.cnpem.br/palhacalc-sucre/) and represents one of the main SUCRE's legacies. The tool generates a report that provide users with the main assumptions for agricultural, industrial, economic evaluation, equipment used, and costs used for the simulations for straw collection and use for electricity production. This is not only open access, but the tool is based on all the scientific and technological knowledge acquired during the five years of the SUCRE Project.

V. LEGAL AND REGULATORY FRAMEWORK: the main goal here is to suggest improvements to overcome the present barriers that hamper the increase of surplus electricity generation by the mills. This task was coordinated by UNICA (Brazilian Sugarcane Industry Association). A consulting company specialized in the electric energy market was contracted to evaluate the bottlenecks and key areas for searching improvements and suggesting the next steps. In 2017, the Brazilian government issued a public call for comments on the existing version of the Legal and Regulatory Framework of the electric sector. SUCRE provided inputs, but the governmental process has not yet been completed as the Brazilian government signals deep changes toward modernizing the entire system.

VI. PROJECT MONITORING, LEARNING, ADAPTIVE FEEDBACK AND EVALUATION: this is the follow up of the Project development in terms of milestones and budget.

The project Monitoring and Evaluation (M&E) was conducted throughout the project development in accordance with established UNDP and GEF procedures. The intent was to provide a clear view, during the project execution, of the status towards meeting project objectives and product development, to provide inputs to the project team, UNDP Country Office and UNDP/GEF to evaluate progress, identify critical issues and implement corrective actions.

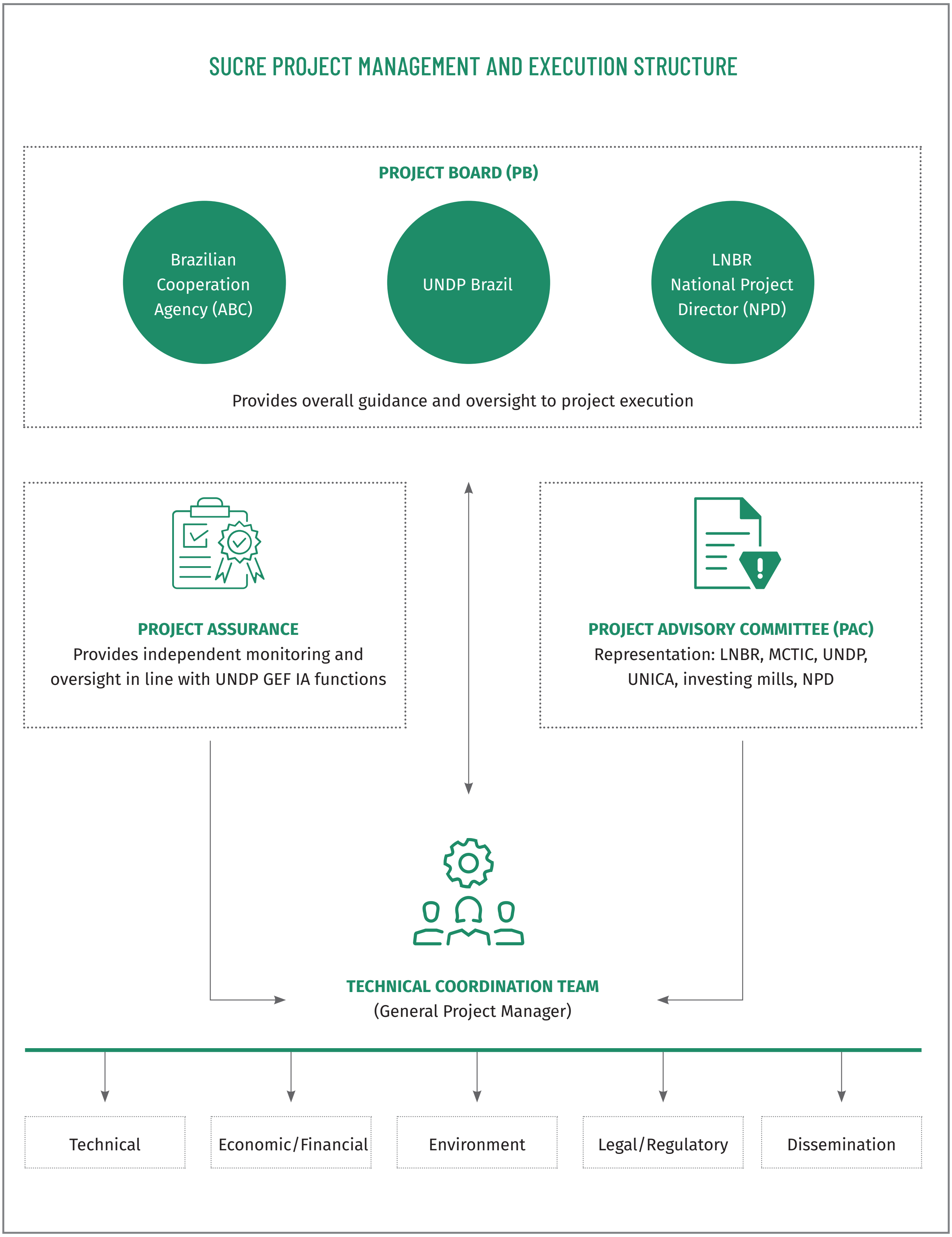
FINAL COMMENTS

This Final Report is intended to give an overview of the SUCRE Project structure and summarize the main results to facilitate the access to relevant information for mills interested in collecting, processing and using sugarcane straw in boilers designed for bagasse firing, aimed to increase renewable power generation in the Brazilian sugar-energy sector. The expected benefits to the country will be the reduction of greenhouse gas (GHG) emission to contribute to its commitments to the Paris Agreement and to the sugar-energy sector interests to increase resilience by enabling the production of a third product (electricity) with significant weight in the total revenues of mills.

The context of the sugar-energy sector of the Brazilian electric energy sector were briefly described to facilitate the understanding the benefits of sugarcane straw. The extent and scope of the Project and its limitation can be perceived by those familiar with both sectors.

2. GOVERNANCE

Authors: *Thayse Aparecida Dourado Hernandes, Manoel Regis Lima Verde Leal*



The Brazilian Biorenewables National Laboratory (LNBR), which is a National Laboratory of the Brazilian Center for Research in Energy and Materials (CNPEM), and the United Nations Development Programme (UNDP) were partners on the project management working as Global Environment Facility (GEF) implementing agencies. LNBR was in charge to coordinate the project through a Technical Coordination Team (TCT) consisting of a National Project Director, a General Project Manager, a Technical Manager, a Financial Manager, an Environmental Manager, a Legal Manager and a Dissemination Manager. The team was responsible for overseeing the day-to-day implementation of Project activities, the project's operational planning, the administrative and financial management and the adaptive management of the Project. UNDP performed the Monitoring and Evaluation during the Project development through independent evaluations and independent audits during all the project development (Project Assurance).

The Project Board (PB) provided the overall managerial guidance for project execution: (i) Analyzed and discussed the development of the Project activities and recommend changes as required based on project monitoring and evaluation processes and products and in line with GEF and UNDP policies; (ii) Discussed and approved the Annual Work Plan ensuring that required resources are committed; (iii) Discussed and approved the Progress Reports and Final Report of the Project; (iv) Analyzed Project achievements and assure these used for performance improvement, accountability and learning; and (v) Settled controversies arbitrating on any conflicts within the project or negotiating a solution to any problems with external bodies. UNDP represented the project ownership, chairing the PB and organizing its meetings at least once a year or upon request of either of the Parties. The Brazilian Cooperation Agency (ABC) as the agency in charge of international technical cooperation involving Brazil and international organizations, was responsible within the Brazilian government for following up the activities stem from this project; and LNBR/CNPEM, as an executing partner, represented the parties that provided funding for cost-sharing and led the technical expertise and guidance to the project.

The Project Advisory Committee (PAC) provided political and technical advice and guidance through periodic meetings. Representation on the PAC included LNBR/CNPEM, UNDP, mills that were funding partners, the Brazilian Sugarcane Industry Association (UNICA), the Brazilian government (MCTIC), the NPD and the General Project Manager. Government representation on the PAC was designed to ensure that the project was kept abreast of and maintained consistency with current policies and evolving national strategies and priorities. The PAC met annually to review project activities and analyze the process and results of implementation to guide execution of the remaining Project actions. It also identified and monitored adaptive measures to correct problems identified during project implementation and supported the incorporation of experiences and lessons learned generated by the project into national public policy.

METHODOLOGY USED: FIELD TESTS AND EVALUATION IN PARTNER MILLS

Project activities were conducted by a multidisciplinary team of more than 60 professionals of diverse background ranging from agricultural and food engineering, chemistry to mechanical and process engineering at LNBR/CNPEM. Activities began with an initial survey of the available literature to guide the design of extensive field experiments and transportation and industry tests. These included assessments of the agro-environmental impact of straw in the field and of the performance of equipment used for sugarcane straw recovery, processing and burning.

SUCRE's implementation plan was performed in two phases: one with in-depth and broad studies on agro-environmental impacts, technological challenges and economic feasibility of straw recovery and use in four sugarcane mills, known as Batch 1; and in at least seven other mills, known as Batch 2, which applied knowledge acquired in Batch 1 to carry out economic feasibility and environment studies of sugarcane straw recovery and use for electricity production.

LNBR/CNPEM and UNICA, with technical support of a consulting company, also conducted a study on legal and regulatory framework to identify and suggest improvements on it to favor sugarcane biomass-based electricity production and sales. The Project partnered with sugarcane mills and sugarcane farmers in Brazil to identify problems faced throughout the entire process of recovery, processing and burning straw to generate electricity.

3. SUCRE RESULTS

This report is outlined as follows: (i) agricultural systems discusses the impact of straw removal on the soil quality, on soil nutrient losses and erosion, on soil carbon stocks and GHG emissions, and on sugarcane yields; (ii) agronomic routes for straw recovery assessed performance of the recovery systems regarding costs, energy, GHG emissions, and the quality of the raw material; (iii) industrial processing addresses receival of straw at the processing unit, storage issues, pre-processing and burning at boilers, considering existing solutions and alternative adjustments on them to a proper conditioning of sugarcane straw ; (iv) guidelines brought a step-by-step process to support straw removal planning at the mills by considering the combined effects of the straw blanket width and climatic conditions on soil conservation and sugarcane yields; (v) assessments of case studies aimed to address sugarcane straw removal, processing and burning regarding techno-economic and environmental issues; (vi) customized assessment evaluated case studies considering the techno-economic feasibility for different scenarios of sugarcane straw collection and use for electricity production for two partner mills; (vii) Country level environmental and social impacts assessed the Brazilian potential impacts of a country-wide sugarcane biomass-based electricity production; (viii) herein authors highlighted issues and possible adjustments to the legal and regulatory framework of the Electric Sector in Brazil to foster biomass-based electricity production and commercialization; and finally, (iv) the dissemination section describes the Project's legacy and presents tools and consolidated knowledge produced during project development.

3.1 AGRICULTURAL SYSTEMS

Authors: *Guilherme Adalberto Ferreira Castioni, Lauren Maine Santos Menandro, Sérgio Gustavo Quassi de Castro, Leandro Carolino Gonzaga, Sarah Tenelli, Ricardo de Oliveira Bordonal, João Luís Nunes Carvalho*

The following sections discuss the main results of straw removal on soil quality indicators (physical, chemical and biological), soil and nutrient loss by erosion, soil greenhouse gas emissions and sugarcane yield. Following that, one describes three main agronomical routes for recovering, including hay harvester, baling and integral routes and a fourth route proposed by SUCRE, in which straw is shredded within the integral harvesting route. In addition, there is section on costs, energy and greenhouse emissions from straw removal.

3.1.1 AGRONOMIC AND ENVIRONMENTAL IMPLICATIONS OF STRAW REMOVAL

Globally, sugarcane (*Saccharum* spp.) stands out as a crop with a potential to mitigate greenhouse gas (GHG) emissions. Sugarcane-derived products are considered promising renewable energy alternatives to petroleum-based transport fuels and are recognized for its potential ability to emit less GHG in the life cycle and avoid negative impacts on food security and biodiversity (Bordonal et al., 2018). Brazil is the largest world producer of sugarcane, harvesting 620 million tons in 2018 with a production of 33 billion liters of bioethanol and 29 Mt of sugar from a harvested area of 8.7 million hectares (Conab, 2019).

In the last decades, concerns about the sustainability of sugarcane cultivation under pre-harvest burning in Brazil has led to major changes in crop harvesting practices and burned manual harvesting has been gradually replaced by a green mechanized system, Currently, this new system comprises 96% of the cultivated areas in Center-South Brazil (Conab, 2019). Such transition over the last decade has resulted in the deposition of large amounts of straw (10-30 Mg ha^{-1}) on sugarcane fields (Menandro et al., 2017).

The deposition a of large amount of straw on soil surface has influenced the dynamics of sugarcane production in several aspects, including yields (Carvalho et al., 2019), nutrient recycling (Cherubin et al., 2019), soil compaction (Castioni et al., 2019), soil carbon (C) stocks (Tenelli et al., 2019), GHG emissions (Gonzaga et al., 2019), soil erosion (Martins Filho et al., 2009), soil biology (Menandro et al., 2019), pest infestation (Castro et al., 2019), weed control (Hassuani et al., 2005), among others. While straw mulching may benefit the long-term soil quality and crop productivity, such residue also represents a valuable feedstock for bioenergy production and enables new opportunities for the Brazilian sugarcane industry. However, there is, currently, a lack of comprehensive studies that provide technical information about the recommendable amount of straw that can be removed from the fields taking into consideration all these aspects. The balanced combination of these aspects will surely help to promote a more profitable and sustainable sugarcane production chain.

The SUCRE Project aimed at providing scientific-based data to the sugarcane sector to support the decision-making process on straw management, establishing a rational plan to remove the straw from the field without compromising soil health, GHG emissions, and sugarcane yield. Based on this, SUCRE hypothesized that straw has a relevant role in sustaining soil health and plant growth, and therefore excessive straw removal could result in substantial losses of sugarcane yield. To test this hypothesis, SUCRE conducted a broad field experiment network aimed to investigate the effects of straw removal on soil quality indicators, GHG emissions, and sugarcane yield in Center-South Brazil. A set of 32 field experiments was conducted for multiple evaluations of soil health, GHG measurements, and crop yield response to straw removal management in contrasting conditions of soil and climate in Center-South Brazil. In addition to field experiments, they used published data from similar experiments conducted in the same regions to increase the number of observations and to provide a more robust and reliable information at regional scales.

3.1.2 IMPACTS ON SOIL PHYSICAL QUALITY

The maintenance of crop residues on soil surface is recognized as a strategy to improve soil physical attributes. Consequently, the removal of sugarcane straw for bioenergy production can compromise soil physical quality and crop yield. The objective of this study was to assess the four-year effects of straw removal on soil physical quality in areas under contrasting soil conditions. This study included four sites, two under clayey and two under sandy soil conditions. Undisturbed soil samples were collected (*Figure 1*) to measure the following soil physical attributes: soil resistance to penetration (SRP), bulk density (BD), mean aggregate diameter (MWD), and macro (MaP) and microporosity (MiP). More details about the methodology and the main results of this study can be found in Castioni et al. (2019).

Figure 1: Soil sampling for the assessment of soil physical attributes affected by straw removal.

The results showed that straw removal promoted significant increases in SRP and BD in the 0-0.40 m soil layer. The treatments were established as NR (no removal), LR (low removal), HR (high removal) and TR (total removal), corresponding to the maintenance of 15, 10, 5 and 0 Mg ha^{-1} of dry straw on soil surface, respectively. In clayey soil 1, the average SRP in the TR treatment was 28% and 41% greater than in LR and NR, respectively (*Table 2*). A similar pattern was observed in clayey soil 2, with increases of 25% and 42% in TR as compared with LR and NR, respectively. In sandy soils, significant increases in SRP were observed in HR and TR. High values of BD were observed for the TR and HR treatments (0-0.40 m depth), in clayey and sandy soils (*Table 2*).

Table 2. Effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil bulk density (BD) and soil resistance to penetration (SRP) in the 0–0.40 m layer in clayey and sandy soils.

Removal rates	Clayey_1	Clayey_2	Sandy_1	Sandy_2
		Bulk density (Mg m^{-3})		
TR	1.41a	1.44a	1.76a	1.75a
HR	1.40a	1.37ab	1.76a	1.72a
LR	1.26b	1.34b	1.71ab	1.66b
NR	1.27b	1.30b	1.68b	1.65b
		Soil resistance to penetration (MPa)		
TR	2.73a	2.88a	2.80a	2.11a
HR	2.34ab	2.75ab	2.80a	1.97a
LR	2.13bc	2.30b	2.24b	1.63b
NR	1.93c	2.01b	2.12b	1.60b

Means followed by same letter in each column do not differ according to the Tukey's test ($p < 0.05$). Data from Castioni et a. (2019).

Our findings indicate that excessive removal of straw (TR and HR) was detrimental to soil physical quality. Conversely, low removal showed to be an alternative for the sustainable removal of straw with minimal impact on the soil. We advocate that recommendations for straw removal should be combined with other conservationist soil management practices in order to minimize soil compaction and its negative implications on sugarcane yield and other soil ecosystem services.

3.1.3 IMPACTS ON SOIL CHEMICAL ATTRIBUTES

Sugarcane straw has great potential for nutrient cycling and consequently is considered a source of nutrients to the soil. However, there is a paucity of studies evaluating soil fertility changes induced by straw removal management in sugarcane fields. To address this issue, SUCRE conducted experiments on seven locations in Center-South Brazil aiming to evaluate the straw removal effects on soil fertility attributes. The study included the four-year effects of straw removal and analyzed the following soil chemical attributes: pH, potential acidity (H+Al), macronutrient contents (phosphorus - P, potassium - K, calcium - Ca, magnesium - Mg), cation exchange capacity (CEC) and base saturation (BS).

Overall, the implications of straw removal on soil fertility were site-specific and the results were associated with local conditions. However, in order to consolidate the overall information, the average effects of straw removal on soil chemical attributes were plotted in *Figure 2*. The mean values of each soil chemical attribute were transformed into relative scores from 0 to 1 (*Figure 2*). The higher average value of each attribute was normalized to one.

It is possible to infer that straw removal affected some soil fertility indicators, and the most relevant changes occurred mainly on topsoil of 0-0.10 m soil layer (*Figure 2*). Straw removal did not interfere in the soil acidity (pH and H+Al) while macronutrients were affected (*Figure 2*). The nutrients P, Ca and Mg are more affected, reflecting in the base saturation and potential CEC. Note that the real magnitude of these changes was site-specific and varied according to climate and soil conditions. Monitoring soil fertility is imperative to guide fertilization management and meet the nutritional needs of sugarcane crop aiming at a best crop yield. Therefore, it is expected that the results of this study help to build adjustments in fertilizer management on different straw removal scenarios.

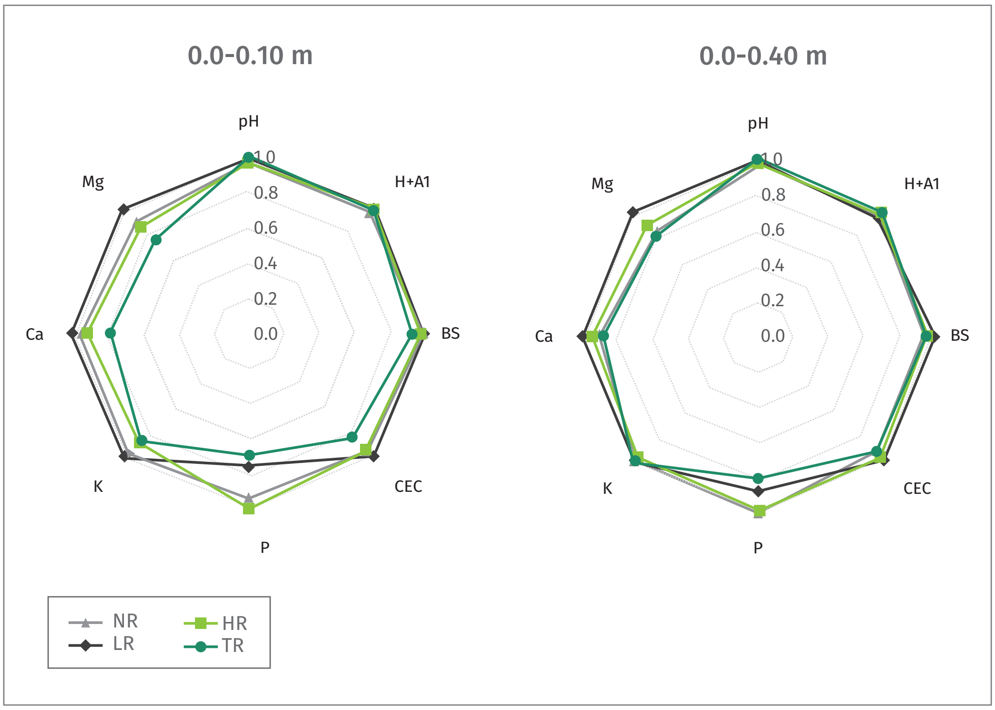
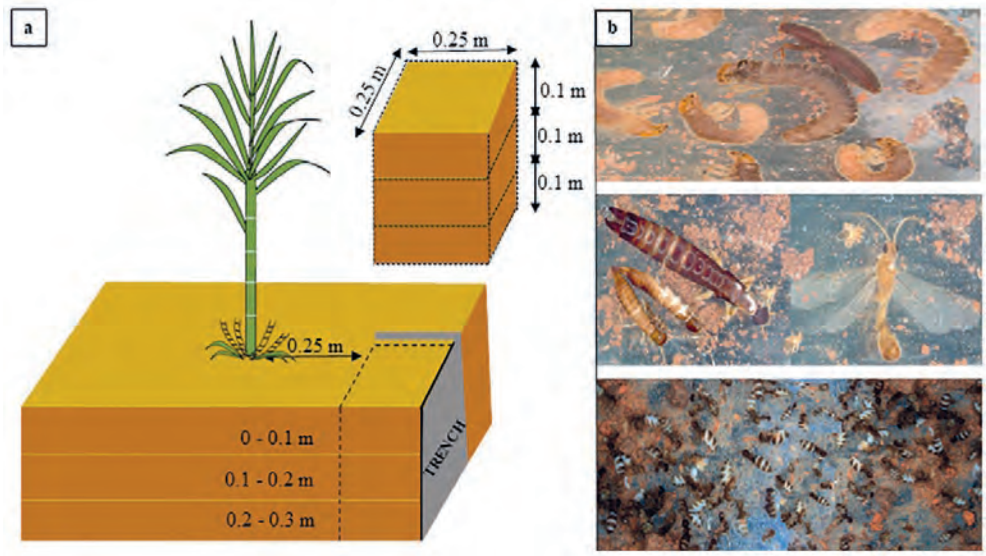


Figure 2: Scores of the soil chemical attributes after four years of straw removal in different soil depths. NR - no removal; LR - low removal; HR - high removal; and TR - total removal. Values were relativized and transformed in scores ranging from 0 to 1. For each attribute, the highest score is normalized to one.

3.1.4 IMPACTS ON SOIL BIOLOGICAL ATTRIBUTES

This study included the implications of straw removal on soil macrofauna diversity (*Figure 3*), microbial biomass carbon (MBC) and enzymatic activity of β-glucosidase in field experiments under different edaphoclimatic conditions in Center-South Brazil. Four straw removal treatments (NR, no removal, LR, low removal, HR, high removal, and TR, total removal) were evaluated and more details about the methodology and complete results can be found in Menandro et al. (2019) and Tenelli et al. (2019).

Figure 3: a) Schematic representation of soil monoliths sampled for soil biology evaluations (b) images of soil macroinvertebrates during taxonomic classification (Menandro et al., 2019).



Briefly, the results showed that the macrofauna study showed that eleven taxonomic groups were found distributed across the areas. Overall, the Formicidae family was the most abundant group, representing 90.6% of the total collected macrofauna, followed by the Hymenoptera (3.1%), Oligochaeta (1.8%), Coleoptera (1.6%), Geophilomorpha (1.0%), Hemiptera (0.7%), Dermaptera (0.5%), Araneae (0.2%), Diplura (0.2%), Isoptera (0.1%), and Diptera (0.1%).

Among several macroorganisms observed in sugarcane fields, earthworms are key, since they are generally recognized as a good soil quality indicator. Our findings indicated higher earthworm abundance in rainy season and the population of this organism was positively correlated to the straw amount left on the soil surface (*Figure* 4). Those findings revealed that excessive straw removal (TR and HR) impaired earthworm population and the magnitude of these responses are closely related to soil and climatic conditions and management practices adopted in sugarcane fields. This study also showed that low straw removal (LR) may be a sustainable strategy to increase bioenergy production with minimum impacts on earthworm population.

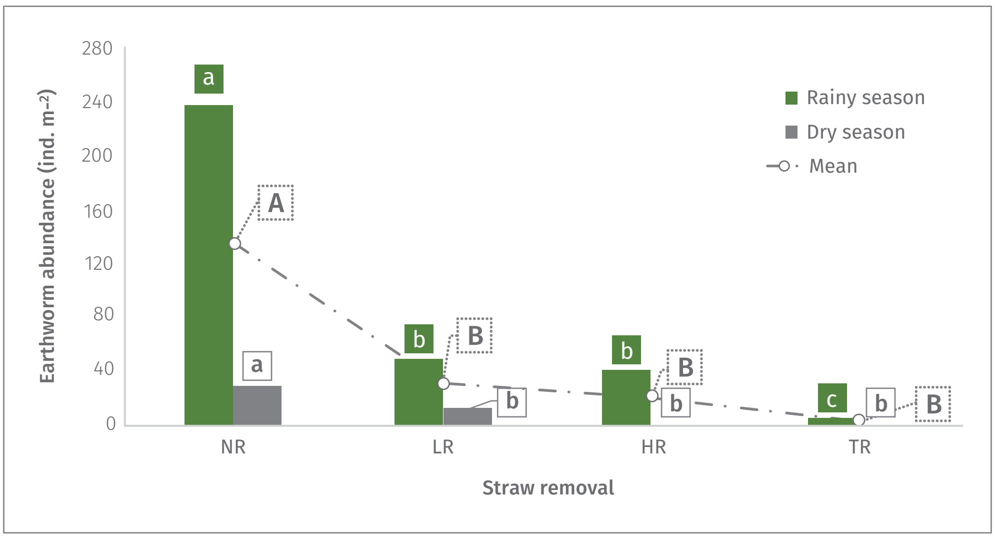


Figure 4: Earthworm abundance under different seasons and amounts of straw. Amount of straw left on soil surface: 0 (TR, total removal), 5 (HR, high removal), 10 (LR, low removal), and 15 (NR, no removal) Mg ha^{-1}. | Adapted from Menandro et al. (2019).)

The soil microbiological attributes were also responsive to straw removal in a clayey soil in the 0-10 cm depth. The decrease in the microbial biomass carbon and β-glucosidase activity was found within the treatments under TR and HR. These findings demonstrate the importance of keeping at least part of the sugarcane straw in the field to preserve soil microbiological quality.

3.1.5 IMPACTS ON SOIL AND NUTRIENT LOSSES BY EROSION

The maintenance of sugarcane straw covering the soil is one of the most important management practices to mitigate soil erosion losses. Conversely, the removal of straw for bioenergy production can intensify erosion losses and compromise soil health and biomass production. This study was established to assess the effects of straw removal on soil and nutrients losses by erosion in areas under sugarcane production in São Paulo state. Two field experiments (under distinct edaphoclimatic conditions) were conducted during two crop seasons (*Figure 5*).

Overall, straw removal rates increased soil erosion losses, with a more pronounced effect on sandy soil compared to clayey soil (*Table 3*). In the sandy area, soil losses by runoff were strongly influenced by straw removal and higher soil losses were observed when all straw was removed. When all straw was removed (TR) the annual soil loss was 22 Mg ha^{-1}, and the losses were significantly reduced with the increase of the amount of straw on soil surface. In clayey soil, the magnitude of soil erosion losses was much lower than observed in sandy soil. However, although lower in all treatments, soil loss by erosion was higher in TR (0.021 Mg ha^{-1}) compared with HR (0.013 Mg ha^{-1}) and NR (0.015 Mg ha^{-1}) (*Table 3*).

Our findings indicated that straw removal increased nutrient and organic matter (OM) losses by erosion processes. In sandy soil, the TR resulted in higher nutrient losses in relation to other treatments (*Table 3*). The treatments HR and TR showed OM losses five times higher than in NR and LR (*Table 3*). In clayey soil, the losses of OM were also higher in TR treatment. Finally, the data showed that, in general, straw removal intensified the soil and nutrient losses by erosion, and the most adverse effects were associated with TR treatment. Sandy soil evidenced more intense soil losses than clayey soil demonstrating higher susceptibility of this soil. However, the data presented herein showed that LR treatment (i.e., keeping about 10 Mg ha^{-1} of straw on the soil surface) can be a suitable strategy to ensure the sustainability of bioenergy production in Brazil without impairing soil and nutrient losses by erosion.

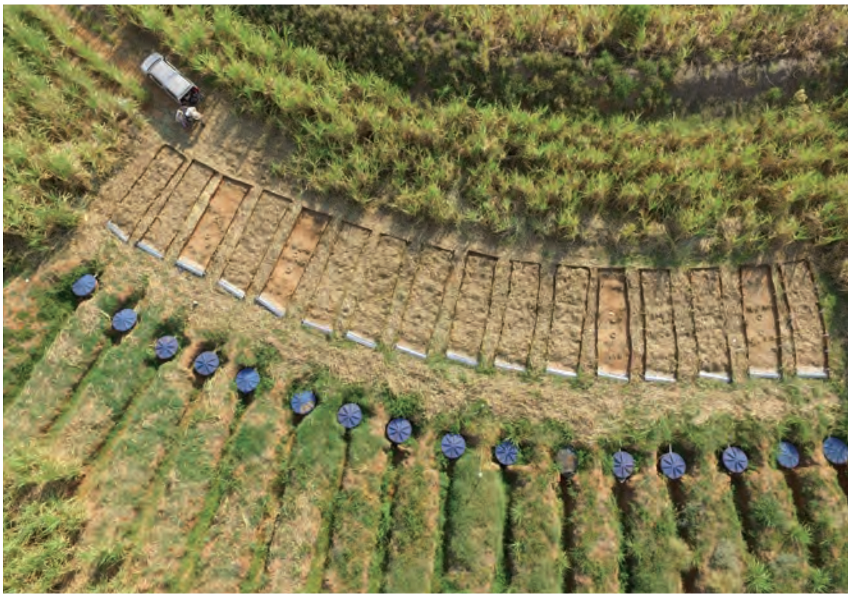


Figure 5: Aerial view of the soil erosion experiment, highlighting the experimental plots.

Straw removal Rate	Runoff amount					
	Soil mass	OM	P	K^{+}	Ca^{2+}	Mg^{2+}
	Mg ha^{-1}	----------------------------- kg ha^{-1}	---------------------------			
			Sandy soil			
NR	1.90c	36.0b	0.10b	0.20b	1.10b	0.20b
LR	3.00b	57.0b	0.15b	0.30b	1.90b	0.30b
HR	5.70b	114.0ab	0.31b	0.71b	3.80b	0.60b
TR	22.00a	352.0a	1.04a	2.32a	11.0a	2.10a
			Clayey soil			
NR	0.015b	0.77b	0.011ns	0.0023ns	0.136ns	0.007ns
HR	0.013b	0.55b	0.012	0.0019	0.148	0.008
TR	0.021a	0.92a	0.014	0.0045	0.190	0.011

Means followed by the same letter within columns for each soil mass and elements leached do not differ from each other according to Tukey's test ($p < 0.05$). ns=not significant.

Table 3: Annual amount of soil (Mg ha^{-1}), organic matter and nutrients (kg ha^{-1}) lost by erosion in sandy and clayey soils under different straw removal scenarios.

3.1.6 SOIL CARBON STOCKS AND GREENHOUSE GASES EMISSIONS

Sugarcane straw is recognized as the main source of C to the soil and the removal of this crop residue has a potential to impair SOC stocks. To evaluate the impacts of straw removal on SOC stocks, ten field experiments under distinct edaphoclimatic conditions were conducted evaluating four straw removal rates: NR- no removal; LR- low removal; HR- high removal and TR- total removal.

Soil samples were collected at a 30-cm depth (*Figure 6*) at the beginning of the trial establishment and after four years of straw removal. Composite soil samples were collected from the sugarcane row and inter-row positions at 0-5, 5-10, 10-20 and 20-30 cm depths for SOC concentration analysis by dry combustion using a Carbon Analyzer - LECO CN 628. In order to facilitate the data analysis the experimental areas were grouped according to soil clay content, in clayey and sandy soils.

Figure 6: Procedures used for soil sampling to determine the soil carbon content.

Our results revealed a depletion of SOC stocks directly proportional to the increase in straw removal rates (*Figure 7*). Overall, TR treatment reduced SOC stocks in the 0-30 cm layer, reaching a mean rate of -0.9 Mg C ha^{-1} $year^{-1}$ in the sandy soils and -0.4 Mg ha^{-1} $year^{-1}$ in the clayey soils, respectively (*Figure 7*). In sandy soils average SOC losses for HR and LR treatments were -0.4 and -0.2 Mg C ha^{-1} $year^{-1}$ (*Figure 7*). For clayey soils, the annual SOC losses induced by HR and LR rates were -0.6 and -0.4 Mg ha^{-1} $year^{-1}$ (*Figure 7*).

The overall results showed that soil C stocks increased linearly as a function of the amount of straw added to the soil. We observed that, on average, 85 kg ha^{-1} of C was retained in the sandy soils for each Mg of dry straw left in the field, varying from 26 to 144 kg of C. Clayey soils showed average C retention of 109 kg ha^{-1} for each Mg of dry straw in the field, varying around 91 to 134 kg of C. Our results suggested that approximately 19% and 25% of the C added via straw was incorporated into the SOC stocks in sandy and clayey sites, respectively.

Conclusions drawn from these experimental sites indicate that excessive rates of straw removal are impairing SOC stocks, suggesting that sustainable straw management must be adopted to prevent additional soil degradation in areas of bioenergy production.

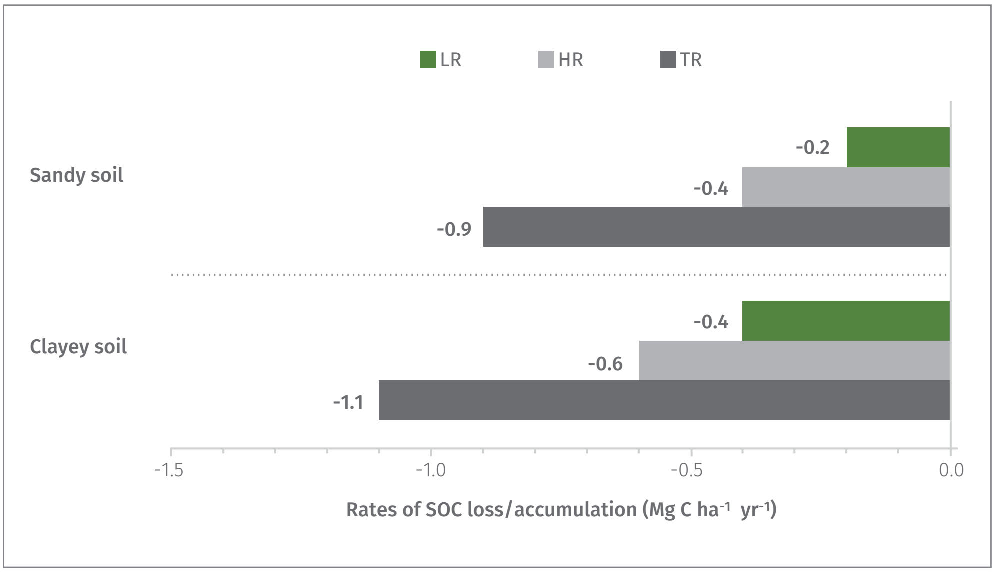


Figure 7: Average annual SOC rates in a 0-30 cm depth in relation to NR treatment in sandy and clayey soils.

This study was conducted to assess the impacts of straw removal on soil CH_4 and N_2O emissions in areas of sugarcane production in São Paulo state, Brazil. The data included herein were obtained by intensive GHG sampling performed in four sites during two crop seasons. In each field experiment, four straw removal rates: no removal (NR); low removal (LR); high removal (HR); and total removal (TR) were evaluated. Greenhouse gas emissions were evaluated using the static chamber methodology (*Figure 8*) and the analyses were performed using gas chromatography. Additionally, this study focused on the derivation of the regional N_2O emission factors (EFs) that represent specific conditions of sugarcane production in the São Paulo state, including data obtained herein and those obtained from literature review. More details about this study can be found in Gonzaga et al. (2019).

Figure 8: Greenhouse gas emissions sampling on sugarcane fields.

No clear effect of straw removal on CH_4 fluxes was observed in all evaluated sites. The cumulative CH_4 fluxes were low for all sites, and in most cases, indicated a modest consumption of CH_4 by the soil. Our data indicate that sugarcane soils, regardless of straw removal rates, acts predominantly as a net sink for CH_4, which should be associated with the high occurrence of deep, well-drained, and highly weathered soils.

Higher N_2O emissions were observed after N fertilizer application following rainfall periods, with significant variations among evaluated sites. The cumulative N_2O emissions ranged from 0.20 to 4.09 kg ha^{-1} year^{-1} and were significantly affected by straw removal. The direct N_2O EFs from N fertilizer plus straw were highly variable across sites, ranging from 0.05 to 1.44% of the N applied. By grouping the N_2O EFs found in this study, we observed a decrease in N_2O EFs as a function of straw removal. Averaged N_2O EFs of 0.28, 0.44, 0.70, and 0.56% were observed for TR, HR, LR, and NR, respectively (*Figure 9*). There was a clear evidence of lower N_2O EF with the scenarios of straw removal, despite the high variability of the data indicated by the boxplots.

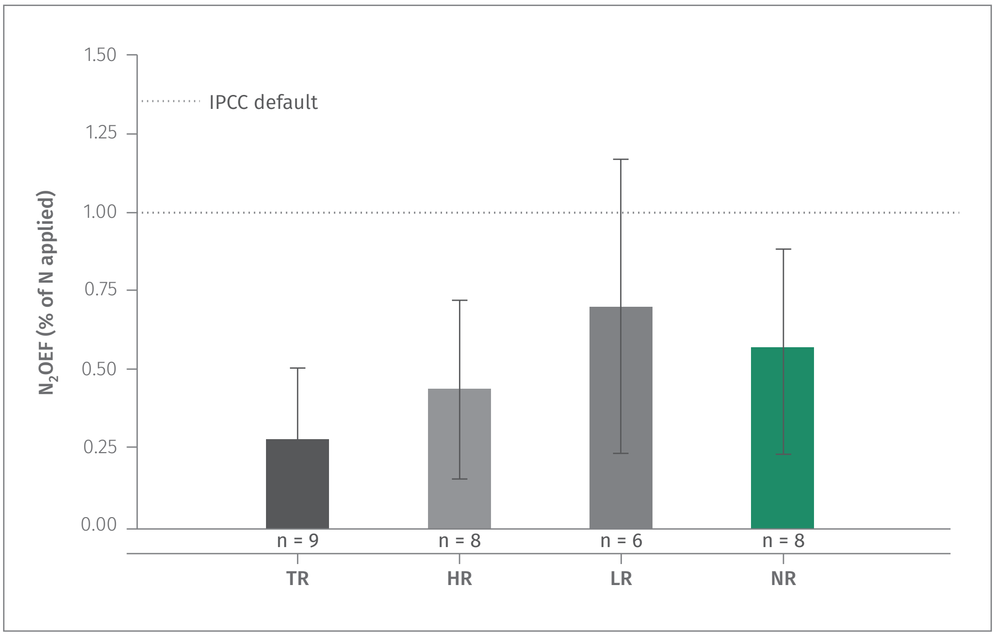


Figure 9: Regional N_2O emission factors from the application of N fertilizers in soils under different straw removal rates in São Paulo state, Brazil. Straw removal rates: total removal (TR), high removal (HR), low removal (LR), and no removal (NR). n, number of observations. Bars indicated the values of standard deviation. Black dashed line indicates the IPCC default value. | Adapted from Gonzaga et al. (2019)

Lastly, this study provides information to guide future inventories about the N_2O emissions from sugarcane soils and how straw management can affect such emissions. This study indicates that the use of default N_2O EF proposed by the IPCC, regardless straw removal rates, overestimate the direct N_2O emissions in sugarcane fields in Brazil and suggests that the use of the regional-specific N_2O EF data can reduce the high levels of uncertainties concerning the GHG emissions of sugarcane bio-based products.

3.1.7 IMPACTS ON SUGARCANE YIELDS

Twenty-one field studies were conducted in SUCRE Project to quantify the impacts of straw removal on sugarcane yields. The experimental sites represent diverse edaphoclimatic conditions in the most intensively cultivated sugarcane regions and those of recent expansion in Center-South Brazil (*Figure 10*). In addition to the experiments conducted by SUCRE project, data from the other seven field studies from literature were included to build a more robust dataset, aiming at a better understanding of the straw removal induced effects on sugarcane yields. In total, there were 28 field experiments and these areas were grouped in four macroregions in order to facilitate data analysis. More information about the methodology, description of the areas, and main results can be found in detail in Carvalho et al. (2019).

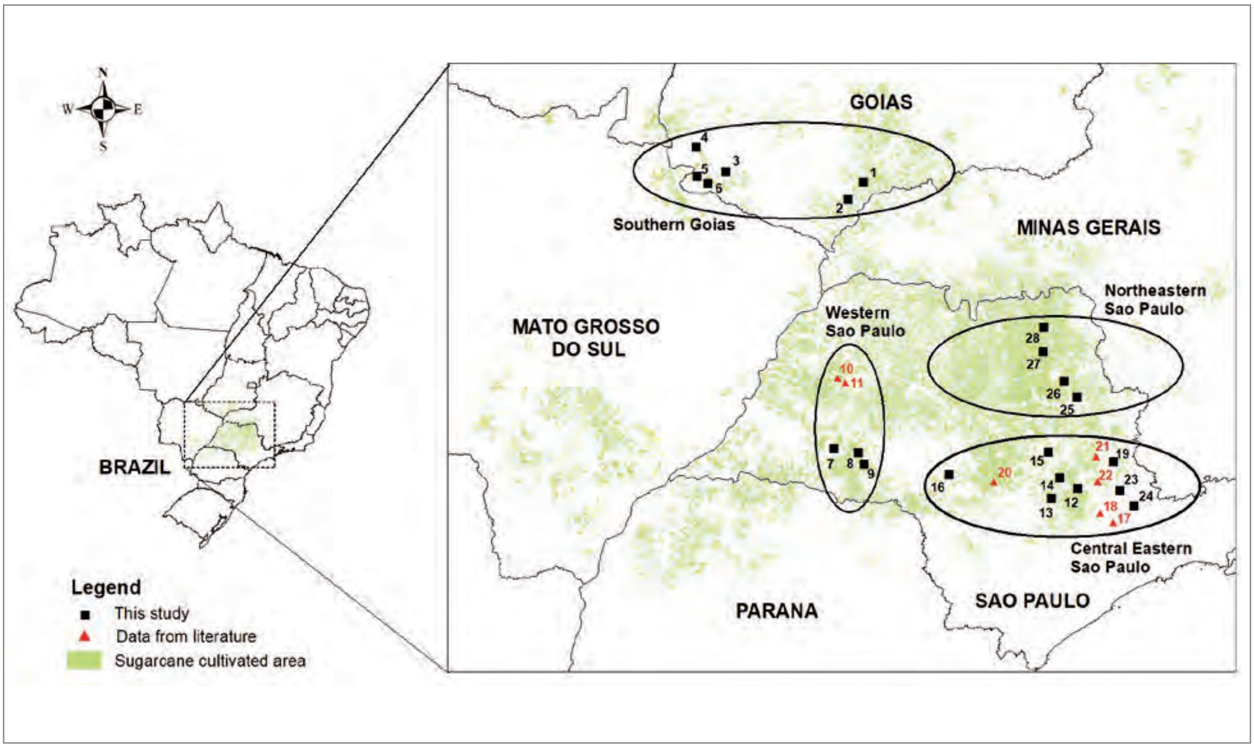


Figure 10: Geographic locations of the sites included in this study (SUCRE's experiments) and those obtained from the literature review. Sugarcane cultivation map was processed according to the updated data from the Canasat's project (www.dsr.inpe.br/laf/canasat/). R1, R2, R3, and R4 represent the following macroregions, respectively: Southern Goiás, Western São Paulo, Central Eastern São Paulo and Northeastern São Paulo. | Adapted from Carvalho et al. (2019) | Credit: Karina Maria Berbert Bruno

All field studies were established in a randomized block design with four replications, composed of four removal rates for some trials and three for others. Dimensions of each plot were 10-m long by 12-m wide, comprising eight sugarcane rows at 1.5-m spacing.

The sugarcane stalk yield in each plot was measured after approximately 360 days of the adoption of straw removal treatments in all experimental sites. At the harvest period, each plot was mechanically harvested and stalk yields (expressed in Mg ha^{-1}) were computed for the four central rows through an instrumented truck equipped with a loading cell (*Figure 11*).

Figure 11: Instrumented truck equipped with a loading cell to weigh sugarcane biomass in experimental plots.

Our study revealed that straw removal affected sugarcane yields in all regions, but the effects were clearly site-specific and dependent on the crop cycles (*Figure 12*). Overall, straw removal effects on sugarcane yields were more significant in southern Goiás and western São Paulo. These regions demonstrated annual losses of sugarcane yield induced by LR, HR and TR averaged 2, 10 and 13 Mg ha^{-1} and 2, 4 and 6 Mg ha^{-1}, respectively (*Figure 12*). Although higher absolute yield losses were observed in southern Goiás compared to western São Paulo, the relative losses (in percentage) were similar for both regions. These responses patterns were associated with the higher sugarcane yields observed in the sites in southern Goiás (average of 129 Mg ha^{-1}) in comparison with western São Paulo macroregion.

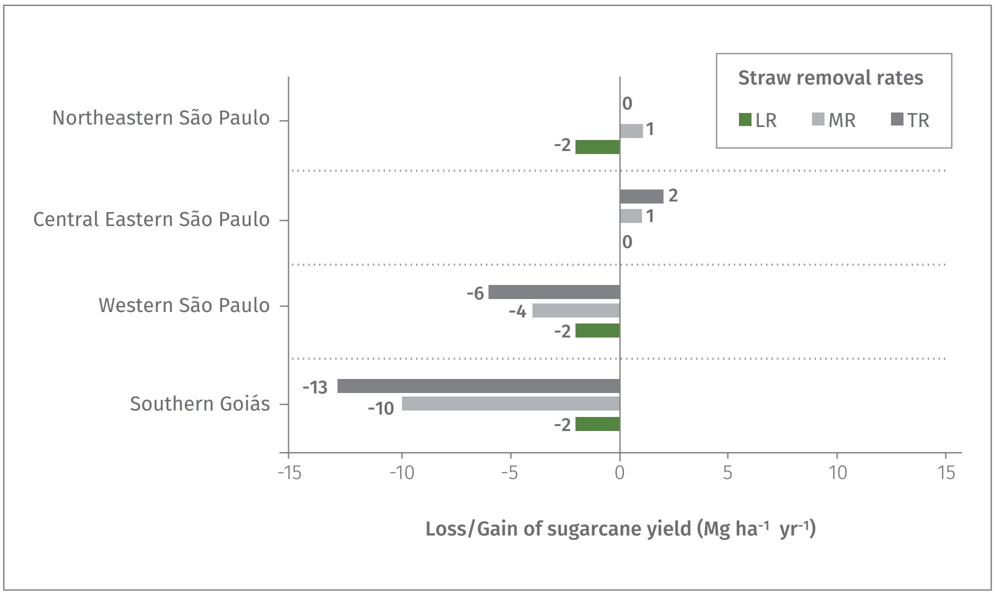


Figure 12: Sugarcane yield loss/gain, in Mg ha^{-1} year^{-1} (a) and in percentage (b), induced by straw removal in relation to no removal treatment (baseline). Data represent the average of all studies in each macroregion. Negative and positive values indicate annual loss and gain of sugar-cane yield, respectively. LR, HR, and TR denote low, high and total removal of sugarcane straw. | Adapted from Carvalho et al. (2019).

In southern Goiás, straw removal resulted in significant changes ($p<0.05$) in sugarcane yields in 13 out of 16 evaluations. Straw removal did not induce yield losses only in a hydromorphic clayey soil and in a clayey soil under regular irrigation.

In a similar way to that observed in southern Goiás, straw removal reduced sugarcane yield in most sites of western São Paulo.

Overall, average yield responses due to straw removal in central-eastern and northeastern São Paulo were quite low and tended to be zero. However, substantial variation in yield responses was observed among sites within both regions, indicating that the effect of straw removal in these regions were site-specific and there is no single effect on crop yields.

3.1.8 FINAL CONSIDERATIONS ON IMPACTS OF STRAW REMOVAL

In summary, our findings indicated that excessive straw removal impair soil quality and increase soil and nutrient losses by soil erosion. Conversely, the adoption of low straw removal rates, in general, resulted in minimal effects on soil quality and could be an alternative for the sustainable removal of straw with minimal impact on the soil. Regarding soil GHG emissions, this study evidenced that straw removal reduces SOC stocks, but also reduce N_2O emissions. We advocate that the comprehensive GHG emission balance should be performed, including N_2O emissions and SOC stock changes induced by straw removal for bioenergy production.

The impacts of straw removal on soil attributes are clear, but the effects of these changes on sugarcane yield are not always evident. Sugarcane yields are guided by a complex equation and dependent on numerous factors including local weather conditions, soil types, harvesting seasons and crop aging. There is no single answer to recommend straw removal in Center-South Brazil, and the recommendation in a sustainably compatible manner should be prioritized as follows: (i) the first step is to identify the regional weather condition; (ii) soil type is an important factor, but it should be analyzed within a specific region and generalizations about the straw removal according to soil type should be avoided; (iii) harvesting season is another important factor, especially in regions where the minimum temperature is restrictive to sugarcane growth; (iv) the inclusion of crop aging in this complex equation can improve the recommendation of straw removal without significant yield losses. Therefore, we believe that SUCRE Project not only provides an amalgamation of high-level scientific information but also can be used as a strategic basis by academics, sugarcane industry, and policymakers at both state and national government levels.

3.2 AGRONOMIC ROUTES FOR STRAW RECOVERY

Authors: *Douglas de Oliveira Forchezatto, Jorge Luís Mangolini Neves, Terezinha de Fátima Cardoso.*

As discussed previously, in the Center-South region of Brazil, the mechanization of the sugar-energy sector has reached 96.2% of the cane fields (Conab, 2019), representing a sugarcane area of 7.5 Mha. The use of mechanical harvesters for sugarcane in Brazil has grown, mainly in areas with slopes less than 12% and without natural obstacles. As surplus electricity sales have become popular, mills are concerned about thermal and electromechanical efficiencies, aiming to commercialize the surplus of generated energy. In addition to the well-known technique for generating electricity using bagasse from the crushing of sugarcane, the adoption of the mechanized system of harvesting sugarcane, without burning, produces a large amount of vegetal waste, i.e., straw. This straw is separated from sugarcane through the harvester's primary and secondary extractors and can be used as a complementary fuel to bagasse. According to Carvalho et al. (2017), an average sugarcane field contains 8 to 30 tons (dry basis) of straw per hectare. Menandro et al. (2017) reported that the average amount of straw is 120 kg (dry basis) per ton of cane (12%), for cane fields harvested without burning). SUCRE partner mills use three techniques to recover straw remaining in the field after harvesting: bulk collection by hay harvester, recovery by bales, and integral harvesting. Integral harvesting sends a higher percentage of straw to the mill along with the cane, as approximately 6% of a normal load is straw due to inefficient cleaning by the harvester.

The three straw recovery routes were compared with respect to mineral impurities at each stage of agricultural operations: the recovery efficiency, the quantity and distribution of residual straw, vegetal impurities, load density, and losses in the harvest. The evaluations were conducted at partner mills of the SUCRE Project. This evaluation justified the introduction of integral harvesting with shredded straw (Route 4), in the comparative analysis of the routes, as shown in *Figure 13*.

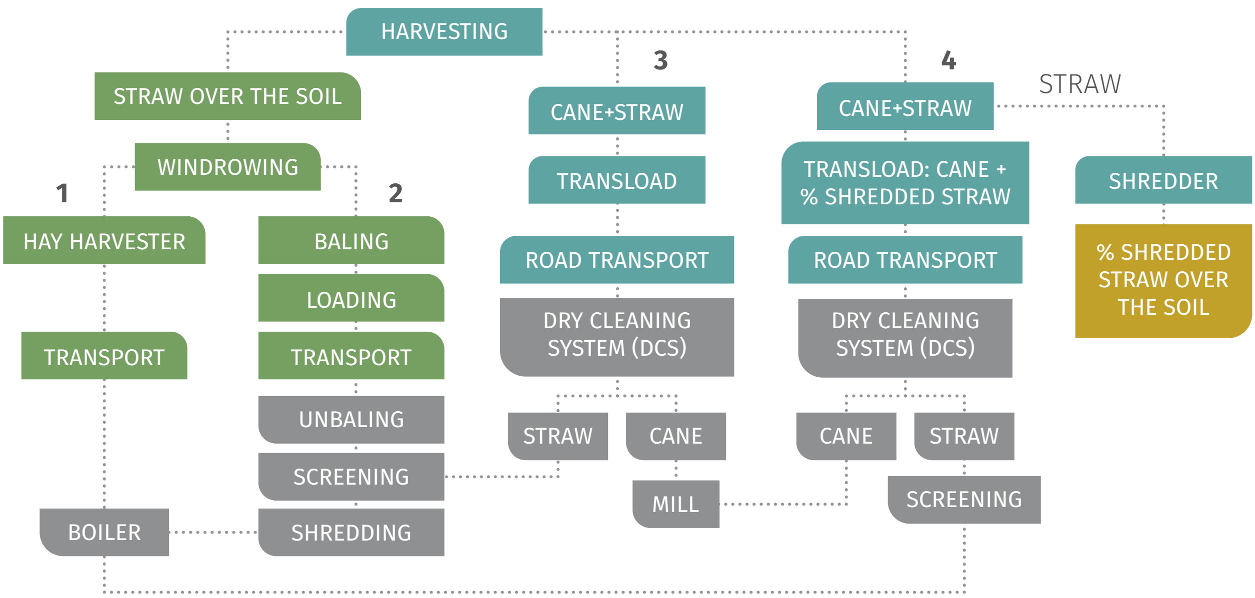


Figure 13: Sugarcane straw recovery | Design credit: Luiz Felipe Nascimento dos Reis

Field trials were performed under specific circumstances: cane field conditions, sugarcane variety, soil texture, implements, and agricultural machinery. Data collected in this work cannot be used generally, as they may not represent other mill production environments in the Brazilian sugar-energy sector. Nevertheless, these provide good indications of merits and problems of each route.

The systems used to recover sugarcane straw for energy cogeneration in Brazilian mills are the bulk straw recovery system with a hay harvester, the baled straw system, and the straw recovery system together with conventional chopped cane, i.e., integral harvesting.

Typically, in the bulk straw recovery route and the baling straw recovery route, after the cane harvesting and before the windrowing operation, the straw remains in the field four to 15 days for drying. Prior to drying, straw has high moisture content that is beyond the capacity of the baling machine to operate properly. After the fifteenth day, tillage operations are prioritized, competing with straw recovery.

Windrowing (*Figure 14*) normally has three rake passes, forming a single windrow. Two rake passes for two adjacent rows, and a third pass joins the two rows, forming a single row.

However, the process incorporates mineral impurities (soil) into the biomass, which causes serious maintenance problems in the industry. SUCRE evaluated the path of mineral impurities and determined that a large part of it that is incorporated in the biomass does not come only from windrowing, because the harvester also contributes to the increase in impurities. *Figure 15* illustrates that the amount of soil (mineral impurities) in cane increases up to four time that in the conventional chopped cane harvesting. An additional increase of almost three times comes from the straw windrowing operation in the field[1].

Figure 14: Windrowing operation in field.

[1] *The equipment used for field test was the H9580 and New Holland H DII Rake windrowers, both powered by a New Holland TL 75 tractor.*

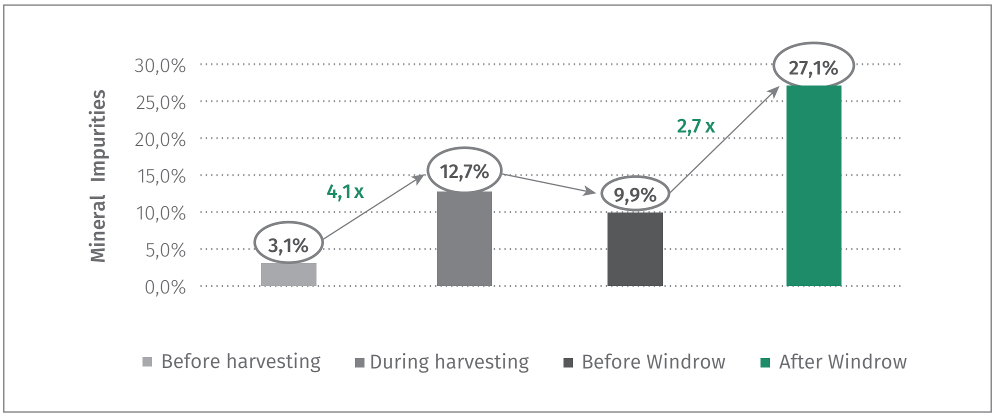


Figure 15: Increase in mineral impurities in straw during cane harvesting and straw windrowing operations.

3.2.1 HAY HARVESTING (ROUTE 1)

After straw is heaped, in Route 1, the hay harvester machine travels over the rows of straw, for straw recovery, chopping, and transfer operations to the trucks or transloader trailers. Trucks unload this straw directly into the mill's bagasse stockyard, forming a mixture of bulk straw and bagasse (RLT-030, 2017; RLT-031, 2017)[2].

The Hay Harvester (Route 1) recovery of straw in bulk (*Figure 16)* has low need for investments in the industrial area. As straw is shredded in the field, the mill does not need to reduce the particle size to be used in the boilers.

Figure 16: Hay harvester operation in the field.

Results for Route 1 include a field capacity of 16.8 t/h, fuel consumption of 3.3 L/t, load density of 93 kg/m³, in addition to a recovery efficiency of 31%, and a mineral impurity index of 16% in the loaded straw. The machine tested in the field was a New Holland FR 9060, 544 cv, 2011.

[2] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

The Hay Harvester operating in the field spends approximately 70% of the time recovering straw. The machine is stopped 21% of the time due to choking, as it was originally developed to harvest hay, a much less aggressive crop than sugarcane straw. Therefore, this equipment must be adapted by the manufacturers to improve its performance harvesting sugarcane straw.

As a final consideration, Hay Harvester (Route 1) was not found to be used by mills, due to high fuel consumption (diesel), high levels of mineral impurities in straw, and high cost of transporting bulk straw.

3.2.2 BALING (ROUTE 2)

Figure 17 outlines the Baling system (Route 2). Baling begins after windrowing, when the baler collects straw from the windrows, compresses it, and ties it with longitudinal twines into prismatic bales, approximately 500 kg each (RLT-027, 2017; RLT-053, 2018; RLT-069/01, 2019)[3].

The baled material is collected and carried out by a cart. The cart groups the bales into piles and transfers them to the edge of the field. The bales are loaded onto the semitrailer by forklift and delivered to the bales processing plant.

Figure 17: Overview of complete of Straw Baling system: straw windrowing, baling, collecting, loading and transporting bales, and bales processing plant.

Field tests show that balers have an average field capacity of approximately 40 t/h, with a straw moisture content of approximately 10%, a fuel consumption of 1.21 L/t, and soil incorporation in the straw near 18%, for a maximum recovery efficiency of 46%.

It is difficult to recover more than 50% of straw from the field because the recovery efficiency is limited by the necessity of leaving a significant amount of straw, due to agronomic reasons. In addition, there are operational and mechanical limitations, as baler parameters are set to prevent mineral impurities collection, requiring adjustments

[3] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

so that the fingers of the windrower and the pick-up of the baler do not touch the ground (RLT-027, 2017[4]; Okuno et al., 2019).

The equipment tested in the field was the Krone Big Pack High Speed and New Holland BB9060 balers, powered by John Deere 7225J and a New Holland TM 7030 tractors, respectively. The Mil Stak PT 2010 bale-collecting cart powered by a New Holland TM 7040 tractor, a JBC TLT 35 forklift, and the Sergomel semitrailer were also tested. *Table 4* outlines measurement amounts of straw available and its relationship with the amounts recovered.

Table 4: Available, recovered and residual amounts of straw, dry basis, and recovery efficiency.

Place - Operation	Potential straw (t /ha)	Recovered Straw (t/ha)	Residual straw (t/ha)	Recovery efficiency
Mill A - Baler	14.6	6.7	7.8	46
Mill B - Baler	13.1	4.5	8.6	34

The amounts of straw that remained in the fields after the two recovery experiments were adequate to maintain the soil quality, if uniformly distributed.

The residual straw distribution in the field, after the recovery operation for both bales and hay harvesters, is important to consider. The lack of homogeneity in straw distribution, which compromises the agronomic benefits of its maintenance in the field, is a result of the recovery process. It concentrates biomass in the windrow (around ¾ of the remaining straw), because the front fingers of the baler are not able to recover all the material. See in *Figure 18*.

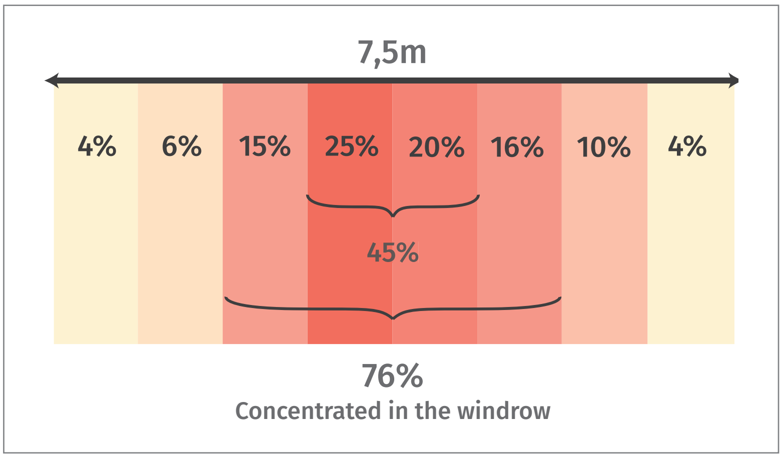


Figure 18: Distribution of residual straw after passing the baler.

The results indicate that baled straw had moisture content lower than bagasse, and straw samples showed greater variations in moisture levels. When evaluating the processing pathway, the moisture content of straw mixed with bagasse is measured to determine the impact of straw in the mixture. Generally, straw quality is inferior to that of bagasse, as straw has higher levels of mineral impurities.

[4] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

Figure 19: Harvesting and transloading operation in field.

3.2.3 INTEGRAL HARVESTING (ROUTE 3)

Integral harvesting does not require the windrowing process, because it does not recover straw from the ground. Instead, when harvested, the straw is not separated from cane billets or only partially removed by extractor fans. Straw is directed to the transloader along with the cane (*Figure 19*). The advantages are: (i) the elimination of subsequent straw harvesting operations, whether by bales or bulk (hay harvester); (ii) the reduction of mineral impurities, due the straw no longer having contact with the soil; and (iii) the immediate release of the fields for the subsequent tillage operations. In addition, the straw no longer requires 4–15 days of sunshine for drying. Disadvantages for Route 3 include (i) the low density of cargo transported to the mill and (ii) the need for additional harvesting fleet equipment, especially transloaders. These imply in higher costs per ton transported, despite the mill's desire for increased amounts of biomass as raw material for burning in the boilers.

To assess the impact of Integral Harvesting (Route 3) on harvesting, transloading, and transporting, tests were conducted to evaluate the influence of the rotation speed of the primary extractor of the chopped sugarcane harvester. There were impacts on (i) the amount of mineral and vegetal impurities in the load, (ii) on sugarcane losses, (iii) on fuel consumption, and (iv) on potential field capacity of the harvester. Four configurations (see Table 5) were used for primary extractor speeds from 650 to 900 revolutions per minute (RPM) (RLT-026, 2017[5]). For each configuration, the topper was turned off, the secondary extractor standard setting (1950 RPM) was maintained, and the ground speed of the harvester was 5 km/h.

[5] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

Mineral impurities between treatments showed an expected behavior. As the primary extractor increased rotation, mineral impurities were lower, demonstrating the cane cleaning function of the device. Vegetal impurities are illustrated in *Figure 20* as the sum of straw (green leaves plus dry leaves), tops, and roots. Billets are pieces of a whole stalk cane.

Figure 20: Constituent parts of sugarcane and vegetal impurities in the load.

Results from field trials[6] are shown in *Figure 21*. Reducing the speed of the primary extractor to 650 RPM in the cane harvester allows for a greater amount of straw to be transported with the cane billets, but this increases the transport cost because of the reduction in the load density. *Figure 21* also shows that the percentage of vegetal impurities decrease as the speed of the primary extractor increases, with an inverse effect on load density.

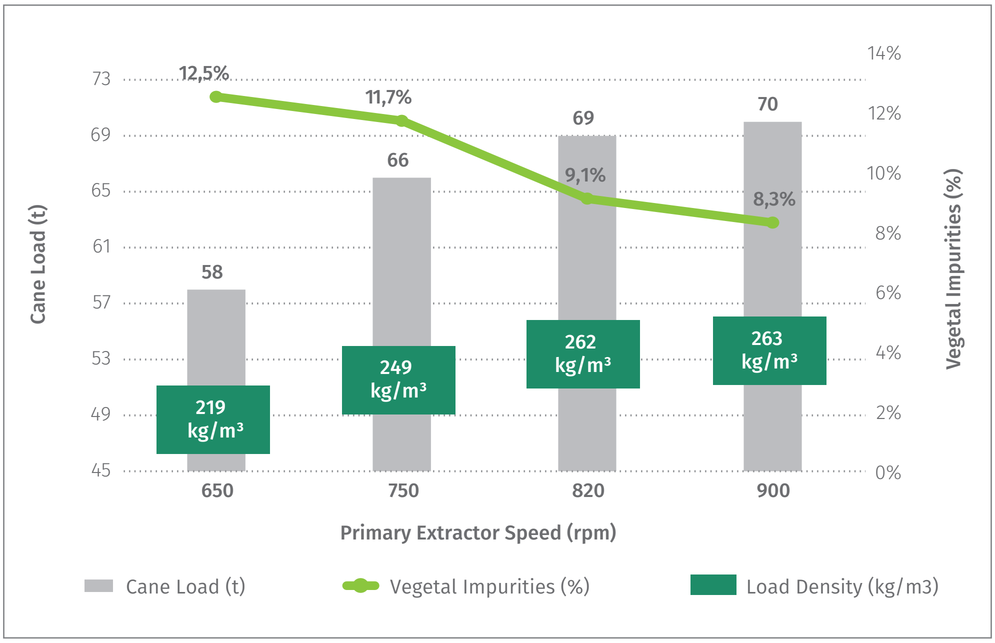


Figure 21: Field Trial – Cane Load versus Vegetal Impurities (wb) tested at four primary extractor speeds.

[6] *For the field trial, the sugarcane variety harvested was RB 86-7515, in which biometrics indicated an average yield of 115 TCH, 6th cut, with 1.5 m of interrow spacing. Vegetal residues were 9% for dry straw fraction and 14% for tops plus green leaves, on a wet basis, and without prior burning of the cane field (green cane). The test area had erect cane on medium-textured soil.*

Operational harvesting capacity (t/h) in the field was obtained by measuring the time required for the transloader to be filled and weighed. For this test, the time required for harvesting the entire area destined for the test was registered. For the calculation of operational capacity, maneuver times were not considered. Results were obtained for the same range of rotation speeds and showed behavior, where increased cleaning (straw removal) decreased the mass harvested per unit of time. There was 4% less straw in the load between extreme fan speeds with a 20% increase in density, resulting in an additional 12t in transported weight. This provides a lower load density at the transloader, requiring increased numbers of travel per unit of time.

As expected, the greatest losses occurred at the highest speed of the primary extractor. Results indicate that higher extractor speeds resulted in visible losses 2.5 times greater than at lower speeds. The loss difference between extreme treatments of 650 and 900 RPM was 2.8 percentage points. Invisible losses of sugarcane (juice, shrapnel, powder, and sawdust) from the harvesting operation were not counted; however, it is considered that the magnitude is comparable to visible losses, resulting in total losses twice the visible loss index (Neves, 2003; Neves et al., 2003; Neves et al., 2006; and Norris, 2019).

Fuel consumption value includes total time of the harvest plus maneuvers, displacement, waiting for the transloader, and administrative stops. Fuel consumption was lower when operating the harvester with the primary extractor speed set at 650 RPM. The consumption of diesel per ton of cane harvested increased when primary extractor speed was 900 RPM. Setting the primary extractor at 650 RPM reduced fuel consumption by 30% when compared to 900 RPM: 0.88 and 1.26 L, respectively.

In summary, integral harvesting, despite reducing the number of agricultural operations to recover straw, increased the costs of harvesting and transporting sugarcane due to increases in vegetal impurities and, consequently, decreased load density for transportation. Nevertheless, there was also a reduction in cane losses (*Table 5*).

Speed (RPM)	**Vegetal Impurities (%)**	**Load Density (kg/m³)**	**Total Losses (%)**
650	12.5%	219	2.0%
750	11.7%	249	2.2%
820	9.1%	262	4.5%
900	8.3%	263	4.8%

Table 5: Primary extractor speed, vegetal impurities, load density, and total visible losses.

Field tests have shown that reducing the speed of the primary extractor makes it is possible to increase the amount of biomass that can be transported along with sugarcane. In addition, decreased speeds reduce visible losses and fuel consumption, and increase operational capacity in tons per hour. *Figure 22* provides a summary of test results with all variables evaluated in the field associated with each speed of the primary extractor.

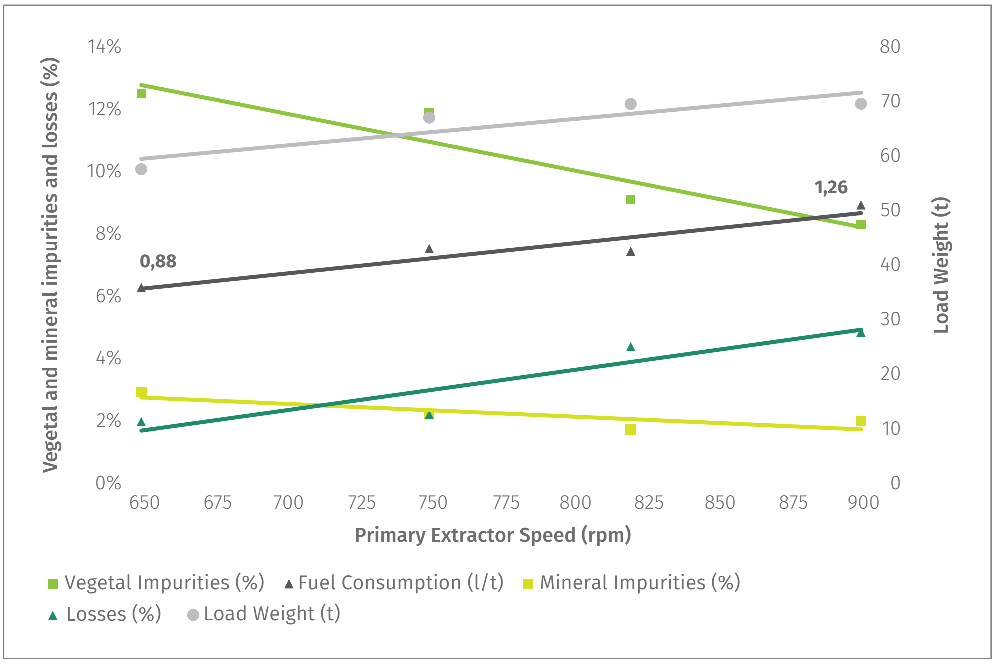


Figure 22: Effect of primary extractor RPM setting on each field variable.

This comprehensive analysis of extractor speed impacts on vegetal impurities, transportation costs, cane losses, and fuel consumption are normally excluded in comparisons found in the literature. However, they can be considered "hidden costs" when comparison between the integral harvesting straw recovery system (Route 3) with other recovery options such as baling (Route 2) and hay harvester (Route 1) are made (Norris et al., 1998; Norris et al., 2000; Davis and Norris 2002; Norris et al., 2015; Meyer et al., 2016; Norris, 2019).

3.2.4 INTEGRAL HARVESTING WITH SHREDDED STRAW (ROUTE 4)

SUCRE proposed an alternate route to Integral Harvesting (Route 4) adding a shredded straw recovery (RLT-053, 2018; RLT-069/01, 2019)[7]. The goal was to reduce impacts of integral harvesting such as, low density of the transported loads, increasing need for equipment in the harvesting fleet, especially transloaders, and low efficiency of the Dry Cleaning System (DCS) in the industry.

This route foresees the implementation of a straw shredder (*Figure 23*), which mounts on the primary extractor of a commercial chopped cane harvester. The harvester chops

[7] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

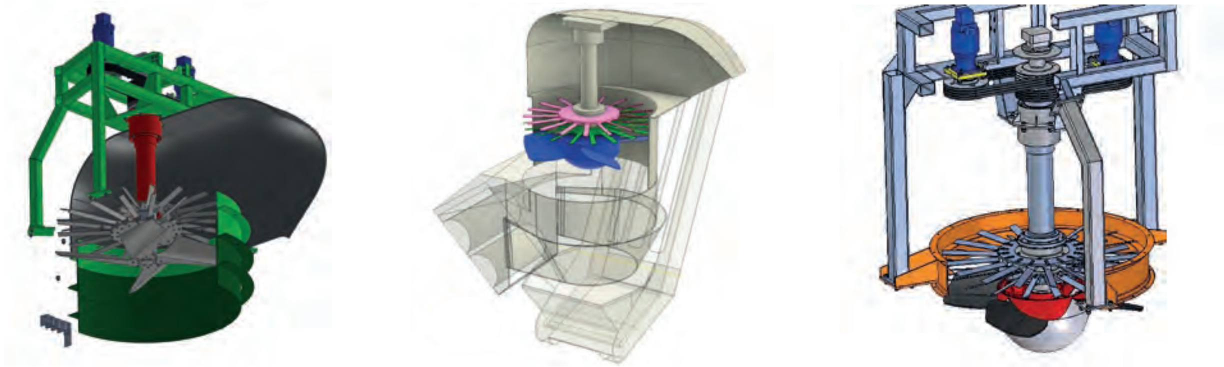


Figure 23: Straw Shredder, set of rotary knives (green) / counter--knives (pink), mounted on the primary extractor of the commercial chopped cane harvester.

all cane straw material, which is blown by the primary extractor, through one set of rotary knives and counter-knives (RLT-053, 2018; RLT-069/01, 2019; Neves et al., 2015; Neves et al., 2016)[7].

LNBR/CNPEM, with the permission of the Sugarcane Technology Center (CTC), built a prototype of the straw shredder, to evaluate the effect of straw shredded on load density and transport cost, and on the efficiency of an industrial Dry Cleaning System. The new component was assembled on the primary extractor of a Case A7700 commercial chopped cane harvester from a SUCRE partner mill. The device allowed the cane to be harvested and the straw to be processed (separation and shredding) simultaneously directly in the field.

The straw shredder's main purpose is to reduce straw particle sizes, thereby occupying the empty spaces between cane billets in transloader/semitrailer. This allows larger amounts of straw to be transported to the mill without decreasing the density of the mixture. The quantity and particle size distribution of the straw defines the density of the load transported to the mill, and higher densities lower cane transportation costs. Shredded straw was expected to increase operating efficiency of the conventional Dry Cleaning System (DCS) installed in the mills.

For this evaluation, the primary extractor on the harvester adapted with the straw shredder was maintain at maximum extraction, approximately 1,000 RPM, and both rotors (knife and counter-knife) of the shredder was set at 1,000 RPM. The secondary extractor and topper were off. The differentiation was the extractor hood positioning, so that half of the shredded straw flow reaches the harvester side elevator (and into the transloaders), while the other half is directed to the ground[8] (*Figure 24*).

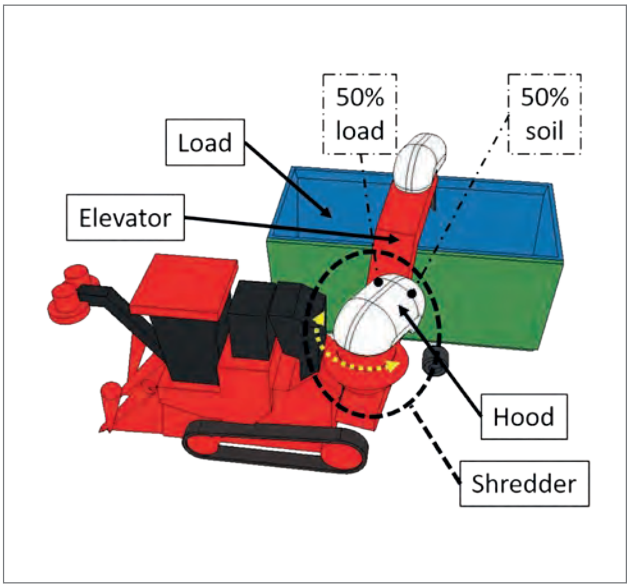


Figure 24: Hood position to recover 50% of available straw.

[8] This adjustment is carried out prior to the mill with the placement of shims welded on the primary extractor ring, which restricts the rotation of the device to ensure a dosage of approximately 50% straw for the load. The control machine, a conventional chopped cane harvester, had its primary extractor set for minimum extraction (about 650 RPM) and its topper and secondary extractor turned off. The straw flow from the primary extractor hood was directed to the ground.

When biomass arrives at the mill it is pre-processed before the material can be mixed with bagasse and fed into the boiler. For example, biomass from the Hay Harvester (Route 1) has a particle size distribution and condition close to bagasse, while biomass from Baling (Route 2) requires processing of unbaling, screening, and shredding in a specific plant. Biomass from Integral Harvesting (Route 3) or from Integral Harvesting with Shredded Straw, (Route 4) requires separating straw from the cane billet, which occurs in the Dry Cleaning System (DCS). After separation, the conventional straw from Integral Harvesting (Route 3) requires screening and shredding.

The SUCRE Project conducted a field evaluation of the efficiencies of DCSs (*Figure 25*), and the results range from 17-49% efficiency for the tested DCSs (RLT-028, 2017; RLT-052, 2017; RLT-053, 2018; RLT-068, 2018; RLT-069, 2019; Soares et al., 2019)[9].

The assessment of the impact on the efficiency of the Dry Cleaning System (DCS) was performed by comparing two conditions. The first was the recovery of 100% of the available straw in the field, and the second was the recovery of 50% of the available straw. In both, comparisons were made between shredded straw and conventional straw, that is processed by chopped cane harvester (RLT-053, 2018; RLT-069, 2019)[10].

Figures 26 and *27* illustrate the cleaning efficiency and the amount of vegetal impurities measured at the inlet before the DCS. For the configuration that recovers 50% of the straw available in the sugarcane field (*Figure 26*) there was an increase in cleaning efficiency of 67% (from 9% to 15%) operating with shredded straw. The percentage of straw in the load consisted of 27% higher (7% to 9%) vegetal impurity compared to that of the conventional straw. The low efficiency of the tested DCS should be considered only as an indication of trend and not as a representative value.

[9, 10] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

Figure 25: Dry Cleaning System (DCS) layout.

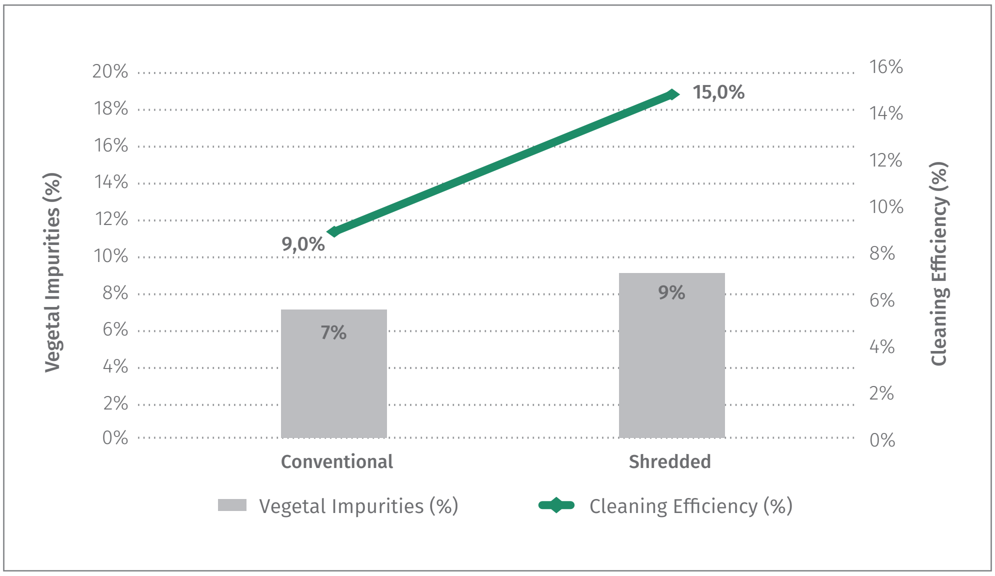


Figure 26: Efficiency of the DCS and percentages (%) of straw in the load in harvesting of approximately 50% of the straw available in the sugarcane field.

When recovering 100% of the straw available in the sugarcane field (*Figure 27*), the results indicate that the DCS had the same cleaning efficiency of about 13%. However, note that the percentage of straw in the load as vegetal impurity was 50% higher, from 11.8% to 17.6%.

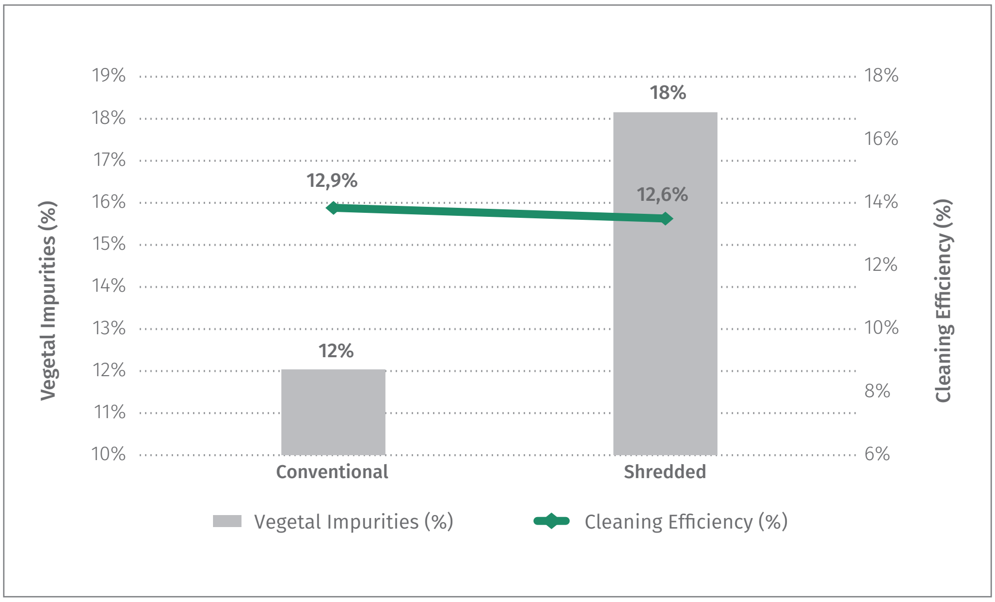


Figure 27: Efficiency of the DCS and percentages (%) of straw in the cane load in the harvesting of 100% of the straw available in the sugarcane field.

An increase in the vegetal impurity (straw) of the transported load was observed during the field tests. The shredded straw with smaller particle sizes occupies the empty spaces, while the load with conventional straw, originating from the harvester without straw shredder, shows larger straw particles and has a greater impact on reducing load density. *Figure 28* shows load densities for conventional and shredded loads with 100% Shredded Straw: + 9% straw (1.5%) with 41% more weight, in the same volume (m^3) transported and 50% Shredded Straw: + 37% straw (2.7%) with 5% less weight, in the same volume (m^3) transported. Conventional straw was processed by a chopped cane harvester without straw shredding.

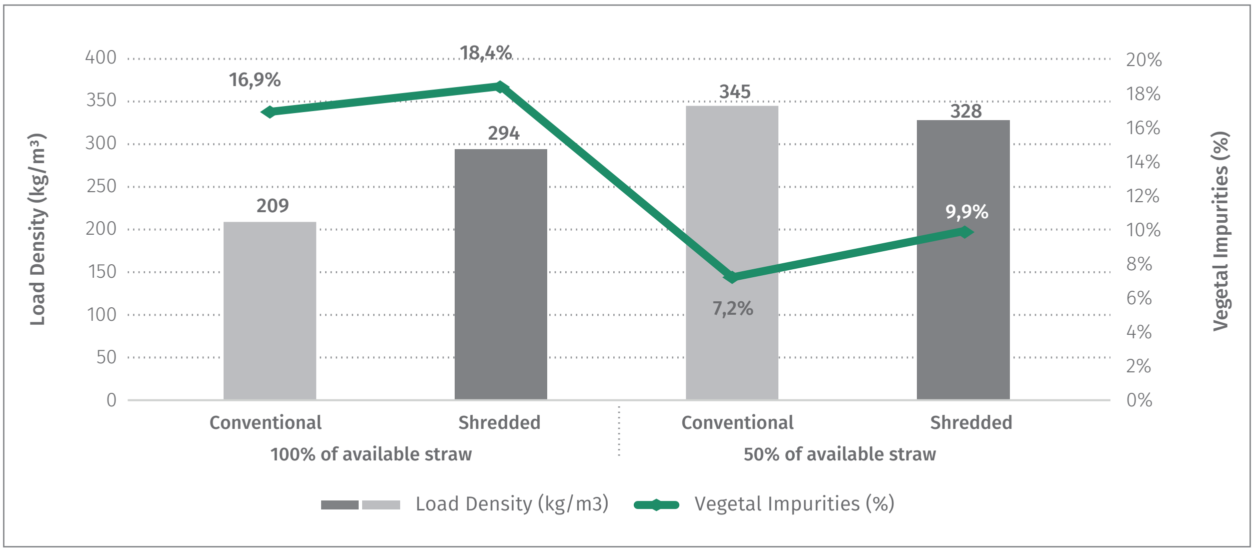


Figure 28: Load densities and vegetal impurities for shredded and conventional straw.

An important contribution from LNBR/CNPEM to SUCRE was the ability to guide improvements in the straw processing equipment, through virtual prototyping and computer simulation (RLT-069/01, 2019)[11]. *Figure 29* illustrates a straw shredder in Computational Fluid Dynamics (CFD) with a simulation of the recommended operating condition: primary extractor at 1,000 RPM, straw shredder set rotor No. 1 (19 knives) at 1,000 RPM, and shredder rotor No. 2 (17 counter knives) at 1,000 RPM.

The main improvement, guided by simulations, was the removal of the vortex that allowed increase in the equipment operation efficiency. *Figure 30* illustrates the standard model DCS in CFD indicating vortex formation.

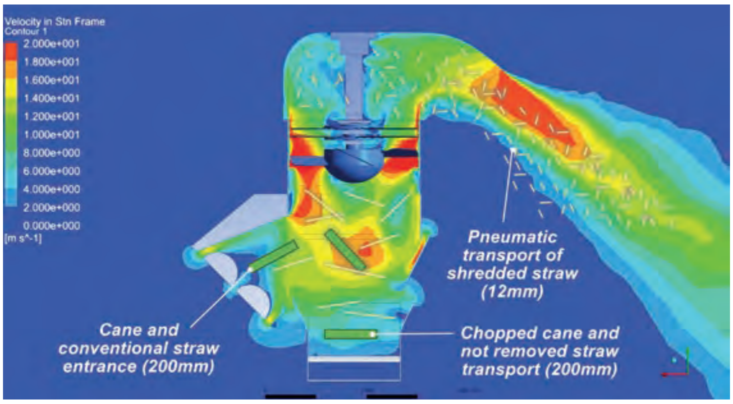


Figure 29: Straw Shredder in CFD (Computational Fluid Dynamics).

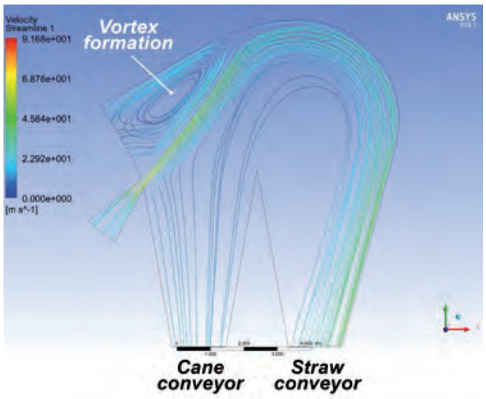


Figure 30: Standard model DCS in CFD (Computational Fluid Dynamics) indicating vortex formation.

Figure 31 illustrates the separation of the straw in the DCS, coupling CFD and discrete element method (DEM). When evaluating the process of separating straw from sugarcane

[11] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

billets in the decompression chamber of the DCS, it is possible to choose the airflow best speed (m/s) during the blowing of the equipment fans.

Virtual prototyping studies were conducted for an alternative DCS, owned by the partner mill of the Sucre Project (*Figure 32*). The computer simulation of this DCS being evaluated in CFD + DEM is Scenario 1. An analysis of the separation of straw (yellow color) and cane billets (green color) is conducted with an extractor air speed of 50 m/s. This showed the need to build a second conveyor to recover the separated straw.

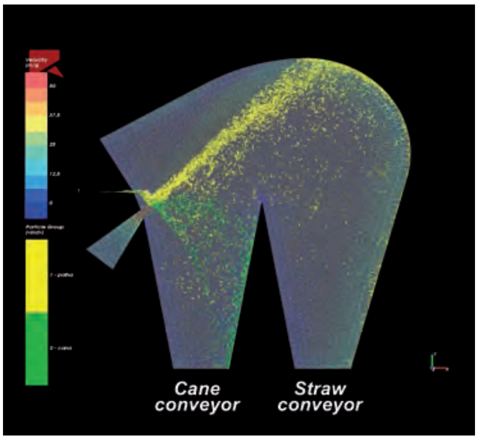


Figure 31: Standard model DCS in coupling CFD and Discrete Element Method (DEM).

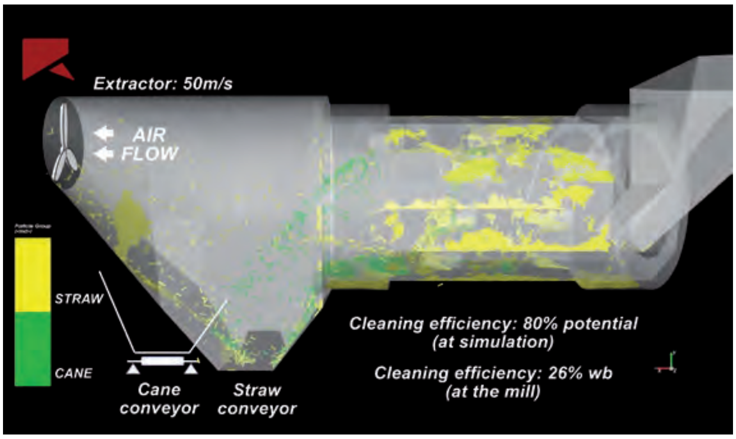


Figure 32: Virtual prototyping: alternative DCS during the CFD + DEM analysis (Scenario 1).

The use of virtual prototyping with the aid of CFD and DEM techniques improved the performance of the straw shredder mounted on a chopped sugarcane harvester. This result suggests that is possible to increase the efficiency of the DCS equipment. Future work shall involve equipment manufacturers and mill owners, using DCS models and SUCRE to investigate options for improving performance of their DCSs such as including another conveyor.

3.2.5 COSTS, ENERGY AND GHG EMISSIONS IN RECOVERY ROUTES

The sustainability assessment methodologies are described in reports RLT-014 (2016), RLT-019 (2016), and RLT-032 (2017)[12] as well as in Bonomi et al., 2016.

For each one of the three recovery systems, three different recovery amounts of available straw were evaluated. Thus, 2, 3, 4 tons of straw, dry basis, were considered per hectare. The straw recovery costs were calculated considering the additional costs compared to an equivalent scenario, but without straw recovery. Therefore, one scenario without straw recovery was also evaluated (Base).

[12] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

For higher amounts of straw recovery per hectare (3 t/ha and 4 t/ha), it is necessary to consider areas with higher sugarcane yield, and consequently the higher amount of available straw. This is due to the machinery recovery efficiency in function on the amount of straw that can be recovered per hectare, mainly the baler. Thus, even though the recovery is in a smaller total area, part of the straw recovery can occur in further areas. This keep the average transport distance approximately the same. More precise determination of the average distances in each case (3 and 4 tons of straw per hectare) would require a detailed sugarcane yield map, which is beyond the scope of this work. Moreover, for baling costs, the amount of straw recovered per hectare is more important than the transport distance. For better comparison, the same criterion was adopted for the scenarios with the other straw recovery systems assessed.

I. BALING

The main parameters used for straw recovery assessment by Baling are presented in Table 6 and more details about the scenario evaluated are in RLT-090 (2020)[13].

Parameters	Quantity	Unit
Average yield	77	TC/ha
Average transport distance	35	km
Total straw recovered	100,000	t_{db} /season
Baler - effective working hours (baling)	6	h/day
Harvester - effective working hours	10	h/day

Table 6: Main parameters – Baling system.

The calculation of straw recovery costs considers additional costs per hectare for each straw recovery scenario in comparison with the scenario without straw recovery. The straw recovery costs through the Baling system include straw windrowing, recovery and compaction in bales, and loading and transporting to the mill. For bales, additional costs are allocated to the straw recovered (Dias et al., 2016; RLT-032,2017[14]; Cardoso et al., 2018).

Figure 33 shows the straw recovery costs considering three different amounts of straw recovered, on dry basis, per hectare. (Exchange rate: 3.95 R$/US$)

[13, 14] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

Figure 33: Straw recovery cost for different straw quantities, on dry basis, per hectare.

Fuel consumption per ton of straw recovered is shown in *Table 7*, considering agricultural operations and transport to the mill. The average transport distance is the same for the scenarios assessed (35 km). The difference in the fuel consumption is due to the distance between straw recovery plots.

	Fuel consumption (L/$t_{straw\ (db)}$)		
	Baling		
	2 t_{db}/ha	3 t_{db}/ha	4 t_{db}/ha
Agricultural operations	8.24	5.67	4.60
Transport	1.81	1.84	1.87
Total	10.05	7.50	6.46

Table 7: Average fuel consumption in the straw recovery by Baling system.

The evaluation of the greenhouse gas (GHG) emissions was performed using the environmental life cycle assessment (LCA) (RLT-032, 2017[15]; Sampaio et al., 2019; Cardoso et al., 2019).

Straw recovery can reduce nitrous oxide (N_2O) emissions, due to the degradation of the straw remaining on the soil. Higher amounts of straw recovery per hectare present better machinery efficiency, mainly of the baler, reducing the fuel consumption. The lower fuel consumption per ton of straw reduces the greenhouse gas (GHG) emissions of straw recovery. Therefore, straw recovery can reduce emissions in the agricultural phase, as in the scenario with 4 tdb/ha that presents a lower emission when compared to the scenario without straw recovery (*Table 8*).

[15] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

Table 8: Agricultural emissions per ton of straw on dry basis, in the Baling scenarios compared to the scenario without straw recovery.

	Bales		
	2 t_{db}/ha	3 t_{db}/ha	4 t_{db}/ha
Climate change ($10^{-6}gCO_2$ eq/t_{db})	2.49	0.09	- 0.88

II. INTEGRAL HARVESTING

The main parameters used for straw recovery assessment by the Integral Harvesting system are presented in Table 9. More details about the scenarios evaluated are in RLT-090 (2020)[16].

Table 9: Main parameters – Integral Harvesting system.

Parameter	Quantity	Unit
Average yield	77	TC/ha
Average transport distance	35	km
Total straw recovered	100,000	t $_{db}$ /season
Harvester - effective working hours	10	h/day

The calculation of straw recovery costs considers additional costs per hectare for each straw recovery scenario in comparison with the scenario without straw recovery. For Integral Harvesting, the additional cost is divided between straw and extra stalks (stalks resulting from lower losses), proportional to the amount of straw recovered (Dias et al., 2016; RLT-032 (2017)[17]; Cardoso et al., 2018).

Figure 34 shows the straw recovery costs considering three different amounts of straw recovered, on dry basis, per hectare. (Exchange rate: 3.95 R$/US$)

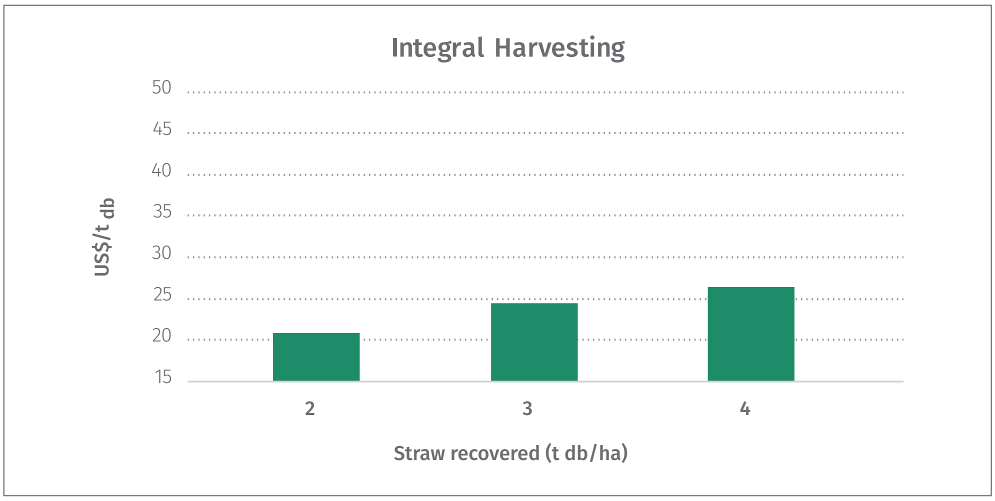


Figure 34: Straw recovery cost for different straw quantities, on dry basis, per hectare.

[16, 17] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

Fuel consumption per ton of straw recovered is shown in *Table 10*, considering agricultural operations and transport to the mill.

	Fuel consumption (L/t $_{straw (db)}$)		
	Integral		
	2 t_{db}/ha	**3 t_{db}/ha**	**4 t_{db}/ha**
Agricultural operations	-2.88	-1.49	-0.81
Transport	7.84	8.34	8.61
Total	4.96	6.85	7.79

Table 10: Average fuel consumption in the straw recovery by Integral Harvesting.

Despite higher fuel consumption, straw recovery reduces N_2O emissions due to the degradation of the straw remaining on the soil. Thus, the emissions in the Integral Harvesting scenarios are smaller when compared to the scenario without straw recovery (*Table 11*). Greenhouse gas emissions were evaluated using the environmental life cycle assessment (LCA) (RLT-032, 2017 [18]; Sampaio et al., 2019; Cardoso et al., 2019).

	Integral Harvesting		
	2 t_{db}/ha	3 t_{db}/ha	4 t_{db}/ha
Climate change (10^{-6}gCO_2 eq/t $_{db}$)	- 7.42	- 5.64	- 4.64

Table 11: Agricultural emissions per ton of straw on dry basis in the Integral Harvesting scenarios compared to the scenario without straw recovery.

III. INTEGRAL HARVESTING WITH SHREDDED STRAW

The main parameters used for straw recovery assessment by Integral Harvesting with Shredded Straw system are presented in *Table 12*. More details about the scenarios evaluated are in RLT-090 (2020)[19].

Parameter	Quantity	Unit
Average yield	77	TC/ha
Average transport distance	35	km
Total straw recovered	100,000	t $_{db}$ /season
Shredded (investment cost)	35,485	US$/harvester
Harvester - effective working hours	10	h/day

Table 12: Main parameters – Integral Harvesting with Shredded Straw system.

[18, 19] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

The calculation of straw recovery costs considers the additional costs per hectare for each straw recovery scenario in comparison with the scenario without straw recovery. For Integral Harvesting with Shredded Straw, the additional cost is divided between straw recovered and extra cane stalks (stalks resulting from lower losses), proportional to the amount of straw recovered (Dias et al., 2016; RLT-032 (2017)[20]; Cardoso et al., 2018).

Figure 35 shows the straw recovery costs considering three different amounts of straw recovered, on dry basis, per hectare. (Exchange rate: 3.95 R$/US$).

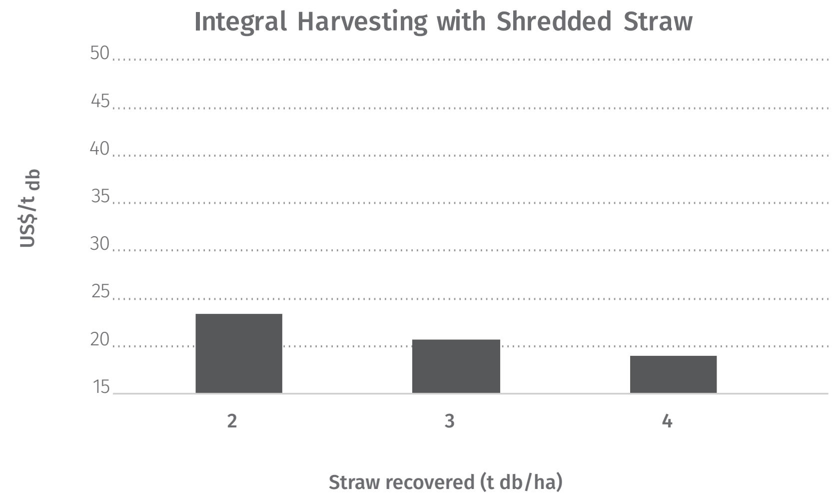


Figure 35: Straw recovery cost for different straw quantities, dry basis, per hectare.

Fuel consumption per ton of straw recovered is shown in *Table 13*, considering the agricultural operations and transport to the mill.

Table 13: Average fuel consumption in the straw recovery by Integral Harvesting with shredded straw.

	Fuel consumption (L/$t_{straw\ (db)}$)		
	Integral harvesting with shredded straw		
	2 t_{db}/ha	3 t_{db}/ha	4 t_{db}/ha
Agricultural operations	0.90	0.99	1.06
Transport	3.57	3.49	3.33
Total	4.48	4.48	4.38

Increasing the amount of straw recovered by Integral Harvesting with Shredded Straw increases fuel consumption in agricultural operations, mainly through harvester consumption. However, fuel consumption in transport decreases when the amount of straw recovered increases due to increase in load density. Considering the evaluated different amounts of straw recovered, fuel consumption remains practically the same.

[20] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

When compared to the Integral Harvesting (*Table 10*), the Integral Harvesting with Shredder Straw scenarios show an increase in fuel consumption in agricultural operations due to shredder in the harvester. However, it shows a reduction in fuel consumption in transportation due to the higher load density (RLT-069/01, 2019)[21].

Greenhouse gas (GHG) emissions were evaluated using the environmental life cycle assessment (LCA) (RLT-032, 2017 [22]; Sampaio et al., 2019; Cardoso et al., 2019).

The straw remaining on the soil produces N_2O emissions due to degradation of straw in contact with soil. However, fuel consumption has a greater influence on emissions, per ton of straw (dry base) recovered, compared to the amount of straw recovered in the field, as shown in *Table 14*. There is a slight increase in emissions between the extremes, 2 and 4 tdb /ha, of straw recovered in the field. It is noteworthy that these scenarios still have lower emissions compared to the other straw recovery routes evaluated and the scenario without straw recovery (Base).

	Integral Harvesting with Shredded Straw		
	2 t_{db}/ha	3 t_{db}/ha	4 t_{db}/ha
Climate change (10^{-6}gCO_2 eq/t_{db})	- 9.97	- 9.75	- 9.62

Table 14: Agricultural emissions per ton of straw recovered on dry basis, in the Integral Harvesting with Shredded Straw scenarios compared to the scenario without straw recovery.

COMPARING COSTS AND EMISSIONS OF STRAW RECOVERY ROUTES

The main parameters used for straw recovery assessment are presented in *Table 6* (Baling), *Table 9* (Integral Harvesting) and *Table 12* (Integral Harvesting with Shredded Straw).

Straw recovery by bales is more expensive for small amounts of straw per hectare due to the low operational efficiency of the machinery. The costs of the Integral Harvesting show the opposite behavior, benefiting from lower amounts of straw since it presents a lower loss of load density. The Integral Harvesting with Shredder Straw route behaves similarly to the Baling route, where the load density is not as affected, resulting in lower transport cost (*Figure 36*). (Exchange rate: 3.95 R$/US$)

[21, 22] *RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.*

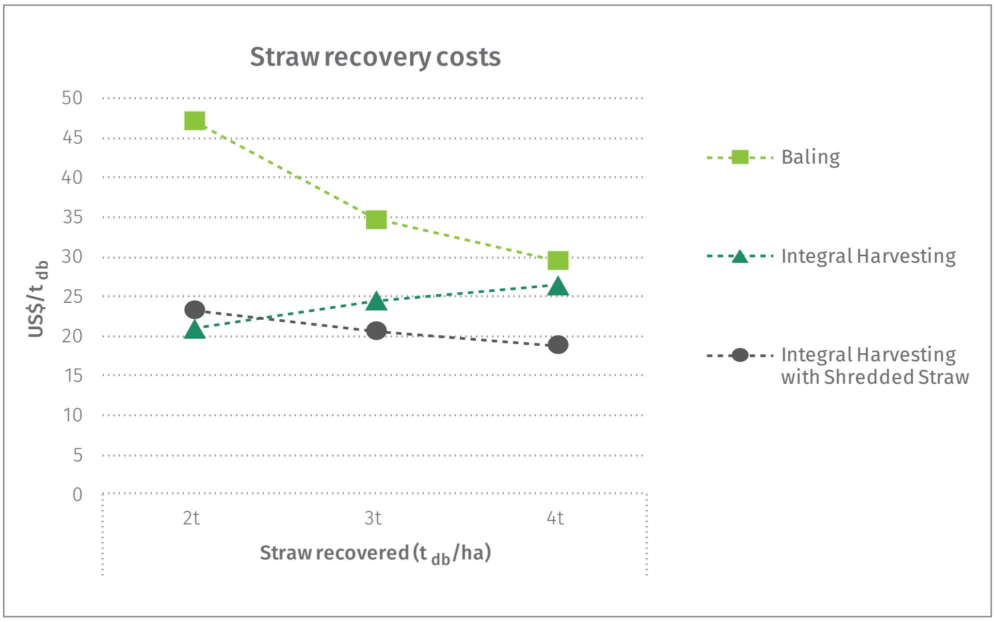


Figure 36: Straw recovery costs for three different routes.

Higher amounts of straw recovered can also reduce N_2O emissions, due to degradation of straw remaining on the soil. Higher amounts of straw per hectare, by bales, reduces the emission of straw recovery due to higher machinery efficiency. Despite lower emissions in Integral Harvesting, they are increasing when the amount of straw recovered per hectare also increases, due to the higher fuel consumption. The same occurs in Integral Harvesting with Shredded Straw but with lower emission levels (*Figure 37*).

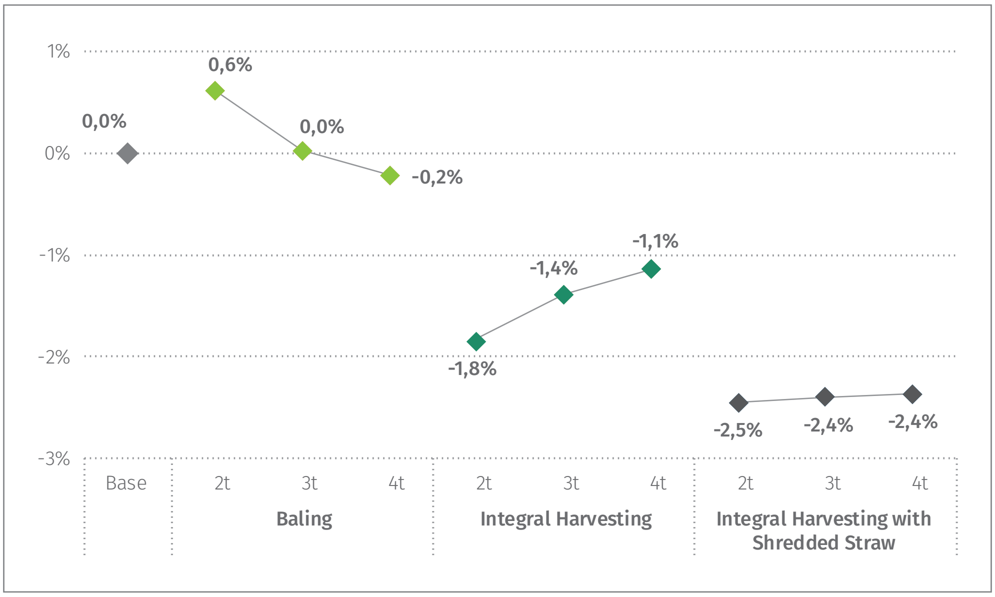


Figure 37: Percentage emissions variation compared to the scenario without straw recovery (Base).

In comparison to the base scenario (without straw recovery), bales have higher fuel consumption and lower machinery efficiency for small amounts of straw recovery, which increases emissions. Emissions present negative values due to the removal of straw, which reduces the amount of straw degrading on the soil, reducing N_2O emissions, as previously mentioned.

3.2.6 FINAL COMMENTS ON RECOVERY ROUTES

Results from the SUCRE Project tests at the partner mills indicate that increase in mineral impurity in straw comes from sugarcane harvesting, and the windrowing operation is also a major contributor to impurities.

Field tests demonstrate that reducing the harvester extractor speed serves to increase the amount of biomass transported along with sugarcane billets. Additionally, lower speeds favor the reduction of visible losses during harvesting, reduce fuel consumption, and increase the operational capacity of the harvester.

Total costs and emissions of recovery in each route depend on the assumed parameters, with the most important parameters being the amount of straw recovered per hectare and the average transport distance. For some mills, the best option could be a combination of baling and integral harvesting.

The proposed recovery route, Integral Harvesting with Shredded Straw, showed potential for reducing costs and emissions. However, further tests are necessary to confirm gains presented in this study. The CTC model for straw shredding, proved to be promising, since the shredded straw has particle sizes smaller than those from conventional chopped cane straw without shredding. Shredded straw increased the load density, reducing the cane plus straw transport costs, and the impact on efficiency (%) of the Dry Cleaning System was positive. However, only one trial was conducted under the agricultural and industrial conditions specific to that particular sugarcane producer.

3.3 INDUSTRIAL PROCESSING

Authors: *Paulo Eduardo Mantelatto, Caio César dos Santos Penteado Soares, Danilo José Carvalho, Paulo César Guizelini Júnior, Carlos Roberto Trez, Manoel Regis Lima Verde Leal, André Luís Enders Jair, José Antonio Bressiani*

3.3.1 STRAW HANDLING AND STORAGE

The practice of storing sugarcane straw in the form of bales has been gaining strength in Brazil with the increase in the use of this biomass to supplement bagasse in the generation of electric energy. Several sugar-energy companies already follow this practice. Some basic rules must be observed for proper straw storage and handling, especially as several instances of fire caused by stored straw have been reported in Brazil. There are several potential causes for these fires, such as lightning, sparks, or even biomass self-ignition. Buggeln and Rynk (2002) define spontaneous combustion (SC) as the combustion of a material in the absence of a "forced ignition" agent, that is, an externally applied flame or spark. In this report, we describe how SC processes occur in biomass stacks, beginning with chemical and physical events that initiate heat-producing reactions via biotic and abiotic processes involving mainly oxygen and moisture. Buggeln and Rynk (2002) pointed out that the accumulation of heat inside a pile depends on the equilibrium between the rate of internal heat production and the rate of heat loss to the external environment. When the rate of the first process is greater than that of the second, a "critical" internal temperature is reached, triggering an SC process. Water plays an important role in the change in temperature and heat exchange inside a biomass pile, as well as in the loss of internal heat to the environment. While heat in the form of water vapor is lost from a self-heating stack, the pile's internal temperature does not rise above 70 °C until all the free water has evaporated; the straw only starts to burn after this. Important experiments with eucalyptus leaves, sawdust, and other types of plant material demonstrate an inverse relationship between material mass and ambient temperature that can lead to SC. Thus, the larger the stack, the lower the ambient temperature at which the SC can occur.

According to Extension and Preventing Fires in Baled Hay Straw (2018), the moisture content is the main factor that causes a straw bale to spontaneously combust. It is recommended that the straw be stored with a moisture content of less than 20 wt%. When the moisture level exceeds this limit, it encourages the growth and multiplication of mesophilic bacteria found in forage crops. The metabolic processes of the mesophilic bacteria release heat inside the bale and cause the internal temperature to rise to 55–60 °C. In this temperature range, the bacteria die, and the bale temperature decreases. The risk of fire is higher for harvested hay than for straw because the temperature inside a bale of hay does not cool after the first initial heating cycle. The heat created by the mesophilic bacteria action provides a suitable environment for the growth of thermophilic bacteria. Basically, the higher the moisture content, the longer the bale will remain at a higher temperature. For example, a bale with 30 wt% moisture may cause the internal temperature to increase for up to 40 days. When thermophilic bacteria are present, they multiply and produce more heat; this can raise the internal bale temperature to over 75 °C. In this temperature range, spontaneous combustion may occur. Additional factors contributing to the risk of fires include the volume of the bale stack, its bulk density, and the ventilation or airflow around the stacked bales. Bales with lower density, that are stacked, and have good ventilation present less risk of overheating. Another important factor is monitoring the temperature in the bales. When the bale's internal temperature reaches 65–75 °C, there is a high potential for spontaneous combustion. The recommended weather conditions for baling are a slight wind and relative humidity of 50% or less. Davis (2012) presents the main conditions to be met in the design of medium and small units of straw bales.

To guide this practice, this report presents several guidelines to be followed to prevent fires during straw bale storage, handling, and distribution at straw bale centers (CDs).

The main aspects related to the storage of large volumes of baled straw and presented at the Workshop on straw storage at the GranBio unit (São Miguel dos Campos - Alagoas, Brazil on 09/02/2017). Only GranBio's experience, which operates with large-scale bales of sugarcane straw, was reported in detail. The nominal consumption of straw bales by GranBio is about 450 thousand metric tons per year. This company has a storage area of 28 ha that can store up to 60,000 metric tons of bales. There are ten layers of bales in a pyramidal format, covered by a sheet to ensure good protection against rainwater seepage in the stored bales. The bales are sorted into piles of 1,000 metric tons, is arranged at a distance of 30 m from other piles. According to GranBio, there is no loss in the straw quality irrespective of the storage time, as long as there is no infiltration of water into the pile; however, it is recommended that the bales be stored for a maximum period of one year. The bale moisture on arrival is controlled at a maximum of 12 wt%. The height of the piles is limited by the capacity of the piling machine. In every area, precautions are taken to control rats and snakes. The straw has a sucrose content of around 0.8 wt% and it is, therefore, susceptible to fermentation. Normally, the maximum temperature observed is 42°C, and the alarm point is set at 60 °C. The ground slope for pluvial drainage is 0.5%.

The company witnessed a series of three large fires in quick succession in 2015, which consumed 250,000 metric tons of baled straw over several days.

Based on the Brazilian experience with sugarcane straw and that of the international companies with the storage of wheat and corn stover bales, the following is a summary of the main results. (i) Experience shows that straw storage and handling are relatively complex and high fire-risk operations, no matter how careful one is; (ii) Straw storage involves the intensive use of labor and relatively high costs, (iii) Careful storage and handling, as well as constant care about fire safety and firefighting should be considered when designing the storage site; (iv) There is a need for the development of lighter and stronger cover sheets; (v) The cover sheet exposed on the stack has a durability of approximately three years; (vi) The cover sheet cost is approximately BRL 5/m^2 (2016); (vi) There is the possibility of testing the European model, where only the top of the pile is covered; (vii) Rope lashing causes intense damage to the cover sheet and (viii) In terms of the yard design, the dimensions used by each company are shown in *Table 15*.

Table 15: Main conditions for straw storage based on worldwide practical experience.

Item	GranBio (São Miguel dos Campos – Al)	Dupont (Iowa-Nebraska)	Raízen (Ipaússu-SP)
Size	250,000 tons	48,000 tons	32,500 tons
Pile dimensions	H=9 m x W=2m x L=70 m (1kt/pile)	H=7 x W=12x L=150 m (2kt/pile)	H=4.5 m x W=9.2 m x L= 40 m (270t)
Bales			
Moisture	8 a 15 wt%	22 a 25 wt%	18 wt%
Size	0.90 x 1.20 x 2.40 m	0.90 x 1.20 x 2.40 m	0.90 x 1.20 x 2.40 m
Weight	420 kg	535 kg	420 kg
Distance between piles	30 m each group of 2 piles (6 m)	60 m each group of 6 piles (6.6 m within piles)	15 m
Soil drainage	Compacted soil, slope for rainwater flow of 0.5 wt%	Compacted soil covered with stones and then with water-proofing material	Compacted soil covered with stones and then with water-proofing material
Cover sheet	Thickness 200 microns (30 x 50m) – All the pile	400 microns (15x19m) – pile tops	Thickness 200 microns (20x50m) – All the pile
Monitoring system	Temperature (pilot project in 2 piles)	Infrared camera	No
Surveys	Daily	Farm routine	Daily
Infrastructure			
Fences	Barbed wire	Signaling and restricted access	Signaling and restricted access
Fire Fighting	Water truck / LGE	Local fireman	Water truck / LGE
Lighting	Generator	None	None
Security			
Workers	2 people to cover the piles	5 people to cover the piles	4 people for this operation
Video Camera	No	Yes	No

Note: H is height, W is width and L is stack length, unit in the table. Liquid Generared Extinctor-Foam Generator (LGE)

3.3.2 STRAW PROCESSING

This section discusses the processing routes in the industry, from the straw reception to mixing it with bagasse and burning the mixture in the boilers. Straw removal and recovery were addressed previously.

BALED STRAW PROCESSING

Basically, the quality and availability of the straw depend mainly on how it is recovered, transported, and processed in the industry before being sent for burning in the boilers. There are, basically, three systems used for the recovery of straw for energy cogeneration in Brazilian sugarcane mills: hay harvester straw recovery route and processing; baling; and integral or partial harvesting with straw separation by dry cleaning systems (DCS) (Hassuani et al., 2005; Leal et al., 2013; Cardoso et al., 2015; Okuno et al., 2019). In this section, we present the results of the industrial straw bales processing evaluation.

Upon reaching the industrial unit, the bales need processing before being used, either for the generation of energy or as a raw material in the production of second-generation (2G) ethanol. There are some differences among the bale processing plants installed in Brazil, but the model plant consists of the following: bale reception, short-duration storage area, string removal, unbaling, straw screening, and shredding. *Figure 38* presents the basic unit operation modules. There has been an evolution in recent years with gains in scale and efficiency of systems that can process up to 25 tons per hour. Unfortunately, it is still possible to find many systems with low efficiency, mainly in the shredding operation. Next, we discuss each of these operations and their limitations.

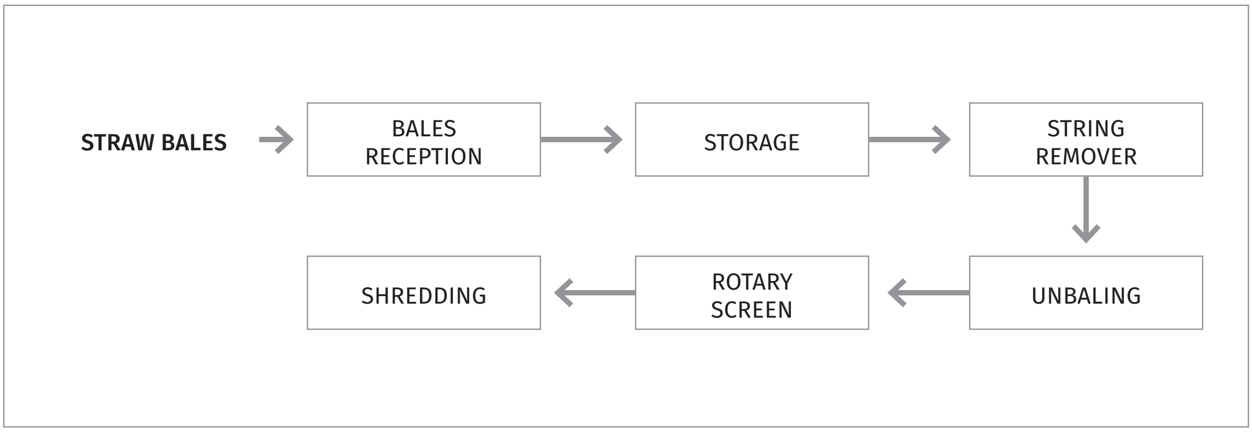


Figure 38: Unit Operation of Straw Bale Processing – Benchmark Case – Mill 3.

I. STRAW BALES RECEPTION

In the bale reception, the bales are removed from the transport trucks and placed in a covered area or directly on a belt conveyor for immediate processing (*Figures 39* and *40*). Unloading is normally carried out by overhead crane or mobile equipment, such as adapted cane loaders or telescopic handlers.

In the benchmark system, the bale reception consists of removing the bales from the trucks by overhead crane and unloading them in a covered storage area or belt conveyor with an automatic weighing system; it has the capacity to simultaneously unload 10 bales. This system is installed at Mill 3 according to a CTC project.

II. STRAW BALES SHORT-DURATION STORAGE

The storage in Mill 3 (CTC Project) is sufficient for approximately eight hours of operation, thereby preventing any variation in the agricultural operations from the impacting operation of the system. Each project must consider the need for straw, as well as the availability of bagasse to fill the supply shortages.

Figure 39: Unloading Straw Bales using adapted Cane Loader Machinery (Mill 2).

Figure 40: Automatic overhead crane for simultaneously unloading 10 bales (CTC).

III. STRAW BALE STRING REMOVAL AND UNBALING

The bales are secured by six longitudinal polymer strings, amounting to approximately 400 to 450 g per ton of straw. This material is unsuitable for burning in boilers and can be present in huge quantities in large plants. The best way to prevent the entry of this material, which can also cause problems in the straw and/or bagasse feeding system, is to use string-removal devices. These devices consist of blades that cut and remove the strings from the bales. In Brazil, there are at least two distinct designs for this equipment: the CTC configuration in the plant installed at Mill 3 and the hammer-type unbaler manufactured by METSO.

IV. ROTARY SCREENING AND SHREDDING

The last step in straw processing is to shred the previously unbaled and cleaned straw by using a rotary screen (*Figure 41*). The shredders used can be fitted with hammers (*Figure 42*) or knives (*Figure 43*). The shredder is at the center of all straw processing and has some features that need improvement.

The bottleneck in the system is the low durability of the knives and the constant choking of the system. The knives need to be sharpened constantly, reducing the availability of the bale processing system. This aspect has been the subject of constant development since its introduction in the processing of straw.

Figure 41: Rotary screen for straw cleaning.

Figure 42: View of the hammer shredder.

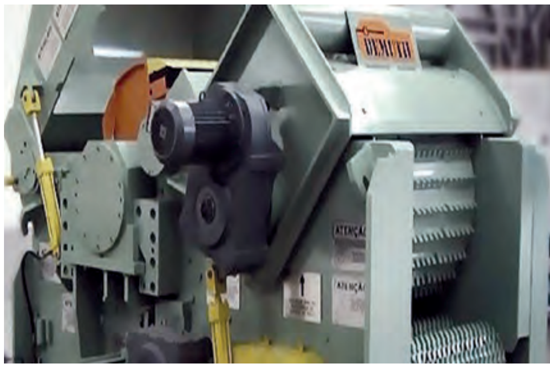


Figure 43: Knife and counter-knife system for straw shredding | Source: Manufacturer's digital catalog.

Owing to the large amount of mineral impurities (MI) present in bales, the unbaling and shredding operations produce large amounts of dust, thereby necessitating a dust control system (*Figure 44*).

Figure 44: Model Straw Bale processing with a dust collection system installed in mill M3.

RESULTS

The main results of the system tests are shown below.

PHYSICAL-CHEMICAL ANALYSIS THROUGHOUT THE STRAW BALES PROCESSING SYSTEM

In this section, we present the results of the assessment of the industrial processing of the baled straw, which are divided by case study. **Case study 1:** Mill 1, tests carried out on June 28th and June 29th, 2016. **Case study 2:** Mill 2, trials were carried out from July 12th to July 14th, 2017 and 08/17/2016. **Case study 3:** Mill 3, trials carried out on November 17th, 2016 and June 27th, 2017.

I. MOISTURE CONTENT OF STRAW DURING THE PROCESS

In general, the physical-chemical properties of straw are different from that of bagasse. In addition, straw samples generally exhibit a wide variation in moisture content over a day and also along the season. When evaluating the processing system, it is important to determine the moisture content of the straw that is mixed with bagasse, to assess the impact of the straw on the properties of the mixture. At Mill 1, the average straw moisture was 10 wt%; at Mill 2, it was 12 wt%; and at Mill 3, it was 15 wt%. Owing to the low moisture content of the baled straw, the mixture with bagasse is considered superior from an energy point of view. However, it should be noted that most of the boilers currently installed in the mills were designed to burn bagasse with a moisture content of 30–60 wt%. In this way, the level of moisture may constrain the straw quantity added to bagasse. In addition, it is important to assess whether the differences in chemical composition will significantly affect boiler operation.

Conversely, the bagasse showed, as expected, more consistency in terms of moisture content. At Mills 1 and 2, the average bagasse moisture was 47.0 wt% and at Mill 3, it was 48.5 wt%. To assess the impact of straw in the mixture, one must take into account the proportion of straw being mixed; however, this information is not available in all mills. The straw and bagasse mixtures at Mill 1 had an average moisture of 43.7 wt%, 7 wt% lower than bagasse; at Mill 2, it was 47.0 wt%, showing that the straw did not affect the moisture of the final mixture in the proportion used; at Mill 3, it was 45.8 wt%. Considering the straw/bagasse ratio of 8.5 wt% reported by the plant, there is a 5.6 wt% reduction in relation to bagasse.

II. STRAW ASH CONTENT DURING THE PROCESS

In this study, total ash consists of the sum of the constitutive ash content in straw (normally between 1.5–3 wt% on dry basis [db]) plus the MI that are adhered to the external surface of biomass.

Regarding the ash content of the straw throughout the process, the straw had higher levels of total ash compared to bagasse. The performance of the straw processing in relation to the reduction in MI was assessed by measuring the total ash content of the straw before and after processing. Mill 2 and Mill 3 used a rotating screen to remove MI from the straw; however, Mill 1 did not have a rotating screen. The transfer of straw from one conveyor to the other created an intense dust release, thereby contributing to the reduction of MI in the straw. *Figure 45* shows the contents of straw ash before and after processing at Mills 1, 2, and 3.

From these results, it was found that processing reduced, on average, the ash content of straw by 25 wt% (db).

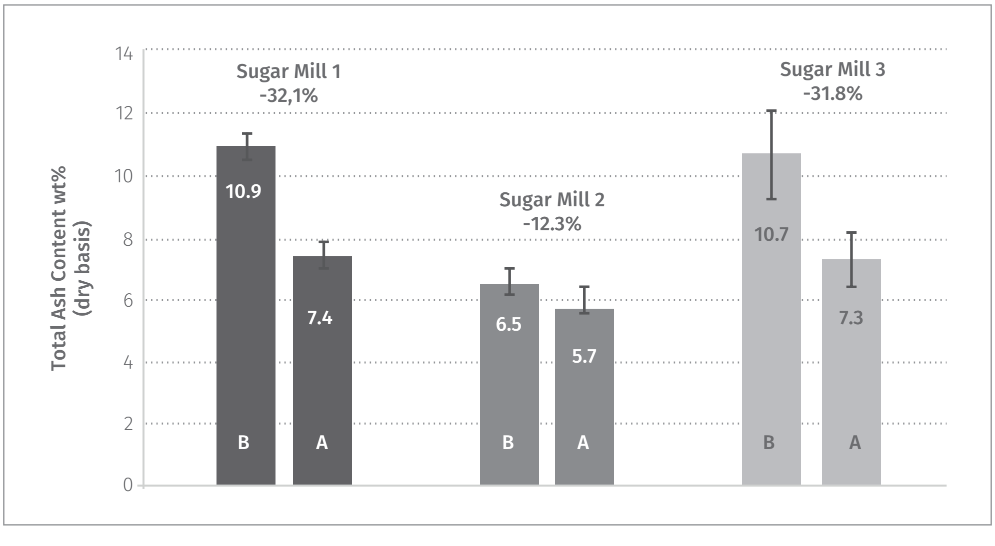


Figure 45: Ash content reduction before (B) and after (A) straw processing.

It seems that the process of removing MI from the straw is difficult because these impurities adhere to the straw. In a previous work carried out by the SUCRE team (Soares et al., 2019a), it was shown that 70 wt% of MI of raw sugarcane strongly adhered to the straw.

As the smaller straw particles are very similar in size to MI, they end up passing through the rotary screen. In this way, the separated fine particles consist of both mineral and vegetal parts, reducing the efficiency of the MI separation process. To evaluate this operation, the total ash content was analyzed using the muffle method (Soares et. al. 2019b) to determine the proportion of straw (organic) and inorganic matter in the effluent residues of the rotary screens. The results showed an inorganic matter proportion on a dry basis of 43 wt% in Mill 2 and 68 wt% in Mill 3. Consequently, the straw proportion were 57 wt% and 32 wt% in Mill 2 and Mill 3, respectively.

III. STRAW PARTICLE SIZE DISTRIBUTION

Normally, bagasse exhibits a more regular particle size distribution, if the cane preparation and juice extraction sessions are well-adjusted. In general, it is expected that 100 wt% (db) of bagasse particles are retained on sieves with opening sizes equal or smaller than 12.5 mm during particle size distribution analysis.

SUCRE adopted this result as a reference to assess whether the straw is suitable for burning in bagasse boilers. In the three mills evaluated, the shredded straw showed a wide variation in particle size distribution, and coarse particles larger than 90 mm were also found. These coarse particles can cause problems in the belt conveyor and, more frequently, in the boiler fuel feeder. In view of these observations, it is clear that the adequacy of the straw particle size is highly recommended to ensure good feeding and combustion processes in a boiler designed for bagasse.

The fact that the particle size distribution in the baled straw is highly irregular makes the work of the shredder difficult and, as a consequence, the shredded straw also has an irregular behavior. At Mill 1, shredding straw produced consistent particle size distribution for approximately 90 wt% (db), referring to particles smaller than 12.5 mm. However, at Mill 2, only 70 wt% of shredded straw samples corresponded to particles smaller than 12.5 mm. At Mill 3, only 61 wt% of the sample was suitable for use (<12.5 mm). To reduce the problems with the shredder and minimize fluctuations in the shredded straw particle size distribution, it is necessary to make periodic adjustments, change the knife or hammer set, and control the straw feeding in the shredder more rigorously.

CONCLUSIONS

1. The average moisture content of the bales arriving at the mills varied from 10 wt% to 15 wt%.

2. The average total ash content present in the straw bales before processing varied from 6.5 wt% (db) (best case) to 10.9 wt% (db) (worst case).

3. After the process of removing MI, the processed straw showed a total ash content (on a dry basis) between 5.7 wt% (best case) and 7.4 wt% (worst case).

4. The baled straw processing and cleaning systems presented a low efficiency in removing MI.

5. The mineral impurity removal efficiency seems to be affected by the straw ash content at the system inlet. The cleanest straw (6.5 wt%) had the lowest efficiency (12.3%), while the dirtiest straw (10.9 wt%) achieved the highest efficiency (32.1%).

6. In general, the straw shredded by the conventional system presented an irregular particle size distribution, along with the presence of coarse straw particles (> 90 mm).

STRAW PROCESSING RECOVERED BY HAY HARVESTER

The bulk straw recovery route, used by hay harvesters (Michelazzo et al., 2008; Carvalho, 2015; Netto, 2018), is the main reason for the low level of investments in the industrial area. As the straw is chopped in the field, it does not need to, on its arrival at the industrial plant, pass through a shredder to reduce the particle size before being burned in the boilers. Apparently, straw already arrives at the mill with an appropriate particle size distribution (CanaOnline, 2015). As already discussed, the raw material particle size distribution has a strong impact on the fuel feeder operation and on the burning efficiency of the boiler.

In addition, there is no rotary screen for the removal of MI from the straw. Usually, the screening process takes place before shredding to avoid excessive loss of straw through the screens. In the study carried out in the SUCRE project, only one mill in Brazil used this route, which was interrupted in 2017. There are no reports or records that indicate that the hay harvester is currently being used in any mill for straw recovery.

RESULTS AND DISCUSSION

In the hay harvester route, wherein the straw arrives from the field is directly discharged into the bagasse yard (*Figure 46*), it is mixed with bagasse by a tractor-type backhoe (*Figure 47*).

Figure 46: Hay harvested straw being discharged into the bagasse yard .

Figure 47: Bagasse and straw mixing by a tractor-type backhoe.

The major challenges of this route are the low density of straw (70–120 kg/m³) in the load and its high content of MI. Because the plant does not use devices to remove these impurities, the quality of the straw depends entirely on the way the straw is treated in the field during recovery. During the tests, the total ash content was 9–25 wt% (db) in the straw samples.

As is the case for MI, the straw particle size is also dependent on the field operation. In the trials carried out during the SUCRE project, it was verified that 90 wt% (db) of the chopped straw sample was below 12.5 mm. This result indicates that a large part of the sample had a particle size that was suitable for use. *Figure 48* shows the results of the straw particle size distribution of the samples collected from the hay harvester.

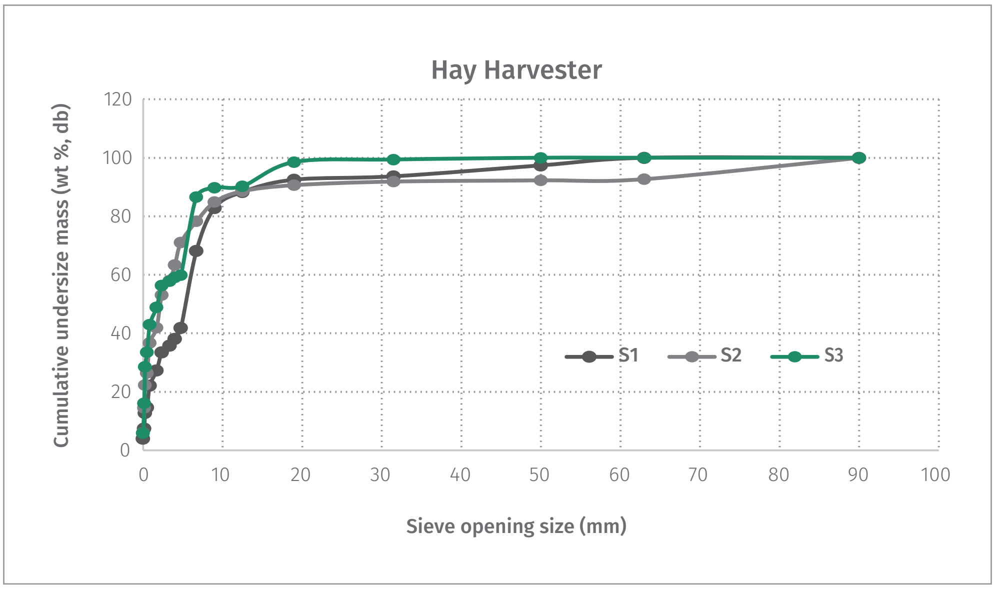


Figure 48: Cumulative undersize mass (wt %) as a function of the sieve opening size of bulk straw (hay harvester) samples (S1, S2 and S3).

In addition to the high fuel consumption of the hay harvester machine (3.3 l of diesel per ton of straw), the cost of knives and counter-knives, which wear out, on average, after 150 h of use, is quite high (see *Figure 49*).

During the field tests, a high idle time of the harvester was also observed; this was mainly owing to the high moisture content of the straw during a major part of the day (operation time of 9–16h). The recommendation is to operate the machine only when the straw has moisture content below 15 wt%. Values above this content make operation difficult, presenting problems, such as frequent “clogging” of the machine.

Using transloaders coupled with trucks results in a high transport cost, making the route unfeasible when the distance between the recovery point and the mill is large.

Figure 49: Wear of hay harvester knives and counter-knives.

Table 16 presents the reference values for the operational parameters of the straw recovery with hay harvester.

Table 16: Operational data of the route for straw recovery with hay harvester.

Parameters	Unit	Value
Ash content	(wt%, d.b.)	9-25
Particle Size	(wt%, d.b. <12.5 mm)	90
Machine consumption	Diesel (l/ton)	3.3
Knife wear	h	150
Moisture content	wt%	< 15
Load density	kg/m³	70-120

CONCLUSIONS

1. The straw recovered using a hay harvester has a low load density (70–120 kg/m³).
2. The total ash content of the hay harvester straw samples was very high, varying from 9 wt% to 25 wt%.
3. Straw samples chopped by hay harvester had 90 wt% (db) for particles smaller than 12.5 mm, indicating that a large part of the sample had a particle size suitable for use as a fuel in biomass boilers.
4. Straw moisture contents above 15 wt% makes the operation difficult, presenting problems, such as frequent “clogging” of machine.
5. This route is unfeasible when the distance between the recovery area and the mill is large.

3.3.3 SUGARCANE DRY CLEANING SYSTEMS (DCS)

DCS play a key role in the green cane integral harvesting system. In this system, a fraction, or the entire amount, of the straw is harvested and transported, together with the sugarcane stalks, to be processed at the factory. After sugarcane reception in the mill, the straw is separated from the stalks using a DCS (Bernhardt, 1994; Rivalland, 1999; Schembri et al., 2002; Rein, 2007; Soares et al., 2019a). In response to the growing demand for the use of straw in various industries, as well as the adverse effects caused by milling sugarcane with high rates of extraneous matter (Scott, 1977; Reid and Lionnet, 1989; Rein, 2005; Muir et al., 2009; Kent et al., 2010; Eggleston et al., 2012ab), DCS has been proposed to overcome and mitigate these problems. Indeed, the separated straw can be used as a fuel for power generation. DCS reduces vegetal and mineral impurities (extraneous matter) from cane through non-water techniques that would, otherwise, lead to significant sugar losses. However, there is a need for additional investments in equipment that generate operating and maintenance costs. *Figure 50* and *51* show pneumatic DCS with downward and upward air blowing, respectively.

Figure 50: DCS with downward air blowing.

Figure 51: DCS with upward air blowing.

RESULTS AND DISCUSSION

The SUCRE Project evaluated five different DCS using a standard methodology. This study involved seven mills located in the states of São Paulo (5 mills; M2, M5, M10, M11, and M13) and Goiás (2 mills; M8 and M12). Among the evaluated mills, five types of DCS were found, and several differences were detected, including the direction of air flow, number of fans, stages of separation, and processing capacity. They were identified using the following codes: DB2F1S (descending blowing – 2 Fans – 1 stage), AB1F1S (ascending blowing – 1 Fan – 1 stage), AB2F1S (ascending blowing – 2 Fans – 1 stage) DB2F2S (descending blowing – 2 Fans – 2 stages), and ROC (rotating octagonal cylinder). The evaluations were carried out between October 2017 and August 2018, corresponding to the 2017/2018 and 2018/2019 harvesting seasons.

Table 17 shows the straw and MI separation efficiencies measured for a DCS operating with green billeted cane. In this case, the straw content was calculated only for the dry and green leaves. Cane tops and roots were not considered because of the system's limitation in separating these components. MI contents were calculated subtracting the inherent ash content from the total ash. MI is composed of extrinsic inorganic compounds that adhere to the external surface of biomass.

According to *Table 17*, straw separation efficiencies determined for systems operating at full ventilation capacity were 17–49 wt% (kg of straw separated by 100 kg fed straw, wb). Simultaneously, the efficiencies of separation of MI were 18–76 wt% (kg of separated MI by

100 kg of fed MI, wb). The results indicate that straw and MI separation efficiencies are related, since when the straw separation efficiency increases, the MI removal efficiency increases too. This was a common trend in almost all mills (M12 was an exception) and is in accordance with MI analysis in raw cane samples, which showed about 70 wt% of MI in the whole sugarcane is adhered to the vegetal impurities (dry and green leaves, tops, and roots).

The efficiencies obtained are lower than those reported by manufacturers or those in previous studies; however, it is important to note that there are differences between the evaluation methods and processing capacities; further, the fact that many systems were not operating under optimal conditions should also be considered. Processing capacity is important because it directly affects the cane layer height at the system inlet. The height or amount of sugarcane piled at the DCS inlet can influence interactions between stalk billets and straw, which, in turn, can prove detrimental during the separation process. Finally, deficiencies involving DCS design, operation, and maintenance parameters were identified during the trials.

Table 17: Operational data, straw and MI separation efficiencies in evaluated DCS- Data on wet basis (w.b.)

Mill	Type	Trial	Damper Opening (%)	Sugarcane Processing during trial (t/h)	Straw Content in Input Cane (wt%)	MI Content in Input Cane (wt%)	Separated Straw During Trial (t/h)	Straw Separation Efficiency (wt%)	MI Separation Efficiency (wt%)
M2	DB2F1S	1	100	754	5.0	0.43	7.2	19.2	29.1
		2	100	657	5.9	0.55	6.5	16.9	24.2
M5	AB1F1S	3[a]	33[a]	120	8.1	1.15	2.5	25.8[d]	16.5
		4[a]	50[a]	116	7.7	1.30	3.3	37.4[d]	20.0
M8	AB2F1S	5	100	1209	5.8	0.78	15.2	21.6	17.6
		6	100	999	3.0	0.15	14.8	49.0	76.1
		7	100	1003	3.6	0.21	14.9	41.2	52.0
		8	100	993	3.7	0.42	14.7	40.0	35.9
M10	DB2F2S	9[b]	55[b]	687	11.9	1.27	4.8	5.9	8.6
		10[b]	55[b]	576	12.3	1.47	6.1	8.6	12.3
		11[b]	65[b]	491	15.0	1.82	13.3	18.1	15.4
		12	100[c]	555	12.8	1.11	17.6	24.8	24.1
M11	DB2F2S	13	100	402	11.7	0.72	16.0	34.0	62.2
		14	100	378	13.8	0.99	13.7	26.4	31.7
		15	100	360	11.6	1.19	13.4	32.1	36.4
M12	DB2F2S	16	100	814	10.7	0.25	21.5	24.7	48.5
		17	100	687	13.8	0.38	23.5	24.7	30.9
		18	100	719	14.6	0.33	25.6	24.6	37.2
M13	ROC	19	-	430	3.4	0.60	3.9	26.5[d]	23.2
		20	-	460	5.7	0.71	3.2	12.1[d]	18.1

[a]Trials conducted below full ventilation capacity owing to stalk losses; [b]Trials performed below full ventilation capacity owing to the limited capacity of shredders; [c]Trial conducted after disassembly of straw shredders; [d]Efficiency values corrected owing to the presence of 10 wt% (trials 3 and 4), 55 wt% (trial 19), and 63 wt% (trial 20) stalks in the separated straw.

Modeling the data from a partner mill (Mill 2) that has a hybrid straw processing system, which can operate concurrently with DCS and the bale processing system (BPS), SUCRE found that DCS efficiency has an important impact on electrical energy operation costs. The energy operation costs for Mill 1 (BPS), Mill 2 (DCS and BPS), Mill 10 (DCS), and Mill 3 (BPS) were calculated.

Figure 52 shows an example of the energy operation cost of straw processing as a function of DCS efficiency for a DCS plus BPS, and for DCS alone.

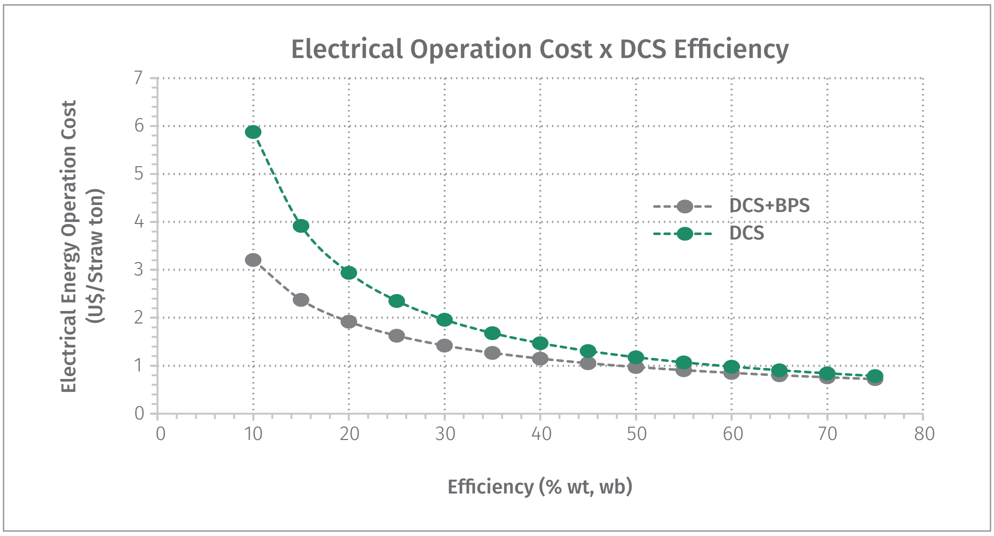


Figure 52: Electrical Energy Operating Cost in USD/ton (BRL/USD 3.25, 2018); DCS: Dry Cleaning System; BPS: Bale Processing System, Data: Considering Electrical Energy Price USD 50 /MWh.

For the energy consumed calculation, the DCS system, rotary screen, and straw shredder were considered. In the BPS, reception, string removal, unbaling, rotary screening, and straw shredding were considered. In the hybrid system (Mill 2), with DCS and BPS operating under current conditions (DCS with 18 wt% of straw separation efficiency and 28,000 tons of baled straw per crop), the cost is USD 2.07 per ton of sugarcane straw. Considering the operation under ideal conditions, with the equipment running at full capacity (DCS with about 65 wt% of straw separation efficiency and 28,000 tons of baled straw per crop), the energy operating cost would be USD 0.80 per ton of sugarcane straw processed; this is about 2.6 times lower.

The operating costs corresponding to the energy consumed by the DCS alone, operating under current conditions (DCS with 18 wt% of efficiency) was USD 3.26 per ton of sugarcane straw. Considering the operation under ideal conditions, with the equipment running at full capacity (DCS with approximately 65 wt% efficiency), the operating cost of energy would be USD 0.90 per ton of sugarcane straw processed; this is approximately 3.6 times lower.

CONCLUSIONS

1. Straw (dry and green leaves) separation efficiencies in DCS were 17–49 wt% (kg of straw separated by 100 kg fed straw, wb).

2. The efficiencies of separation of MI in DCS ranged from 18 wt% to 76 wt% (kg of separated MI by 100 kg of fed MI, wb).

3. The straw and MI separation efficiencies were related. Therefore, since the cleaning system increased straw removal, it is very likely that the MI removal efficiency will also increase.

4. The efficiencies obtained in the tests are lower than those reported by the manufacturers and previous studies. However, deficiencies involving DCS design, operation, and maintenance parameters were identified during the trials.

5. DCS processing capacity is important because of its relationship with the cane layer height at the system inlet, and a higher layer height can prove detrimental to the separation process.

6. The separation efficiency of DCS plays a key role in the operational costs. In Mill 2, considering the operation under ideal conditions, the operating cost of energy would be USD 0.80 per ton of sugarcane straw processed.

3.3.4 ALTERNATIVE STRAW PROCESSING SYSTEMS

Some studies have shown the application of water-washing processes to improve the biomass properties to be used as a fuel (Jenkins et al., 1996; Turn et al., 1997; Yu et al., 2014; Vassilev and Vassileva, 2019). Although this topic has been studied to some extent, there are only a few examples using sugarcane straw as a feedstock. The exceptions are the reports published by the IEA Bioenergy (Biomass pretreatment for bioenergy) and the University of Hawaii (Improving Fuel Characteristics of Sugar Cane Trash), which contain specific results for sugarcane straw (Meesters et al. 2018; Turn et al., 2008).

To mitigate the straw-related problems found in bagasse fired boilers, some Brazilian mills use alternative straw processing systems. In contrast to conventional conditioning systems based on sieving and shredding, the alternative systems included the washing and transportation of DCS separated straw in a water channel (*Figure 53*), followed by cush-cush screen drainage (*Figure 54*) and straw feeding in the last mill of the milling tandem (*Figure 55*), producing a bagasse-straw mixture (Mill 5 and Mill 6). Another processing alternative was the milling of drained straw in an independent mill (*Figure 56*), followed by the production of a bagasse-straw mixture on the belt conveyors (Mill 7).

Figure 53: DCS separated straw washing and transporting in a water channel.

Figure 54: Washed straw drainage in the cush-cush screen.

Figure 55: Straw feeding into the last mill of the milling tande.

Figure 56: Independent mill for straw shredding.

The assessment of these alternative systems was carried out in collaboration with three partner mills located in the Brazilian state of São Paulo (Mills 5, 6, and 7). During the evaluation trials, straw and bagasse samples were collected throughout the conditioning process and the following physicochemical analyses were conducted: moisture, ash, elemental analysis (C, H, N, S, and Cl), ash chemical composition by X-ray fluorescence, higher heating value (HHV), and particle size distribution.

Additionally, to better understand the straw washing and leaching processes, laboratory- and bench-scale studies were carried out in shakers and extractors under varying process conditions, such as water temperature (20–60 °C), washing time (5–55 minutes), straw-to-water ratio (1:20–1:75 w/w), and agitation (250–1500 rpm).

RESULTS AND DISCUSSION

I. STRAW WASHING AND LEACHING PROCESSES

Although the systems examined were not optimized, the straw washing process proved to be rather promising, given that the average efficiency for ash content reduction for the tested plants was 39%–46%, as shown in *Figure 57*.

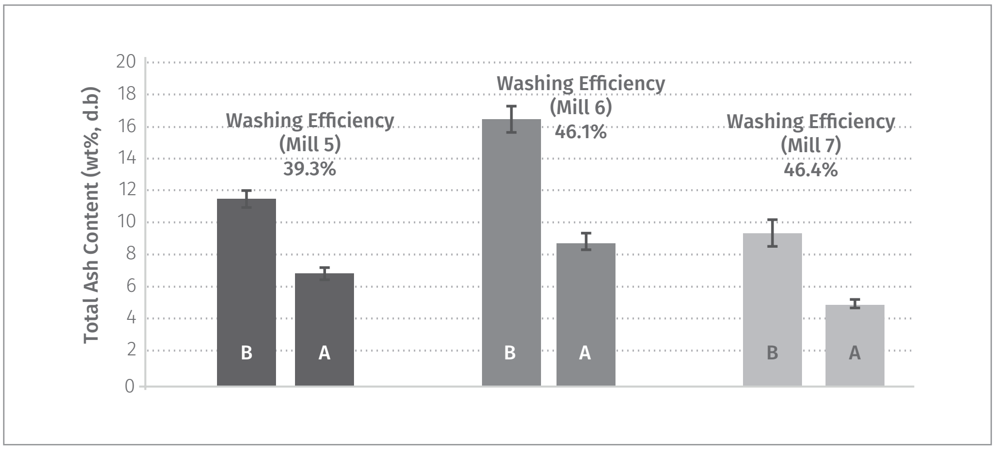


Figure 57: Total ash contents before (B) and after (A) straw washing process.

In addition, the washing process has been shown to promote the leaching of chemical elements that are critical for burning in boilers; these include silicon (Si), potassium (K), sulfur (S), and chlorine (Cl). Lastly, it was noted that leaching efficiencies can reach greater values in optimized washing processes.

This hypothesis was confirmed by the results of the laboratory- and bench-scale experiments. The best efficiencies were obtained for the leaching process in the extractor (*Figure 58*) under the following process conditions: dry and shredded straw (20 g); distilled water (1.5 L); 20 °C; 1,500 rpm; and 3 minutes of operation; this was done twice more (a total of 3 steps of washing) using 1.5 L of clean fresh water.

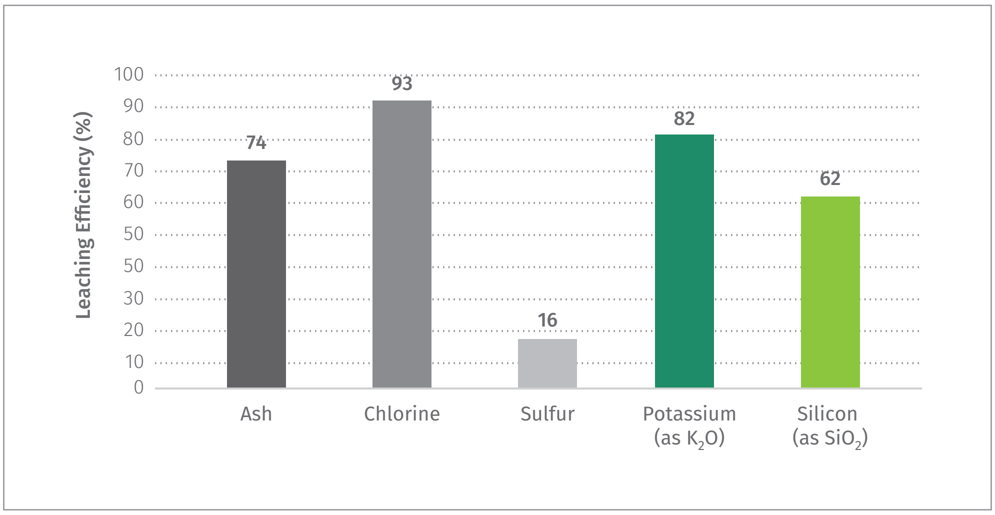


Figure 58: Water washing and leaching efficiencies obtained during trials carried out in an extractor.

From laboratory - and bench-scale studies, parameters were identified to be optimized in commercial systems, such as agitation efficiency, contact time, temperature, and washing water quality.

II. USE OF CONVENTIONAL MILL FOR STRAW SHREDDING

The assessment of the straw shredding processes using conventional sugarcane mills to reduce the particle size distribution presented very interesting results. After shredding using an independent mill, it was observed that 90 wt% (on average) of the straw refers to particles smaller than 12.5 mm (*Figure 59*); this shows a strong similarity with the bagasse particle size distribution. In addition, the mill presented higher operational regularity than the hammer and knife shredders. The mill produced straw samples with higher homogeneity and smaller particle size variations.

Feeding straw in the last mill of the milling tandem produced more homogeneous bagasse-straw mixtures, with a particle size distribution very similar to that of bagasse (90 wt% were smaller than 12.5 mm). By contrast, adding straw to bagasse on belt conveyors produces more heterogeneous mixtures (*Figure 60*). In short, mills have proven to be more efficient than shredders because they are better at achieving the desired straw particle size distribution. Preliminary studies carried out by SUCRE and reported in the project reports indicate that CAPEX should stay between 50% for Alternative 1 and up to 70% for Alternative 3, in relation to a conventional sugarcane straw processing system. These alternatives are detailed in the next section (3.3.5). However, only after completing the detailed investment studies can a definitive assessment of the amounts involved be made.

Figure 59: Cumulative undersize mass (wt%, db) as a function of the sieve opening size of shredded straw (independent mill) samples (SS1, SS2, SS3 and SS4) collected at Mill 7.

Figure 60: Typical appearance of straw processed by conventional hammer shredder (A), straw shredded in an independent mill (B) and bagasse-straw mixture produced through the straw feeding in the last mill of the milling tandem (C).

3.3.5 SUCRE'S PROPOSALS FOR STRAW PROCESSING

After four years of tests and assessments in collaboration with partner mills, the SUCRE Project has developed some proposals to improve the efficiency of straw processing. The proposed configurations aim to improve the quality of straw, allowing greater use of this biomass in the mixture with bagasse to increase the bioelectricity generation potential of the Brazilian sugarcane industry.

The project proposals were designed to process not only the DCS separated straw, but also the unbaled straw. *Figure 61* shows a simplified flowchart of the proposed process. The first step involves the straw pre-washing, followed by cush-cush drainage and milling in an independent mill, along with the addition of hot imbibition water (50–60°C). These steps remove some of the impurities and improve the straw particle size distribution. Then, the straw is washed with water in an extractor with a mechanical agitation device, which increases the contact between water and straw, in addition to transporting the straw along the equipment. Next, the straw is drained again in another cush-cush, and based on this step, SUCRE proposes three possible configurations. In the first one, which was designed for mills with spare milling capacity, the straw is fed in the last mill of the milling tandem and mixed with bagasse (C1: Alternative 1). In the second method, the straw is shredded in an independent mill and then added to the bagasse on the belt conveyors (C2: Alternative 2). In the third, the straw is milled and mixed with a part of the bagasse produced using an independent mill (C3: Alternative 3). For a more conscious consumption, the water used in the process should be treated and reused, allowing for low replacement rates of this resource.

It is expected that SUCRE´s proposals would enable the use of higher contents of straw in the mixture with bagasse, such as 25 wt% (db).

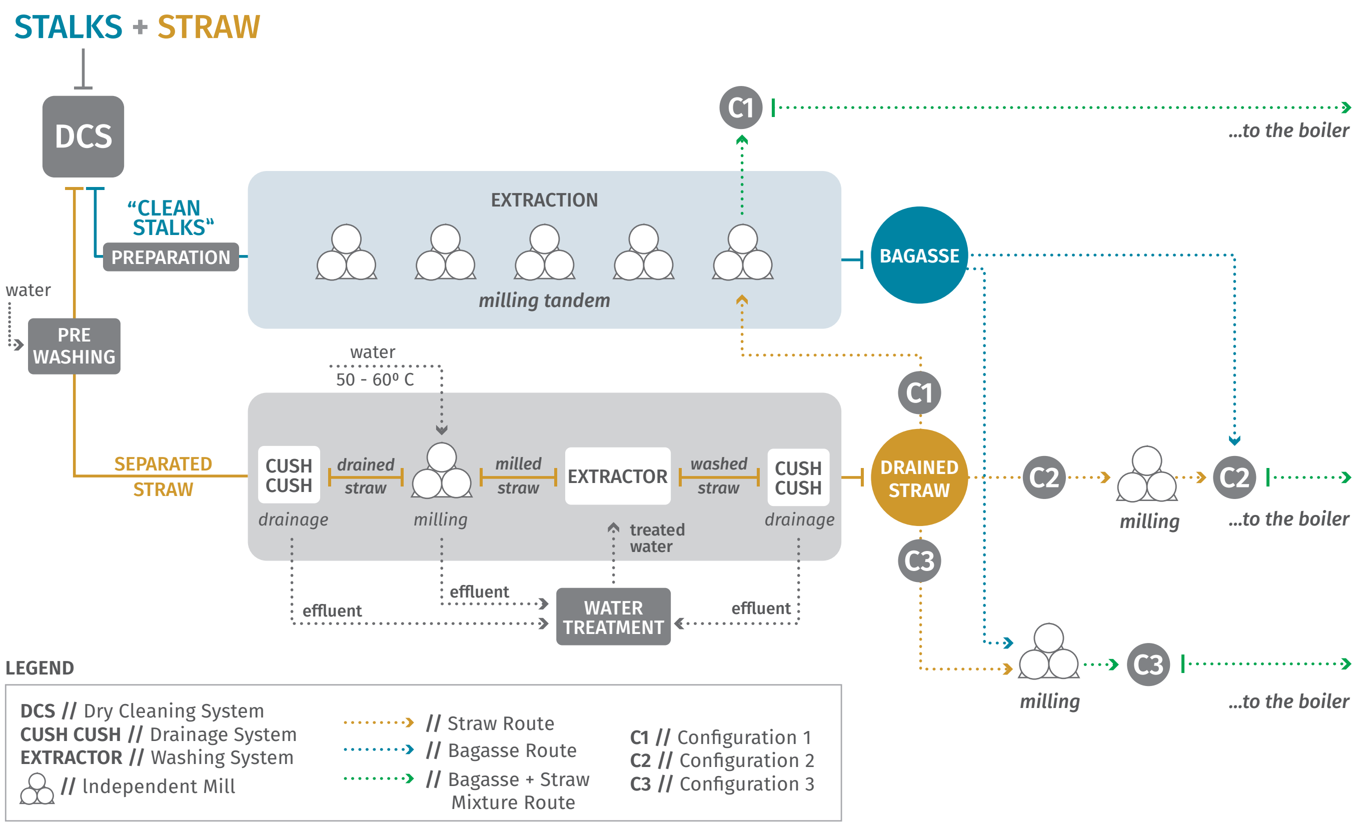


Figure 61: Process Flowchart: Configurations proposed by SUCRE for straw processing, C1, C2 and C3: Alternative 1, 2 e 3, respectively | Design credit: Luiz Nascimento/Comunicação CNPEM.

CONCLUSIONS

1. The straw washing process proved to be rather promising, given that the average efficiency for ash content reduction was 39%–46% wt%.

2. The best efficiencies were obtained for the leaching process in an extractor, which performed the removal of 74 wt% of ash, 93 wt% of Cl, 16 wt% of S, 82 wt% of K_2O and 62 wt% of SiO_2.

3. The use of a conventional milling system proved to be more efficient than conventional shredders in the reduction of the straw particle size.

4. SUCRE´s proposals are expected to enable the use of higher contents of straw in the mixture with bagasse, such as 25 wt% (db).

3.3.6 EVALUATION OF SUGARCANE STRAW AND BAGASSE BURNING IN BIOMASS BOILERS

In the past, sugarcane straw was burned off in the field before manual harvesting. With the end of cane burning, it started to be harvested, processed and added to bagasse at the industrial plant, thus increasing the potential for additional electricity generation that could be exported to the public grid. However, certain physicochemical properties of straw can affect the performance of the biomass boilers in the mills because the majority of these systems were originally designed to operate with bagasse. This fact, along with other differences between straw and bagasse, such as density, particle size distribution, and the presence of MI, led to the need to better comprehend the behavior of straw when it is burnt in biomass boilers. Feeding straw into the boiler can affect the boiler's performance, increase maintenance costs, and reduce the durability of the components. In addition, straw can contribute to the formation and emission of toxic compounds, such as dioxins. In this work, the factors inherent to the quality and composition of this new raw material were investigated.

RESULTS AND DISCUSSION

I. BRIEF DESCRIPTION OF THE TESTS

The assessed mills present boilers with different designs and operating conditions, in addition to using different routes for straw recovery and processing. The evaluations were based on two main trial types: those performed during the season and those performed in the off-season. The season tests were conducted according to the type of fuel used for burning: (i) using sugarcane bagasse exclusively, and (ii) using a mixture of straw and bagasse in different proportions as the fuel. During the season trials, fuel and ash (produced in the boiler) samples were collected and analyzed. In addition, process data collection and flue gas analysis were carried out during the tests. In the off-season trials, samples of fouling/slagging and corrosion from different regions of the boiler were collected. *Table 18* describes the boiler types and operational conditions of the assessed mills.

Table 18: Boiler type and operating conditions in the mills.

Parameter	M1 -Vibrating grate	M2 - Pin hole grate	M3 - Pin hole grate	M8 - Pin hole grate	M9 - Bubbling fluidized bed
Capacity (TSH)	200	200	200	250	200
Steam temperature (°C)	504.6	500.4	483.9	506.4	499.4
Steam pressure (bar)	70.0	67.0	66.0	68.0	67.0
Flue gas temperature in superheater (°C)	801.0	806.0	695.0	816.0	906.0
Flue gas temperature in the water preheater (°C)	-	382.6	390.0	408.0	436.2

II. MIXTURE OF STRAW AND BAGASSE USED AS FUEL IN THE MILLS

Testing and operational parameters obtained during the harvest season allowed for an estimation of the sugarcane straw content added to sugarcane bagasse in the mixtures used in the evaluated boilers. *Table 19* presents the values of the straw mass fraction used as fuel in the mills on a dry basis. Owing to limitations in measuring the exact amount of sugarcane straw and bagasse in the mixture used in the continuous feeding systems of boilers, we had to rely on estimations.

Table 19: Straw mass fraction used as fuel in the mills.

Mill	M1	M2	M3	M8	M9
Straw(1) (wt%, d.b.)	12.0	5.4	14.0	5.0	18.8

(1)Straw fraction in mixture (Sm, given in wt%) was calculated as follows: Sm = (S / (S + B)) × 100, where B is the amount of sugarcane bagasse and S is the amount of: straw which was processed at the mill

The results indicate a substantial variation in the amount of straw utilized in the assessed mills. The amount of processed straw used in combustion was significantly higher in mills adopting the baling system (M1, M3, and M9), with the average straw utilization being over 100% as compared to mills operating with integral harvesting and straw separation by DCS (M2 and M8), using approximately 5 wt% of straw in the mixture. The current average use of straw is below the potential recovery capacity of most mills; this could reach about 25 wt% of straw in the total fuel used in the mills.

III. FUEL CHARACTERIZATION

Table 20 shows the elemental composition, ash content, and HHV of bagasse, straw, and the straw/bagasse mixtures.

Table 20: Elemental composition of bagasse, straw, and straw/bagasse mixture.

Parameters (wt%, d.b.)	Bagasse	Straw	Mixture (BS)
Carbon (C)	40 - 44	38 - 42	39 – 43
Hydrogen (H)	6.0 – 7.0	5.5 – 7.0	5.5 – 6.4
Nitrogen (N)	0.2 – 0.3	0.5 – 0.6	0.2 – 0.5
Sulfur (S)	0.09 – 0.11	0.12 – 0.20	0.03 – 0.05
Chlorine (Cl)	0.02 – 0.05	0.20 – 0.40	0.02 – 0.1
HHV (MJ/kg)	18.5 – 19.5	16.0 – 18.3	18.0 – 19.5
Ash (wt% d.b.)	2.5 – 5.5	4.5 – 10.5	4.0 – 6.5

Elemental analysis of the fuels showed a small variation in the concentrations of carbon, nitrogen, and hydrogen between the bagasse and straw. The total ash content found in the straw was much higher than that found in bagasse. The comparison between ash content from the baled straw and that separated by the DCS show that, on average, the latter had higher ash contents.

The chlorine concentration in straw was approximately 10 times higher than that found in bagasse. In combustion, chlorine is one of the main elements that cause the vaporization of inorganic compounds containing elements such as potassium, and that increase the formation of fouling and corrosion on the heat exchange surfaces. It is also a constituent of dioxins, which are highly toxic compounds that can be present in combustion gases. The sulfur concentration in the straw samples analyzed was 2–4 times higher than in bagasse. Chlorine, sulfur, and potassium are the main causes of aerosol, fouling/slagging, and corrosion on the heat exchange surfaces of the boilers. The HHVs had similar values for bagasse and straw. However, in relation to the lower heating value (LHV), which considers the moisture content, the straw from the bale route reached values twice as high as that of bagasse, contributing to the increase in the LHV of the bagasse-straw mixture. The moisture of the straw separated by the DCS was similar to the value found for bagasse (49 wt%), whereas the straw recovered by bales showed values of approximately 15 wt% on average.

IV. CHEMICAL COMPOSITION OF THE FUEL ASHES

The analysis of the chemical composition of the fuel ash, particularly the bagasse-straw mixture, is extremely important; this is because the main chemical elements that contribute to fouling/slagging and corrosion formation are identified. Special attention must be paid not only to the chemical elements present in the fuel, but also the possible relationships and interactions among them. This study is the first step in the attempt to define indexes that allow foreseeing the possible problems related to the formation of fouling, slagging, corrosion, and emissions of pollutants in the atmosphere when burnt in a boiler.

V. INDEXES FOR PREDICTION OF FOULING FORMATION, CORROSION, AND GAS EMISSIONS

a) Aerosol emission indicators

The alkali elements, K and Na, as well as S, Zn, and Cl are vaporized during the combustion process, leading to condensation and deposit formation on the heat exchanger surfaces. Normally, the majority of biomasses have high concentrations of K, Na, Zn, Pb, S, and Cl, facilitating K release (Brunner, 2006).

In addition, Jöller (2008) investigated the potassium release process, which has also been investigated in previous studies. Most of the potassium released to the gas phase is in the form of KOH and KCl, with smaller amounts in the form of K_2SO_4 and K_2CO_3 in the temperature range of 500–1150 °C, revealing a substantial influence of sulfur and chlorine on this process. However, several other parameters play a role in potassium release. Studies also highlight that evaluations of reactions between K–Ca–Si systems indicate higher rates of potassium release at 1000 °C than at 900 °C, suggesting a possible reaction between SiO_2 and CaO, and that a greater amount of K is released in the gas phase instead of being incorporated into the silicate structures (Novaković, 2009).

Based on the results of industrial and pilot-scale tests, the total content of K, Na, Zn, S, and Pb in fuels proved to be an efficient indicator of the emission potential of particulate material in grate-fired boilers. An increase in the proportion of K, Na, Zn, S, and Pb in fuel (fuel index) results in higher aerosol emissions. Higher aerosol emissions are associated with higher formation of deposits on heat exchanger tubes because of the higher condensation of ash vapors on these surfaces.

According to the aerosol emission index, combustible biomasses can be categorized as low particulate or aerosol emissions for a fuel index < 1000 mg/kg on a db; medium particulate or aerosol emission for fuel index in the range of 1,000 – 10,000 mg/kg (db); and high aerosol emissions for fuel index above 10,000 mg/kg (db) (Sommersacher, 2012).

b) K release indicator

Müller et al. (2006) and Knudsen et al. (2004) suggested the utilization of the molar ratio (Si/K) as an indicator for potassium (K) release potential during combustion. A high molar ratio (Si/K) leads to the formation of potassium silicates that tend to be trapped in bottom ashes, reducing the potassium released as aerosol during combustion. However, if less K is available in the gas phase for reactions with S and Cl, the gaseous emissions of SOx and HCl may increase. Results concerning the correlation between the molar ratio (Si/K) and K release as aerosol were obtained from biomass combustion experiments on a laboratory scale (Sommersacher et al. 2012). For ratio values below 2.5, there is a tendency for greater potassium release in combustion.

c) Indicator for ash melting behavior

High-temperature flue gases entrain the vaporized ash particles that undergo condensation during contact with cooler heat exchanger surfaces. Condensation of inorganic vapors occurs when the gas temperature drops below the fusion temperature of vaporized compounds when the biomass contains high levels of chlorine and sulfur. Condensation and melting of ash on a surface (fly ash particles) lead to the formation of a thin and sticky film, which may alter the uptake of other particles (*Kleinhans et al. 2018*).

Several studies have evaluated the influence of elements on the fuel composition of ash melting behavior in biomass. The molar ratio (Si+K+P)/(Ca+Mg+Al) was used as an indicator of the ash melting behavior. This index considers Si, combined with K and P; this usually reduces the ash melting temperature in relation to Ca, Mg, and Al, which increase the ash melting temperature.

The experimental results from the evaluation of several biomasses demonstrated that usually, for a ratio >2.5, the ash melting temperature decreases, reaching levels below 1,100 °C; for a ratio >4.0, the ash melting temperature reaches levels below 1,000 °C. Therefore, there is a linear correlation between the molar ratio (Si+P+K)/(Ca+Mg) and the ash melting temperature; this decreases as the ratio increases *(Sommersacher et al. 2013)*. According to experimental studies, the melting temperature of the ash reduces as the proportion of Si and K increases.

d) Indicator for high-temperature corrosion risks

The potential for greater corrosion on heat exchanger surfaces resulting from biomass combustion with a high content of inorganic components is strongly influenced by the presence and release of chlorides in the reaction. The main corrosion mechanisms on high-temperature surfaces are related to the direct attack of HCl. The formation of alkaline sulfates and chlorides on heat exchanger surfaces dissolves the protective layer and the chloride sulfation reactions close to the deposition layer by releasing Cl, which in turn attacks the tube surface (known as active oxidation).

As mentioned before, sulfur and chlorine are important elements for aerosol formation and deposits of alkaline sulfates and alkaline chlorides, which form particles or condense on heat exchanger surfaces. Investigations indicate a correlation between fuel components as indicators of corrosion risk at high temperatures.

Related studies of Salmenoja (2000) and Obernberger et al. (2004) indicated a correlation between the molar ratio (2S/Cl) in the fuel and aerosol emissions, which can be used as an indicator of the risk of corrosion at high temperatures. Experiments suggest that for a molar ratio (2S/Cl)> 4 in the fuel, the corrosion risks are low, and for a molar ratio (2S/Cl)> 8 in the fuel, the corrosion effects are insignificant.

The presence of S and Cl is fundamental to the formation of vaporized or aerosol particles because they have a direct influence on sulfates and chlorides during combustion, indicating a relation between the molten deposit formation and the presence of those elements in the fuel. The 2S/Cl ratio was applied separately to fuel samples collected in the tests, as shown in *Table 21*.

Mills	**Fuel**	**Aerosol emission (mg/kg)**	**K Release (mol/mol)**	**Ash melting behavior (mol/mol)**	**Corrosion risk (mol/mol)**
	B	2,906.1	3.56	1.60	3.37
M1	S	15,309.2	3.80	1.40	1.07
	BS	3,496.0	3.14	1.61	3.27
	B	5,046.7	2.87	2.46	3.38
M2	S	18,838.1	0.81	1.46	0.77
	BS	7,053.4	2.66	2.16	1.48
	B	4,715.9	6,13	3.32	3.71
M3	S	21,292.3	1.96	1.37	0.75
	BS	11,546.4	2.48	1.76	1.30
	B	4,277.5	2.69	2.24	2.60
M8	S	15,453.8	3.09	1.60	1.40
	BS	8,397.6	3.41	1.88	1.87
	B	3,649.9	10.33	2.77	2.12
M9	S	9,820.6	1.88	1.52	0.81
	BS	5,230.5	5.59	2.34	1.04

Table 21: Fuel indexes applied to biomass used in boilers.

B: Bagasse, S: Straw, BS: Bagasse and straw mixture.

VI. ELEMENTAL CHEMICAL COMPOSITION OF BIOMASS ASH

The results of the ash composition of bagasse and straw-bagasse mixtures are presented in *Table 22*. The analysis of ash composition allows the evaluation of the percentage of chemical agents involved in the ash melting and fouling processes on heat exchanger surfaces.

Table 22: Ash composition of bagasse and mixtures (BS).

Composition (wt %)	M1		M2		M3		M8		M9	
	B	BS	B	BS	B	BS	B	BS	B	BS
SiO_2	45.24	42.79	38.34	37.14	59.97	37.19	42.29	43.24	59.70	49.80
K_2O	12.37	12.63	8.44	9.27	7.67	11.75	12.32	9.95	4.53	6.99
Al_2O_3	9.91	12.88	13.17	9.84	8.38	10.91	13.69	18.78	13.60	15.10
CaO	6.59	6.65	6.66	6.8	4.27	8.07	3.80	2.81	3.25	2.83
Fe_2O3	6.91	7.18	13.76	11.08	5.72	10.61	9.59	9.73	8.59	13.04
P_2O_5	6.78	4.98	4.08	5.32	3.42	3.02	5.64	3.54	2.15	3.28
SO_3	3.58	4,13	5.55	6.77	3.86	8.79	2.66	2.86	2.79	3.64
MgO	5.67	4.61	6.77	9.57	4.96	6.45	5.21	4.21	3.20	3.60
TiO_2	2.08	2.79	3.22	3.64	1.40	2.27	2.013	2.00	0,61	0.43
Na_2O	0.51	0.76	0.20	0.29	0.29	0.74	1.33	0.91	0.61	0.42
Cl	0.12	0.35	0.15	0.58	0.13	0.48	0.10	0.29	0.91	0.74
Others	0.23	0.21	-	-	0.12	0.20	0.27	0.25	0.38	0.32

B: Bagasse, S: Straw, BS: Bagasse and straw mixture.

The ash composition presented in *Table 22* indicates variations in fuels of evaluated mills, such as increased concentrations of potassium, sulfur, and chlorine in mixtures in comparison with sugarcane bagasse. The chlorine content found in ashes of mixtures can be five times higher than that found in ash from bagasse. However, an increase in the concentration of alkali earth metals, such as calcium and magnesium, was identified in ashes of mixtures (BS), in most cases. This may lead to a reduction in the potential for ash deposition at high temperatures, an effect extensively described in the literature.

VII. EVALUATION OF FUEL INDEXES

The investigation of possible effects of sugarcane straw chemical composition on the deposit formation process is based on the analysis of samples obtained during testing. Selected fuel indexes for the prediction of biomass ash melting were applied to evaluate the potential of bagasse, straw, and mixtures used in boilers. *Table 21* presents a comparison of the indexes evaluated.

The results of the evaluation of the aerosol emission index for bagasse, straw, and mixture (BS) obtained by the sum of K, Na, S, Zn, and Cl in the fuel utilized in mills are presented in *Table 21*. The results revealed that about 10 wt% of sugarcane straw mixed with bagasse, as in mill M3, can promote increases of up to 140 wt% in aerosol particles as compared to pure sugarcane bagasse. However, the use of 3.5 wt% of straw in the mixture (BS) in mill M1 resulted in the lowest potential for particulate emissions, with a slight increase of about 15 wt% in the mixture in relation to sugarcane bagasse.

The evaluation of the molar ratio (Si/K) for bagasse in samples of straw and mixture revealed high values for bagasse in all samples. High molar ratio Si/K is an indication of an increased tendency for potassium silicate formation that preferably agglomerates in the bottom ashes, thus reducing K release as aerosols. Nonetheless, indexes calculated for sugarcane straw samples from M2, M3 and M9 were below 2.5, indicating lower potassium adhesion to ashes, according to experimental studies (Mack et al., 2019). Samples from mixtures indicated higher K release potential in comparison with bagasse, yet still showed a moderate potential release in comparison with the current percentage added to sugarcane bagasse. Fuels from Mills M2 and M3 showed the highest risks of K release and aerosol formation.

As shown in *Table 22*, the molar ratio (Si+P+K)/(Ca+Mg+Al) was investigated as an indicator of ash melting behavior for fuels utilized in boilers. In all cases evaluated, sugarcane bagasse showed higher values for the ratio and, therefore, greater risks of decreasing the ash melting temperature. On the other hand, sugarcane straw presented lower indexes in all evaluated samples. With regard to composition, bagasse had a higher proportion of Si in relation to Ca, Mg, and Al, which are indicator components of the ash melting point increase. High concentrations of Si and K released as aerosols favor the decrease in ash melting point. The molar fractions involved in the ratio represent only the content of each element that makes up the ash, and do not consider the amount of ash present in each fuel. On average, sugarcane straw had twice the content of ash found in sugarcane bagasse, a condition that is not considered in the molar ratio.

Fuel indexes evaluated for utilized mixtures (BS) indicated greater differences between M1 and M9, with lower risk presented by the mixture used in M1, and also in fuels of M3 and M8. However, the mixture (BS) used in M9 indicated higher risks of reduced ash melting point, especially due to the combination of a higher content of silicon and potassium.

The index applied in the evaluation of corrosion risks under high temperatures by molar ratio (2S/Cl), as presented in *Table 21*, revealed that all evaluated biomasses presented corrosion risks, yet with a significant difference between sugarcane straw and bagasse, which are traditionally used. Sugarcane bagasse presented a safer condition, with low risk in most samples evaluated, but increased the potential risk for M9. Comparative results between mixtures demonstrate that the highest rates for risks were found in M3 and M9 mills and the lowest in M2 mill. The highest values refer to pure sugarcane bagasse utilized in M2, M3, and M4 mills, that is, for (2S/Cl) > 4, the corrosion risk is reduced. The M9 mill presented the lowest values for the ratio (2S/Cl) for both bagasse and mixture utilized, indicating a higher risk of corrosion at high temperatures on the surfaces where fouling occurs. The evaluation of bagasse and straw mixtures recovered in mills indicated substantial differences between M1, with lower corrosion risk, according to the ratio, and M9, which had the lowest value for the ratio and highest corrosion risk.

VIII. BOILER SURFACE DEPOSITS

The Figure 62 illustrated the regions of deposit and scale formation in biomass boilers.

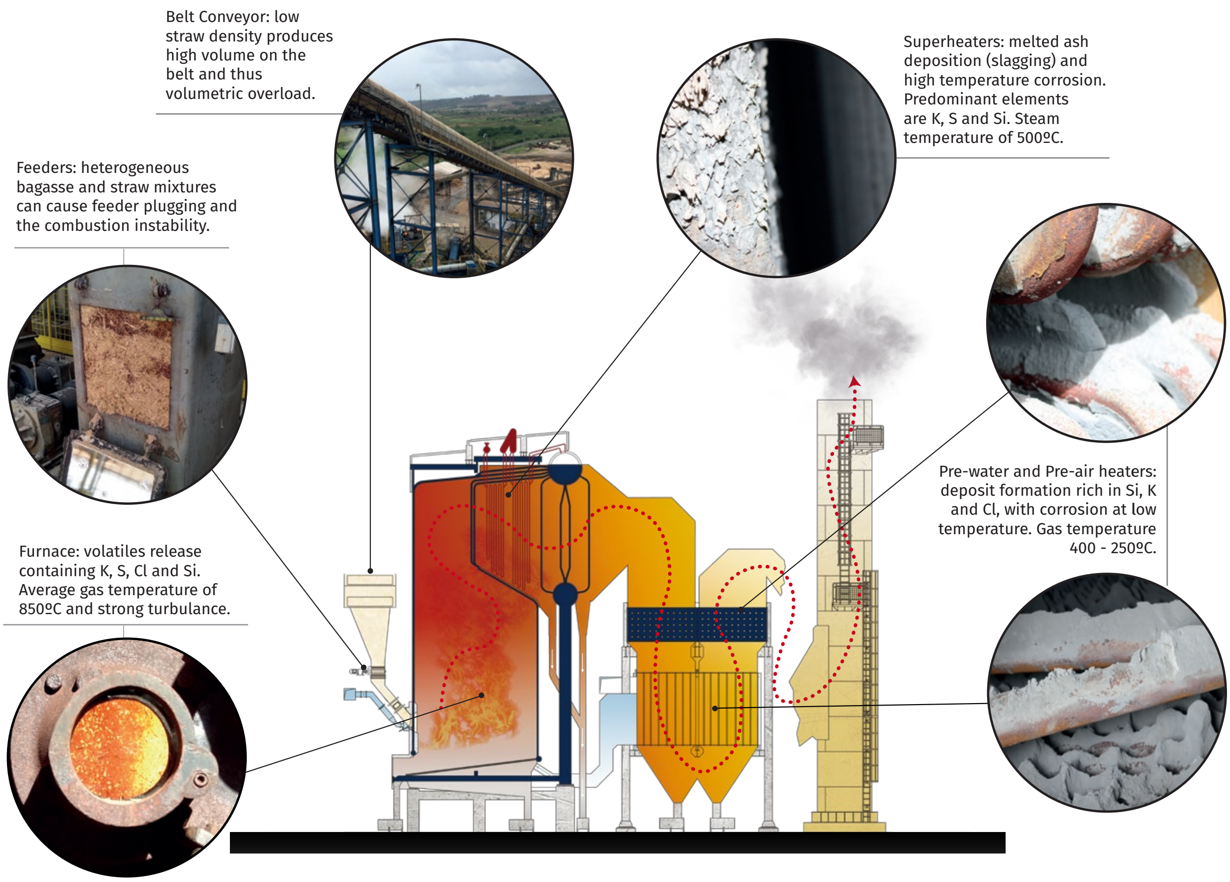


Figure 62: Burning straw impacts on the biomass boiler | Design credit: Luiz Nascimento/Comunicação CNPEM.

For this, fouling deposits and corrosion, formed on the heat exchange surfaces of the boiler, were collected during the off-season. The fouling samples were collected on the secondary superheater, and the deposits formed in the convective tubes bundle, air preheater, and economizer. The secondary superheater is the accessory that operates most critically and under the highest temperatures in the boiler and therefore deserves close attention. The samples were collected in two ways: from the outermost layer and released from the encrustation and, separately, from the innermost layer adhered to the tube. *Tables 23* and *24* show the concentrations of the elements in the two samples.

Table 23: Chemical elements concentration present on external layer of the fouling deposits.

Composition (wt%, db)	M3		M1		M2	M8		M9
	Boiler 03	Boiler 04	Boiler 10	Boiler 11	Boiler 03	Boiler 1	Boiler 2	BFB
K_2O	32.34	33.01	23.90	24.62	24.90	24.66	24.51	25.66
SO_3	5.74	4.06	5.23	6.35	7.54	7.88	9.46	1.12
Fe_2O_3	5.44	4.46	8.84	6.47	5.07	5.73	5.19	5.83
CaO	7.48	7.56	13.80	13.95	11.18	10.95	10.57	15.50
SiO_2	3.48	3.80	5.45	6.71	5.75	1.74	3.45	4.01
Al_2O_3	2.58	2.19	4.80	4.03	3.80	3.31	3.21	3.67
P_2O_5	1.12	2.06	3.86	3.51	2.96	1.71	1.40	2.23
Cl	n.d.	n.d.	0.15	n.d.	n.d.	0.14	n.d.	1.88

n.d.: not detected

Table 24: Concentration in the inner layers adhered to the tube.

Composition (wt%, db)	M3		M1	M9
	Boiler 03	Boiler 04	Boiler 03	BFB
K_2O	42.31	43.73	32.73	41.46
SO_3	29.81	37.61	24.52	23.73
Fe_2O_3	4.87	2.78	7.99	1.83
CaO	6.07	2.54	4.88	4.16
SiO_2	8.25	5.57	12.69	13.17
Al_2O_3	3.30	3.50	7.72	3.95
P_2O_5	2.56	1.84	3.18	2.00
Cl	n.d.	n.d.	0.22	6.42

n.d. = not detected

As indicated in *Tables 23* and *24*, the main elements that make up the fouling, both in the outer layer of the scale and in the layer that adheres to the tube, are potassium and sulfur. However, some of the evaluated mills showed a high concentration of chlorine in the layer adhered to the tube, indicating a potential risk of corrosion by chlorine at high temperatures, as indicated by the value found in that index. With this dataset, it was possible to analyze in more detail the trend towards the formation of scale/corrosion, where the theoretical prediction was close to the results found in the field.

IX. FOULING PREDICTION INDEXES EVALUATED FOR MIXTURES OF STRAW AND BAGASSE

The composition and type of fouling formed in superheater and economizer (water preheater) boiler areas. *Table 25* correlates the fouling risks of each index calculated for the mixtures used in boilers with the constitutive elements and intensity of fouling formed under high temperature of superheater areas.

The description of the intensification of fouling formation on the superheater surface in *Table 25* refers to the thickness and hardness of the layers formed on the tubes. The correlation between the fouling risk indicators evaluated and the level of fouling formation obtained from tests in boilers provided information on the deposition and accumulation of components on fouling layers. Boilers M3 and M9, which presented the highest straw rates in the mixture (BS), showed the most critical fuel indexes and thick deposit layers, especially in the boiler of M9, where layers were strongly fused to the surfaces of the superheater tubes.

Table 25: Evaluation of fuel indexes and fouling levels on superheater surface.

Mills	Intensity of fouling formed	Aerosol emissions	K release	Ash melting behavior	High-temperature corrosion
M1	Low	Medium	Low	Low	Medium
M2	Medium	Medium	Medium	Medium	High
M3	Medium	High	Medium	Medium	High
M8	Medium	Medium	Low	Low	High
M9	High	Medium	Low	Medium	High

The utilization of straw and bagasse mixtures as fuel in boilers promoted an increase in the concentration of elements, such as potassium, sulfur, and chlorine. In most of the evaluated cases, the fouling composition showed high concentrations of potassium and sulfur in almost 60% of the total samples. The higher concentration of chlorine favored the highest volatilization of those elements in the boiler, inducing the formation of silicates and chlorides.

The relationship established (*Table 20*) between the ash melting behavior indicator, by molar ratio (Si+P+K)/(Ca+Mg+Al), and the concentration of chlorine and potassium in fouling, revealed that the fuel with the highest molar ratio, M9, presented, in particular, high chlorine concentration in fouling fused to the superheater.

However, the mixture (BS) used in M1 with the lowest value for the ratio (Si+P+ K)/(Ca+Mg+Al) did not indicate the presence of chlorine in fouling, as was observed for M3 and M8, with their low molar ratio value and lower chlorine concentrations in fouling composition. The difference demonstrated by the relationship between the indexes and the content of potassium and chlorine found in M1 and M9 is supported by the significant difference in the amount of deposits that formed on surfaces. Nonetheless, the ash melting process is influenced by several parameters, such as the variation in gas velocity and temperature of the heat transfer surfaces.

A relevant condition in the evaluation concerns the bagasse utilized in mill M9, which presented an average ash content 50% above the average value of other biomasses used in other mills, shows a significant increase in ash throughout the season and also in the potential for fouling formation.

Evaluation of the potential for corrosion at high temperatures on heat exchanger surfaces, resulting from deposits formed by mixture (B+S) burning in boilers, showed a close relationship between fuel indexes and fouling composition collected during testing. *Table 24* shows the fuel index of risk of corrosion at high temperatures and the distribution of the main corrosion agents, sulfur and chlorine, in fouling samples collected from superheater surfaces.

The values obtained for the molar ratio (2S/Cl) provided an overall indication that all fuels utilized in the boilers offer potential corrosion risk, yet with substantial differences among mills. Depending on the mixture composition (B+S) utilized as fuel in M2, a lower risk of corrosion was verified. The findings in M2 reveal, simultaneously, low fuel risk and chlorine absence in fouling formations, in combination with lower levels of deposit formation fused on the superheater surfaces, as described in *Table 24*. Therefore, the absence of chlorine in the fouling composition indicates the formation and condensation of sulfates with lower corrosion risk and lower adhesion of deposits fused on the superheater surface. Nonetheless, as shown in *Table 19*, even with the increase in straw percentage in M3 (14%) and a tendency to higher fouling according to fuel indexes, a low chlorine fouling concentration was maintained. This behavior resulted from the combination with the lowest gas temperatures, around 700 °C, in superheater areas. However, mill M9, which had a higher straw content (18 wt%) in the mixture (BS), indicated higher ash melting and corrosion at high temperatures, which combined the highest average flue gas temperature (900 °C) in superheater areas, resulting in the highest chlorine deposition and adhesion of fouling formations.

X. EXHAUST GASES

Sugarcane straw contains higher concentrations of potassium, sulfur, and chlorine compared to sugarcane bagasse. Adding the recovered straw, both by the bale route and by the DCS, to the bagasse increases the concentrations of these elements, increasing the problems related to atmospheric emissions, in the form of NOx, SO_2, HCl, and fine particulates as well as the formation of deposits and fouling.

a) Emissions of carbon monoxide (CO)

The results indicate that CO emissions depend on the operating conditions of the boilers and, consequently, on the quality of combustion and, therefore, are not directly related to the quality of fuels. It is observed that the emission of CO is related to the amount of excess air. It was observed that when the boiler used only bagasse as fuel, the excess combustion air suffered less variation than when using a mixture of straw and bagasse. This greater instability during the combustion of the mixture can be caused by the differences between the moisture, density, and particle size distribution between the bagasse and the straw. When fed in the boiler by the same feeding system, the mixture behaves differently during feeding, leading to its irregular burning. *Figure 63* shows the relationship between excess air and CO emissions.

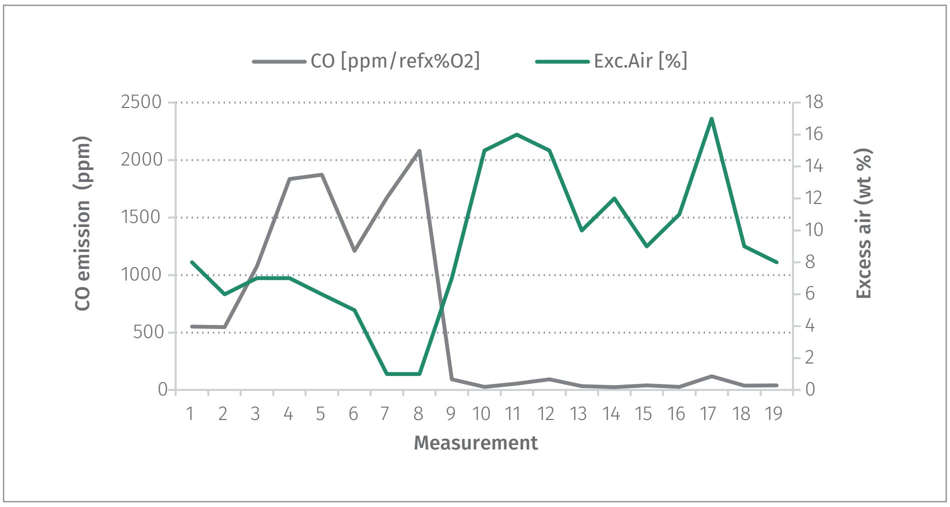


Figure 63: Relationship between CO emissions and excess air.

b) Emission of Nitrogen Oxides (NOx)

Nitrogen oxides (NOx) generally refer to various nitrogen and oxygen compounds, such as NO, NO_2, N_2O, N_2O_3, and N_2O_5; their emission depends on several factors, including the chemical concentration of N present in the biomass composition, combustion air temperature, furnace temperature, among others.

However, the relationship between the formation of NOx as a function of the percentage of nitrogen contained in the fuel, and in relation to the furnace operating temperature, was not evident. However, there is a direct correlation between NOx emissions and excess air factor (*Figure 64*). It was observed that CO emissions decrease when the excess air factor increases; so, it can be inferred that with respect to CO and NOx emissions, the lower the CO concentration, the greater the NOx emission. This can be explained by the equation: $2NO + 2CO \rightarrow 2CO_2 + N_2$, which shows that the dissociation of NO in N_2 is low when less CO is available (Mack, R. et. al, 2019).

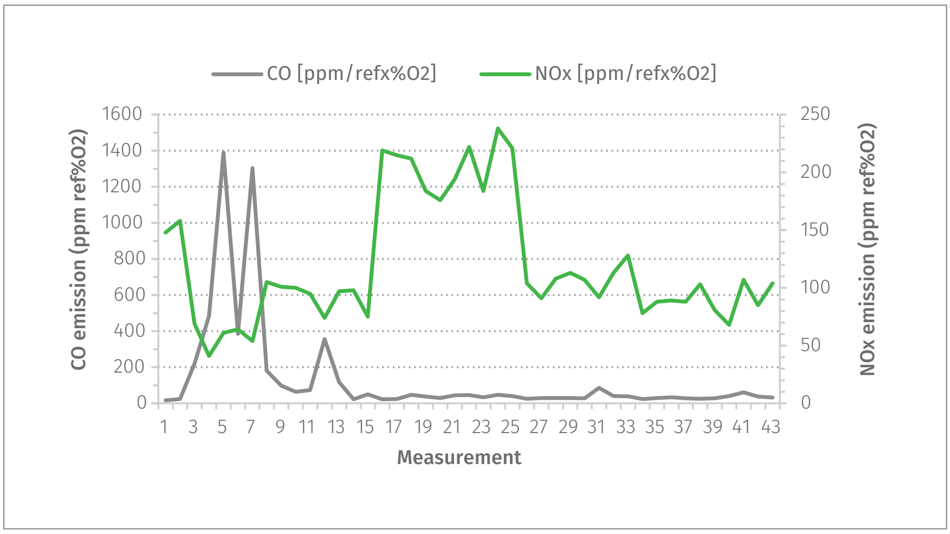


Figure 64: Relationship between CO and NOx emission in boiler.

CONCLUSIONS

1. The elemental fuel analysis showed a small variation between bagasse and straw in their concentrations of carbon, nitrogen, and hydrogen.

2. The moisture content in the straw separated by the DCS was similar to that in the bagasse (49 wt %), while the straw recovered by bales showed values of approximately 15 wt%, on average.

3. The chlorine concentration in the straw was about 10 times higher than that found in bagasse, and the sulfur concentration in the straw was 2–4 times higher than that in the bagasse in the samples analyzed.

4. HHVs are similar for bagasse and straw. However, there are significant differences in the LHV, which considers the moisture content in biomass.

5. The application of fuel indexes as a criterion for fuel characterization provides relevant information for the prediction of problematic issues related to biomass combustion, such as fouling formation and corrosion in boilers.

6. Analysis of fouling samples collected from high gas temperature areas of superheaters showed high potassium and sulfur concentrations in all boilers.

7. It could be observed that in a mill that utilized a greater amount of straw in the mixture (B+S) (about 19 wt%), high chlorine concentrations were identified in deposit samples in relation to other mills, demonstrating strong fouling adhesion to the tubes.

8. The deposits collected under lower gas temperatures in the water preheater areas indicated lower adherence to tubes and high chlorine concentration in most samples analyzed as well as the prevalence of silicon in its composition.

3.4 GUIDELINES FOR SUGARCANE STRAW REMOVAL

Authors: *Lauren Maine Santos Menandro, João Luís Nunes Carvalho, Sérgio Gustavo Quassi de Castro, Guilherme Adalberto Ferreira Castioni, Ricardo de Oliveira Bordonal, Thayse Aparecida Dourado Hernandes*

Recognizing the increase in the world's energy demands and the urgent need for options that reduce environmental degradation and mitigate climate change, producing renewable energy is an attractive option. Renewable energy in Brazil comprises 43.5% of the primary energy matrix, of which 17.4% is derived from sugarcane (EPE, 2019). In addition to bioethanol, a new commodity stands out in the sugar-energy sector: sugarcane lignocellulosic biomass for bioelectricity production. Currently, the industry produces electricity mainly from sugarcane bagasse, a residue derived from juice extraction during sugar and ethanol production. However, as industrial technologies become more advanced, removing some sugarcane straw from the field and using it to produce bioenergy has gained significant attention.

Based on this scenario, a trade-off associated with the dual purposes of straw that is, maintain in the field or be removed for energy cogeneration, has led to several questions such as: How much sugarcane straw is available for bioelectricity production? Is it possible to remove straw without compromising soil conservation? What are the impacts of straw removal on greenhouse gas (GHG) emissions from soil, soil quality, and sugarcane yield? When and where is it suitable to remove straw? To date, the traditional recommendation of removing 50% of sugarcane straw has been adopted, regardless of the amount of straw produced, the edaphoclimatic conditions, or the management practices used in the fields. However, given the complexity of this equation and the variety of factors which it involves such as local climate conditions, soil type, soil slope, harvesting season, specific management practices and also the amount of straw produced, it is expected that this unique and simple recommendation would not be sufficient to plan the best option for the suitable straw removal. This has therefore motivated the SUCRE Project to develop a set of strategic **Guidelines for straw removal in Center-South Brazil.**

These Guidelines are intended to support decision-makers in estimating the volume of available straw and obtaining a suitable method for sugarcane straw removal. They are intended to expand the bioelectricity generated from straw while ensuring soil quality, soil conservation, and sugarcane yield in the field.

3.4.1 METHODOLOGY

I. Study area | The area of cultivated sugarcane in Brazil exceeds 8.7 million hectares, of which 92% is located in the Center-South region (CONAB, 2019). This region comprises the states of Rio de Janeiro, Espírito Santo, Rio Grande do Sul, Paraná, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Goiás, and São Paulo, in which the last two states are the largest sugarcane producing states, responsible for 11% and 54% of national production, respectively (CONAB, 2019). The current study covers this region, which is predominantly of a tropical climate, with cold and dry winters and hot and rainy summers, although subtropical and altitudinal tropical climates can also be found there. The maximum temperature can exceed 30°C during the summer, while in winter the minimum temperature can reach below 10°C. The mean annual precipitation usually ranges between 1250 and 2000 mm. Several soil types are found in the region, varying from sandy to clayey soils. The predominant classes of soil slope with cultivated sugarcane vary from flat (<3%) to undulated (8–20%).

II. Guidelines development | To develop these Guidelines, more than five years of studies to identify and improve knowledge gaps were carried out over several stages, including a review of relevant scientific literature, biomass characterization, field experiments, agroclimatic zoning, and development of strategies for straw removal. These stages were articulated at different levels of detail and were defined according to the modeling framework (*Figure 65*).

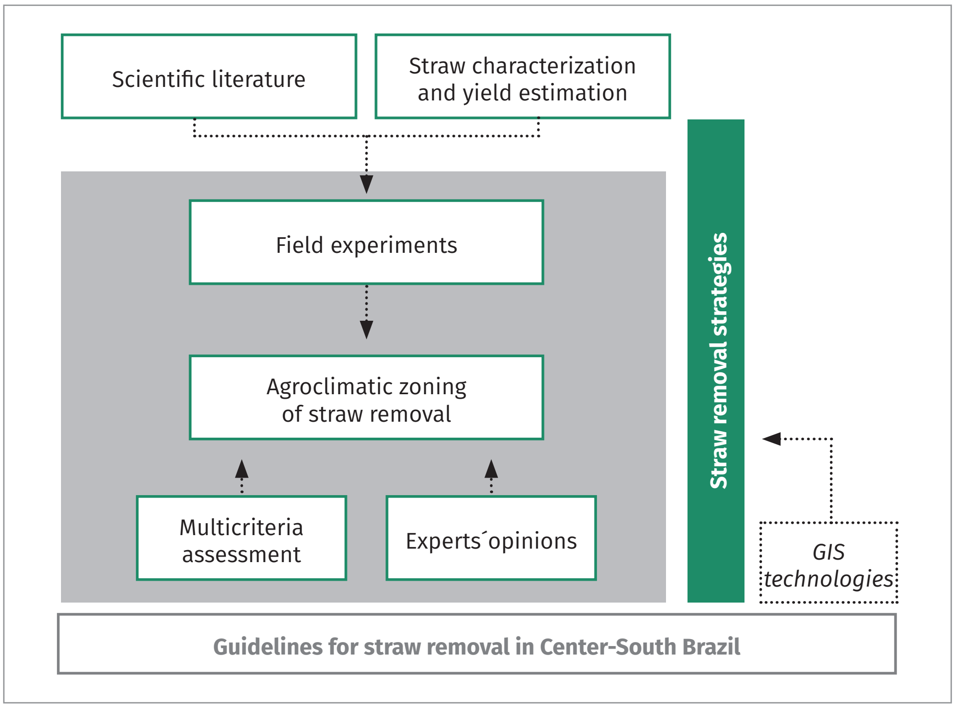


Figure 65: Modeling framework for the development of straw removal Guidelines in Center-South Brazil.

The methodology was initiated with a broad study aimed at characterizing straw composed of green tops and dry leaves and estimating the potential straw yield production in the main areas under sugarcane production. In parallel, a major literature review on the impacts of straw removal on soil quality, greenhouse gas emissions, and biomass production of sugarcane was performed. Overall, the information found in the literature was more qualitative (e.g., comparing areas under burning and green cane management) and was not sufficient to establish the amount of straw that can be removed without compromising soil health and sugarcane yields. Based on this statement, the SUCRE Project team established a broad experimental network in Center-South Brazil. For five years, the project conducted 32 field experiments and collected thousands of samples of soil, plants, water, and gases.

Moreover, agroclimatic zoning of straw removal was performed to define correlations between climate conditions and straw management effects on sugarcane yields. This was done used more than three thousand points of climatic data were collected and treated in a Geographic Information System in order to represent climatic patterns located in Center-South Brazil and the application of specialists' opinions using multicriteria assessment. With these stages, the main steps of the straw removal strategies were defined based on background knowledge and the determination of principles for straw removal. Finally, suggestions for applications and visual maps of straw removal aligned with geotechnologies (GIS) were the last steps that completed the construction of the Guidelines for sugarcane straw removal.

3.4.2 RESULTS

I. GOOD PRACTICES FOR STRAW REMOVAL: KNOWLEDGE BACKGROUND FOR STRATEGIC DECISIONS

An important part of carrying out strategic sugarcane straw removal is the knowledge related to straw characteristics, the potential sugarcane yield, and the impacts of straw removal on the soil-plant-atmosphere system. These aspects allow the definition of principles for strategic removal and also assist in the managers' final decision making.

The study performed in the SUCRE Project showed that straw composition has different potentials for nutrient recycling and for second-generation ethanol and bioelectricity production, depending on whether it is characterized by green tops or dry leaves (*Figure 66*). In addition, this study showed a productive potential of 120 kg of straw (dry basis) for each megagram of stalks produced (wet basis). Thus, a ratio of 12% can be used to estimate straw yield in sugarcane fields of Center-South Brazil (Menandro et al., 2017). This is an important piece of information that is included in the step-by-step process of the removal strategies.

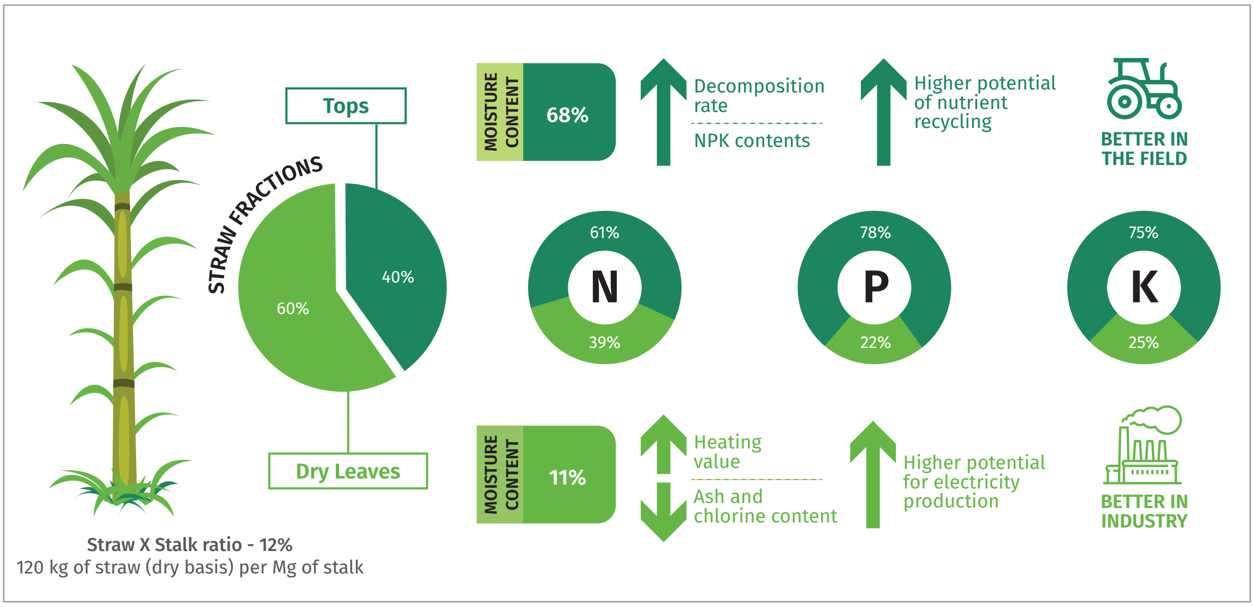


Figure 66: Characterization of the productive potential and use of sugarcane straw. Illustration based on Menandro et al. (2017) | Design credit: Luiz Nascimento/ Comunicação CNPEM.

After summarizing the information from the literature review (Carvalho et al., 2017) and field experiment, the results from the SUCRE Project showed that straw is associated with several ecosystem services and that its removal could provide changes in nutrient cycling, soil water storage, soil temperature, erosion control, soil biological activities, soil carbon stocks, soil compaction, GHG gas emissions, pest populations, and weed control, as well as tillering and sugarcane yield. The main conclusions of these studies suggest that the impacts of straw removal are site-specific and are mainly dependent on climate conditions, soil type, crop management, time of straw removal, and the volume of straw produced, making it impossible to provide a single recommendation for straw removal in Center-South Brazil. The main results of these studies are summarized in several published papers, and in other papers undergoing final adjustments prior to publication, as presented in *Table 26*.

Table 26: Background knowledge of sugarcane straw removal impacts on soil-plant-atmosphere and agroclimatic zoning of straw removal.

	Knowledge	Reference(s)
Scientific literature	Agronomic and environmental implications of sugarcane straw removal	Carvalho et al., 2017
Straw characterization	Nutrient content, moisture, and chemical characterization of straw and yield estimation	Menandro et al., 2017
Field experiments	Straw removal effect on sugarcane yield; soil physical, chemical, and biological attributes; soil moisture and temperature; soil pest populations; soil conservation; GHG emissions	Bordonal et al., 2018; Carvalho et al., 2019; Castioni et al., 2019, 2018; Corrêa et al., 2019; Castro et al., 2019; Gonzaga et al., 2018, 2019; Menandro et al., 2019, 2020 *(i.p)*, Tenelli et al., 2019, 2020 *(i.p)*.
Agroclimatic zoning of straw removal	Correlations of climate conditions with straw removal effects on sugarcane yields	Hernandes et al., 2019

i.p. = in preparation

Another important stage in the development of the Guidelines was the agroclimatic zoning of straw removal. The results of this stage showed that the effects of straw removal on sugarcane yields related to climate conditions are driven by minimum temperature, solar radiation, and precipitation. This spatial climate analysis allowed the creation of a map with a suitability classification for straw removal (Hernandes et al., 2019). Based on these stages, the principles for straw removal were defined, which form the basis for strategic decision-making regarding straw removal.

II. PRINCIPLES FOR STRATEGIC SUGARCANE STRAW REMOVAL

Overall, nine principles were defined and are divided into four categories: excluding factors, climatic suitability factors, restrictive factors, and responsive factors. The excluding factors are defined by the sugarcane cycle stage and the efficiency of straw mulch on soil conservation after soil tillage practices and are: (i) replanting area and (ii) soil tillage. Climatic suitability is defined by considering the agroclimatic zoning of straw removal in order to classify areas according to their (iii) suitability for straw removal and (iv) solar radiation incidence. The restrictive factors are those that limit straw removal due to their impacts on soil conservation (i.e., soil erosion risk) and are composed of (v) soil slope and (vi) minimum amount of straw on the soil surface. Lastly, the responsive factors are described as those that could favor straw removal (or not) due to the responses of sugarcane yield and soil conservation related to (vii) harvesting season period (early, middle, late), (viii) soil texture, and (ix) water availability (i.e., soils which naturally have an excess of water or that receive supplementary water through irrigation management).

III. DECISION-MAKING TOOL FOR STRAW REMOVAL

The application of the nine principles creates a decision-making tool based on a hierarchical approach, in which the first level defines the priority straw removal areas (*Figure 67*). As one moves down through the hierarchy, it is possible to define the immediate level in more meaningful decision making terms and, at the end of each follow-up step, it is possible to classify the sugarcane fields into three categories: “suitable”, “restricted to 7 Mg ha^{-1}”, or “unsuitable” for straw removal.

“Suitable” areas are those whose set of factors do not significantly affect soil conservation, and which have no negative impacts, or even have gains in terms of sugarcane yield under straw removal. For example, areas subject to soil tillage practices during the replanting period, areas without water restriction (i.e., soil with a natural excess of water or that are under full irrigation), or areas in regions with high climatic suitability for straw removal. Areas “restricted to 7 Mg ha^{-1}” of straw left on the soil are normally those in which straw removal would not negatively impact sugarcane yield, but in which the straw performance should be considered as having an important role for soil conservation. Finally, the “unsuitable” areas are those in which straw removal could promote significant sugarcane yield losses. These are located in regions with low climatic suitability for straw removal and that benefit from straw mulch on the soil surface.

This decision-making tool is the “backbone” of the step-by-step strategies for sugarcane straw removal. However, it is not possible to indicate an approximate amount of straw available using only this decision tool, or even "when" and "where" to remove sugarcane straw. For this, it is necessary to apply a step-by-step procedure that involves basic information from farm producers and other relevant aspects. Therefore, a step-by-step procedure was developed to guide sugarcane straw removal at a local level in Center-South Brazil in a feasible and practical way.

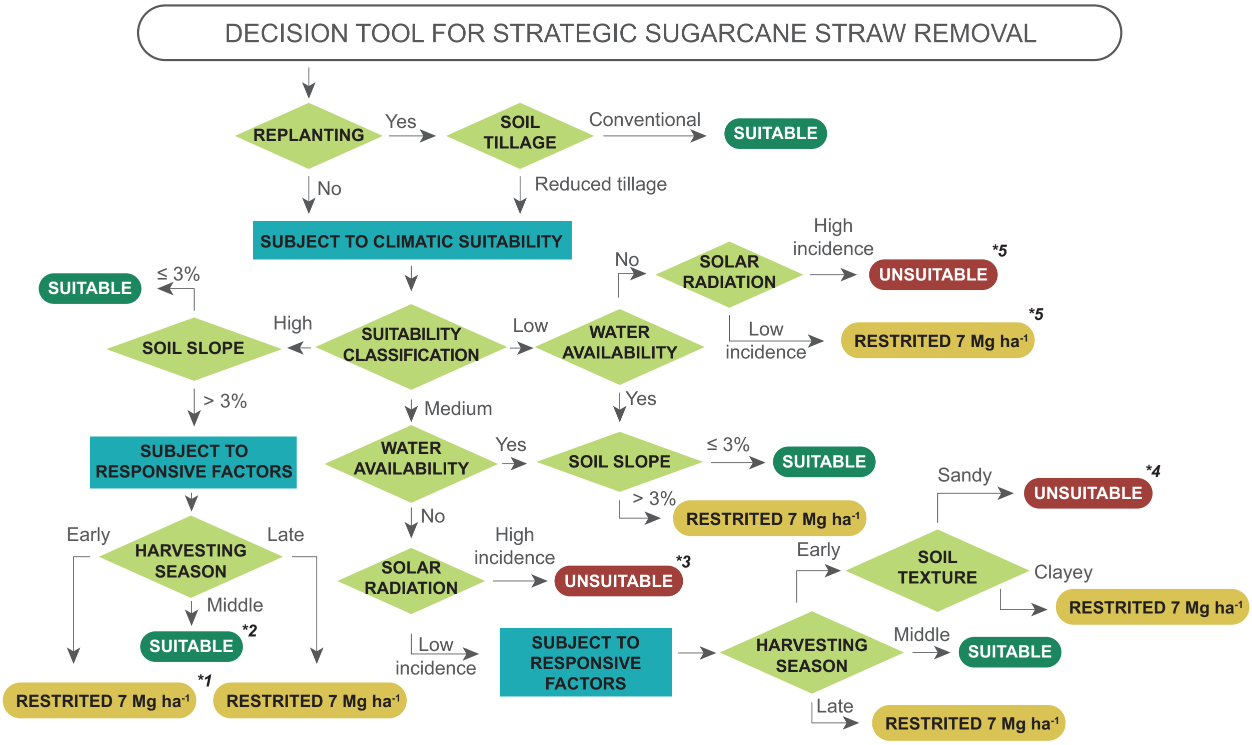


Figure 67: Decision-making tool for straw removal considering the impacts on soil conservation (risk of soil erosion) and sugarcane yield | Design credit: Luiz Nascimento/Comunicação CNPEM.

Notes:

1. At the end of the early harvest season, it is recommended that straw is removed when the minimum temperature is critical and there is low rain intensity. In the presence of intense rains, it is recommended that straw be taken away from the sugarcane line.

2. At the end of the middle harvest season, if there is an intensification of rain, it is recommended to maintain 7 Mg ha^{-1} for the purpose of soil conservation, and to remove straw from the sugarcane line if the minimum temperature is critical.

3. No inflection point was found up to 17.2 Mg ha^{-1} of straw (dry basis).

4. No inflection point was found up to 12.4 Mg ha^{-1} of straw (dry basis).

5. There was no experimental evaluation in these areas. Suitability is based on the response of the potential sugarcane yield.

IV. STEP-BY-STEP PROCESS FOR STRATEGIC STRAW REMOVAL

The strategic straw removal process is structured in five steps (*Figure 68*). The final result will indicate "how much" straw is available and "when" / "where" it is recommended that sugarcane straw can be removed at the local level. The first step (I) organizes information about the sugarcane cultivated area. For instance, basic information that is usually contained in the farm's database is needed, such as the soil slope, soil texture, harvest date, sugarcane cycle stage, level of irrigation, and typical sugarcane yield. The second step (II) estimates the total straw production in a specific area using a ratio of 12%. After that, the areas are assessed by the hierarchical key using the decision-making tool (III) in order to define if the area is suitable, restricted, or unsuitable for straw removal. To facilitate the application of these three steps, a digital tool was developed by the SUCRE Project for the automatic classification of sugarcane fields and is available for open user access on the SUCRE Project website upon request. With the definition of straw removal susceptibility, a potential map (IV) can be obtained, which consists of using a digital tool aligned with geotechnologies (GIS) to produce visual maps of the cultivated area. A tutorial for using the digital tool and a detailed visual map is also available on the SUCRE Project website. Finally, specific conditions, such as degree of pest infestation, impacts on soil quality, operational viability of straw removal, and climate adversities, can certainly influence users in the decision-making process. Therefore, specific adaptations (V) must be considered by decision makers, so that new straw removal scenarios can be obtained at the local level.

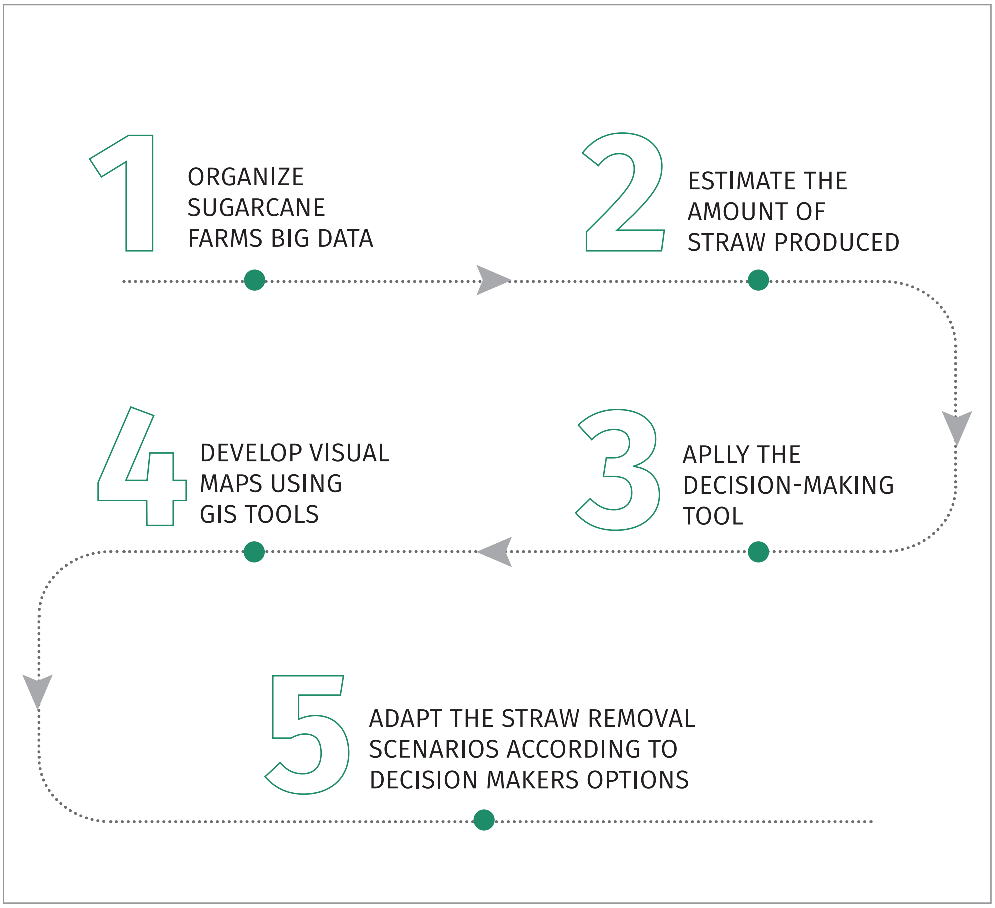


Figure 68 Step-by-step process for strategic sugarcane straw removal.

3.4.3 CASE STUDY: APPLYING THE STEP-BY-STEP PROCESS FOR SUGARCANE STRAW REMOVAL

A case study was carried out at the sugarcane farms of one of the partner mills of the SUCRE Project. The area is located in the state of São Paulo. The data for evaluation is specific to the 2016/2017 sugarcane harvest season. The sugarcane production area was estimated at approximately 50 thousand hectares, with a predominance of sandy soils and low sugarcane yields. The crop area is located in a medium-suitability region for straw removal. By applying the step-by step process, it was possible to estimate that the suitable areas for straw removal correspond to 41.3%, the areas restricted to the maintenance of at least 7 Mg ha^{-1} of straw correspond to 20.9%, and the areas where straw should not be removed (unsuitable) correspond to 37.7% of the total farm area (*Figure 69* and *Table 27*).

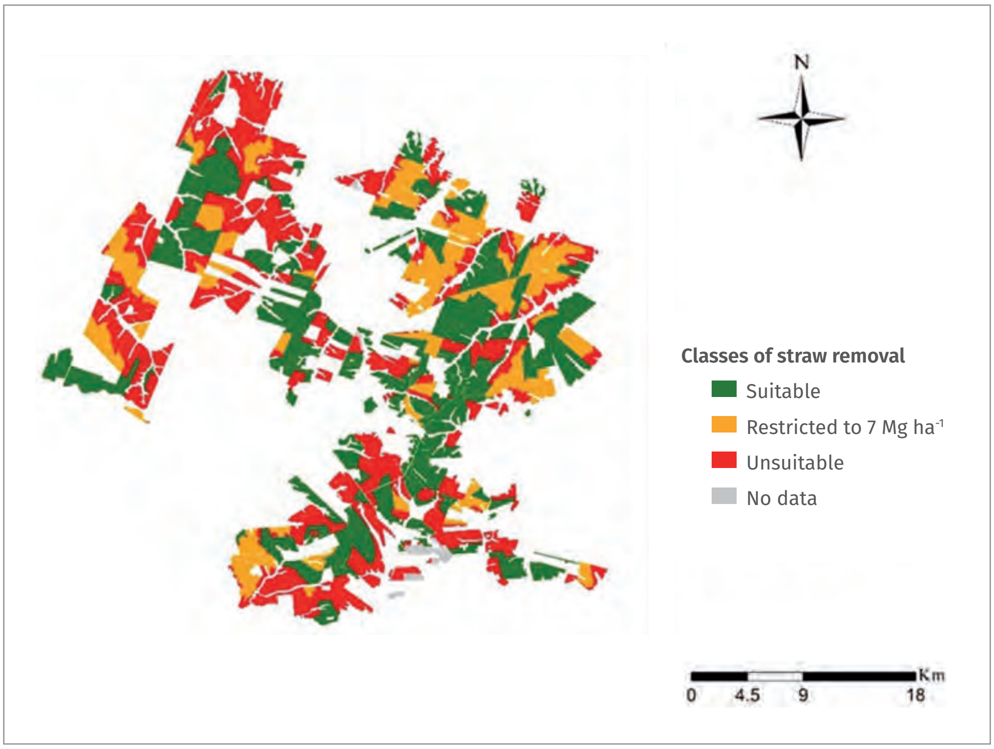


Figure 69: Straw removal map for the case study of a partner mill in the state of São Paulo | Credit: Ana Cláudia Luciano.

Classes of straw removal		Straw (10^3 ton)	Straw (%)	Area (ha)	Area (%)
Suitable (S)	S1	94.92	27.76	20470	41.29
	S2	37.83	11.06		
Restricted to 7 Mg ha^{-1} (R)	R1	15.66	4.58	10389	20.95
	R2	57.89	16.93		
Unsuitable (U)		135.34	39.58	18688	37.69
No data*		0.273	0.08	33	0.07
Total		341.91	100.00	49580	100.00

S1= above 2 Mg ha^{-1} (removed straw), S2 = 2 Mg ha^{-1} kept on the soil, R1= above 7 Mg ha^{-1} (removed straw), and R2= 7 Mg ha^{-1} kept on the soil. 2 Mg ha-1 was considered the minimum amount of straw operationally feasible for removal.

Table 27: Sugarcane straw production and availability estimated amounts according to strategic removal criteria.

In this case study, approximately 110,600 Mg of sugarcane straw (i.e., S1+R1) could be strategically removed from the field for bioelectricity production. Even representing only ~32 % of the straw produced in the field, this amount is enough to supply the mill's need for biomass, which is currently being bought in order to supply the steam and electricity required by the mill's systems. It is worth mentioning that only soil conservation and impacts on sugarcane yield are considered in this map. In step V, scenario adjustments according to decision makers were not applied.

3.4.4 CONCLUSIONS AND COMMENTS

Planning straw removal is important, as are the management practices commonly established in production units, such as fertilization, weed control, and harvesting, among others, since straw management can interfere with several factors that affect sugarcane production. These Guidelines are a pioneering tool and provide more accurate information regarding the volume of straw produced in areas cultivated with sugarcane, "how much" straw is available for removal, and "where" and "when" straw can be removed from cane fields. These Guidelines have a significant advantage over the previous standard recommendation and, followed correctly, will allow the most efficient use of sugarcane straw biomass, helping to meet the trade-off between bioelectricity production and sustainable sugarcane production systems.

3.5 ASSESSMENTS AND TESTS FROM CASE STUDIES

Authors: *Isabelle Lobo de Mesquita Sampaio, Marcos Djun Barbosa Watanabe, Wilson Cleber da Silva Bononi, Terezinha de Fátima Cardoso, Nariê Rinke Dias de Souza*

The assessment of economic and environmental impacts was carried out considering an integrated analysis (industrial and agricultural phases) and evaluated the effects of straw recovery in a sugarcane mill (Bonomi et al., 2016; Watanabe et al., 2020).

3.5.1 RESULTS AND DISCUSSION – INDUSTRIAL SIMULATIONS FOR STRAW RECOVERY

For the present evaluation, a Base scenario without straw recovery from the field and a scenario with straw recovery through Integral Harvesting were evaluated.

Base: The Base scenario considers a mill with an annual crushing capacity of 4 million tons of sugarcane per year, operating for 200 days per year (season period), producing sugar, anhydrous ethanol and electricity. The ethanol/sugar mix assumed that 50% of the sugarcane juice was destined for each product. The Base scenario does not consider a sugarcane Dry Cleaning System (DCS), so all vegetal impurities (sugarcane leaves and tops) and mineral impurities pass through the milling tandem along with cane. In terms of energy, the configuration of the industrial facility considers that this unity has electrified mill drives, high-pressure boilers (67 bar, 485°C steam), two backpressure turbines, and one extraction-condensing turbine. The steam demand of this sugarcane mill is of approximately 500 kg of steam per ton of sugarcane processed and for ethanol dehydration the process is azeotropic distillation.

Integral Harvesting: for the straw recovery scenario by Integral Harvesting, it was considered that the cogeneration sector of the plant would operate for 115 days to process all the additional biomass (straw). This period of operation would include days of off-season (days when the sugarcane harvest has already finished) and days during harvest when only the cogeneration sector of the plant is operating due to problems in other equipment (e.g., problems on the sugarcane juice extraction sector or lack of cane). During this period, only one of the boilers would operate and the condensing-extraction turbine would operate favoring the condensing of steam as opposed to the harvest period when the turbine would operate with high amounts of process steam being extracted. For this scenario, it was assumed that only equipment related to straw processing was acquired by the mill, in this case, the sugarcane Dry Cleaning System and auxiliary equipment.

For Integral Harvesting scenario, the straw recovery scenario, it was assumed that no decrease in the boiler efficiency would occur when the boiler operates with the straw and bagasse mixture. The efficiencies adopted for this work for boilers and turbines were the same applied in the work Sampaio et al. (2019). The main industrial parameters for the cogeneration sector of the plant assumed for this study are presented in *Table 28*.

	Base	Integral harvesting
Operating days – season (days)	200	200
Off-season operating days (days)	-	115
Equipment for straw processing	-	Sugarcane Dry Cleaning System with straw shredders and screening for separated straw
Efficiency of separation of straw and mineral impurities in Dry Cleaning System (%)	-	40
Process electricity demand (kWh/t sugarcane, wet basis)	30	30
Electricity demand for Dry Cleaning System (kWh/t of straw, dry basis)	-	17.7*
Electricity demand for off-season operation	-	8% of the generated electricity
Boiler efficiency (65 bar, 485 °C)	82%	82%
Turbogenerator efficiency (steam turbines + generator)	70%	70%

** All straw entering the DCS, including vegetal impurities.*

Table 28: Main industrial parameters for the cogeneration sector adopted for this study.

The main industrial results obtained are shown in *Table 29*. Two effects can be observed: a drop in sugar and ethanol production due to the increase in fibers entering the milling tandem, causing a decrease in sugar extraction (sugar carryover by the bagasse) and an increase in the electricity surplus.

	Base	Integral harvesting
Sugarcane straw processed (dry basis) (kt/year)	-	100
Anhydrous ethanol production (ML/year)	211.7	210.6
Sugar production (kt/year)	202.6	201.6
Total electricity demanded for industrial operation (GWh/year)	129.1	139.5
Electricity surplus (GWh/year)	320.4	406.3
Electricity surplus (kWh/t of sugarcane)	80.1	101.6

Table 29: Main industrial results for the evaluated scenarios.

The electricity surplus for the Base scenario reported in *Table 29* is 80.1 kWh per ton of sugarcane. This surplus of electricity is similar to the reported values for real sugarcane mills in PECEGE (2014), with new units or retrofitted units aiming better cogeneration performance presenting a surplus of electricity between 40 and 80 kWh per ton of sugarcane processed.

With the increase in sugarcane straw recovery, as expected, there is an increase in electricity generation, because there is more biomass available for steam and electricity generation. This is only possible if there is some idle capacity in cogeneration (for example, if the cogeneration sector of the plant can operate for more days, as was assumed in this study) or if more boilers and/or turbogenerators are acquired.

The electricity demand increases from the Base to Integral Harvesting scenario. This is due to the additional power required for the operations related to sugarcane straw processing (sugarcane Dry Cleaning System fans, straw shredders, etc.). Another factor that causes an increase in the total electricity demand for this scenario is the additional demand of energy necessary to operate the cogeneration sector during the off-season period (see *Table 28*). This resulted in a higher annual demand of energy for this scenario.

For the additional investment required for straw processing, it was considered that only a sugarcane Dry Cleaning System would be acquired (and straw processing: shredder, rotary screen, belt conveyors, etc.). The investment was calculated using the method that correlates the value of a new investment with a similar investment already made, by the ratio of the capacity of the new installation to the capacity of the old one, elevated by a factor ranging from 0.6 to 0.7. CAPEX investments informed by partner plants of the SUCRE Project were used with updated values for December 2019 and corrected by the capacity factor considering the amount of straw processed per hour. The investment was estimated at approximately US$6.91 million.

3.5.2 TECHNO-ECONOMIC ASSESSMENT – ASSUMPTIONS AND RESULTS

An incremental discounted cash flow analysis considers only the effects caused by the decision of recovering straw on the existing agro-industrial system. In this analysis, the additional agricultural costs from straw are included in the industrial cash flows as the annual operating costs associated to biomass. In this agricultural cost, both operating and investment costs related to the integral harvesting system are included. Also, additional operating costs (such as labor, maintenance and chemicals) as well as capital costs related to the additional industrial equipment are accounted for. The metric considered to compare alternatives was the net present value and internal rate of return of the incremental project. The main assumptions used for the discounted cash flow analysis are described in *Table 30*.

Parameter	Value	Unit
Reference date	Dec/2019	-
Exchange rate	3.95	R$/US$
Project implementation	1	year
Project lifetime	20	years
Discount rate, real rate	12	% per year
Working capital	10	% of fixed capital investment
Average annual depreciation	10	% per year, linear
Total employee cost (w/ charges)	955	US$/month
Average maintenance cost	3	% of fixed capital investment
Income tax (IRPJ)	25	% of taxable income
Social contribution on net income (CSLL)	9	% of taxable income

Assessed products	Value	Unit
Electricity - average price	53.45	US$/MWh
Sugar - average price	0.34	US$/kg
Ethanol - average price	0.49	US$/L

Table 30: Main assumptions made in the discounted cash flow analysis.

This scenario considers the recovery of 100 thousand tons of straw on a dry basis by the integral sugarcane harvesting to generate additional 85,944 MWh of bioelectricity. In this case, the incremental investment in the industry (mostly the Dry Cleaning System) was estimated and presented in *Table 31*. A peculiarity of this route (recovery of 2 ton of dry straw per hectare) is that the agricultural cost of straw is benefited by the reduction of stalk losses in the harvest, as explained in the agricultural modelling section (3.2.5). The net effect is a negative operating cost with biomass, that is, a cash flow benefit. Losses of revenue from hydrated ethanol and sugar were also computed due to the entry of straw into the juice extraction area.

Parameter	Value
Additional CAPEX (US$)*	6,909,567*
Additional OPEX (US$/year)	
Agricultural straw costs	-1,511,898**
Chemical inputs	199,974
Industrial labor costs	34,389
Maintenance costs	207,287
Additional revenue (US$/year)	
Additional surplus electricity	4,593,521
Anhydrous ethanol	-533,610
Sugar	-336,390

Table 31: Impacts on additional investment and operating costs.

**Includes equipment, infrastructure and working capital **Annual agricultural cost of straw of US$ 0.57 million, deducted from the benefit of US$ 2.08 million in the reduction of stalk losses.*

Table 32 presents the deterministic result of the agro-industrial system choosing the integral harvesting, in terms of internal rate of return – IRR (real rate) and net present value (NPV). The deterministic value shows that the scenario with straw recovery would be viable against the use of sugarcane bagasse (IRR above the discount rate of 12% per year), showing that the investment made is remunerated at a rate of 17.47% per year, in this specific case.

Parameter	
Incremental IRR (per year)	17.47%
Incremental NPV (US$)	2,659,149

Table 32: Results of discounted cash flow analysis.

Considering that the biomass operating cost associated with straw and stalks play an important role on the economic viability of the project, the effects of different costs were assessed and presented in *Figure 70*. As straw recovery increases from 2 to 3 and 4 tons per hectare, the cost increases from US$ 20.91 to 24.47 and 26.36 per dry ton, respectively. Although there is a slight benefit from sugarcane stalk cost reduction, the net effect is negative in terms of biomass operating costs. As a result, the IRR decreases from approximately 17% to 15% and 13% per year, respectively. The net present value is reduced from US$ 2.6 million to 1.3 and 0.4 million, respectively. Under the assumptions of this sensitivity analysis, the integral harvesting indicates economic feasibility considering the incremental project of this agro-industrial system.

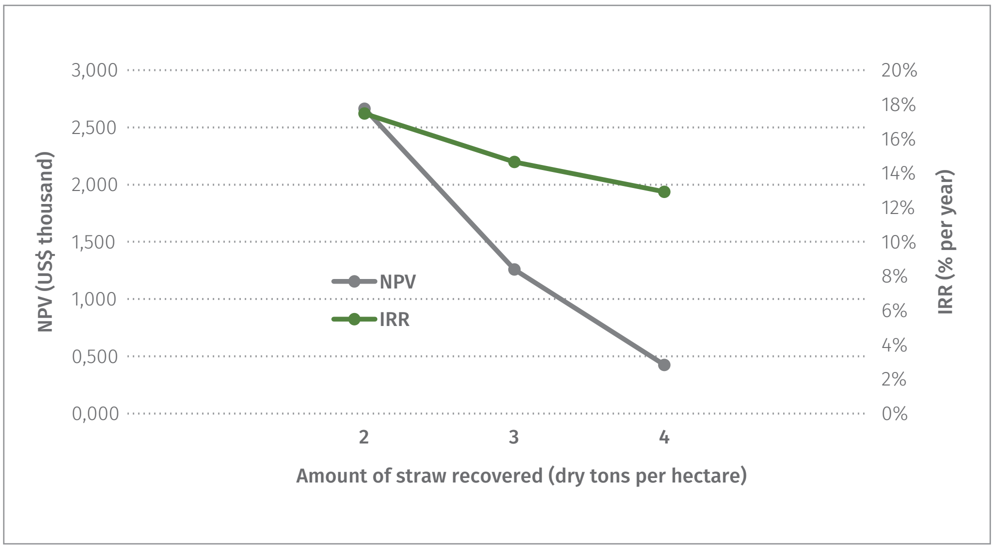


Figure 70: Sensitivity analysis of IRR and NPV to changes in the amount of straw recovered per hectare.

3.5.3 ENVIRONMENTAL ASSESSMENT – ASSUMPTIONS AND RESULTS

The same way as in the item 3.2.5, the methodology to evaluated greenhouse gas (GHG) emissions, was performed using the environmental life cycle assessment (LCA) (RLT-032, 2017 [23]; Sampaio et al., 2019; Cardoso et al., 2019).

However, in this item, the assessment includes the entire production chain, considering both the agricultural and industrial phases. The main agricultural parameters are described in *Table 9* (item 3.2.5) and the industrial parameters are described in *Table 28* (item 3.5.1).

Agricultural GHG emissions in the evaluated scenario (Integral Harvesting - 2 t_{db} /ha), present emission lower than scenario without straw recovery (see 3.2.5, *Table 11*). The emissions reduction occurs due to lower N_2O emissions with less amount straw on the soil. It is important to remember that the stalks harvest losses decrease contributes also to the reduction of emissions in the agricultural phase (see 3.2.5, *Table 11*).

In the industry, the most significant part of the GHG emissions is associated to the burning of the biomass in the boiler, around 70% of emissions. Then, the scenario with straw recovery presents an increase in emissions in the industrial part due to higher amount of biomass burning in the boiler.

On the other hand, the removal of straw from the soil reduces N_2O emissions and as a result reduces the GHG emissions in agricultural phase (*Table 33*).

[23] RLT (Technical Report) is the acronym of reports written during the Project. Project's RLTs can be requested to the Project's coordination team through the SUCRE website. Some of the documents are confidential and access requires prior authorization from the partners involved.

	t CO_2 eq per season		
	Base	Integral Harvesting	Variation*
Agricultural emissions	162,702	159,733	-2,969
Industrial emissions	24,432	27,159	2,727
Biomass burned (boiler)	17,412	20,139	2,727
Total	187,134	186,893	-241

** difference between the integral harvesting scenario and the scenario without straw recovery (Base);*

Table 33: GHG emissions in the season.

Considering the integrated assessment (agricultural and industrial phase), the scenario with straw recovery shows lower emissions (*Table 33*), in the conditions of the evaluated scenarios.

To assess the GHG emissions of electricity produced, an energetic allocation procedure was employed, considering parameters from *Table 34* and *35*.

Product	**Energetic allocation**	
Anhydrous ethanol	22.35[a]	MJ/L
Sugar	16.20[b]	MJ/kg
Electricity	3.60	MJ/kWh

[a]ANP (2019); [b]NEPA (2011)

Table 34: Parameters for energetic allocation.

Product	**Base**	**Integral Harvesting**
Anhydrous etanol (L/TC)	52.92	52.65
Sugar (kg/TC)	50.66	50.41
Electricity (kWh/TC)	80.10	101.60

Table 35: Products from the assessed scenarios.

After allocation of GHG emissions to final products (ethanol, sugar and electricity), the Integral Harvesting presents lower emissions per kWh produced than Base scenario (*Table 36*). Compared to electricity from natural gas, bioelectricity presents much lower GHG emissions.

	Carbon intensity gCO_2eq/kWh			
	Base	**Integral Harvesting**	**Variation**	**Natural Gas**
Total	73	71	- 2	551[a]

[a] *Ecoinvent, n.d*

Table 36: Carbon intensity of electricity in the assessed scenarios.

Considering that the electricity from sugarcane exported to the grid replaces electricity from natural gas, the avoided GHG emissions were calculated for each scenario. Such avoided emissions consider the difference among carbon intensity (CI) of electricity produced from sugarcane in the two assessed scenarios compared to electricity from natural gas, presented in *Table 36*. These differences are then multiplied by total amount of electricity produced per season, per scenario. The results are shown in *Table 37*.

	Avoided emissions kt CO_2eq/season		
	Base	**Integral Harvesting**	**Variation**
Total	153	195	- 42

Table 37: Avoided emissions when replacing electricity from natural gas with bioelectricity in the assessed scenarios.

3.5.4 FINAL COMMENTS

In these conditions, the straw recovery with Integral Harvesting indicates economic feasibility considering the incremental project of this agro-industrial system. Moreover, the straw recovery can reduce the GHG emissions mainly due to lower N_2O emissions in the field, and the increase in electricity generation.

The results of this assessment present the importance of evaluating the whole production chain, considering both the agricultural and industrial phases in the integrated way.

3.6 CUSTOMIZED ASSESSMENTS

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Anticipating the impacts of bioelectricity production from sugarcane straw is a very important task when thinking about sustainable energy production. In the context of SUCRE Project, tailor made assessments for partner mills were performed to accurately quantify the economic and environmental impacts of each conversion technology using the Virtual Sugarcane Biorefinery (VSB). This simulation framework integrates both agricultural and industrial models to anticipate the impacts of biorefineries on different sustainability aspects (Bonomi et al. 2016). It is vitally important that partner mills can anticipate the economic and environmental outcomes before carrying out any recovery. This facilitates crucial decision making, allowing the sugarcane mills to target their resources towards projects with sound economic and environmental potential. For example, knowing what kind of straw recovery route is most suitable in the field or which equipment to use in the industry can be anticipated through computer calculations, in order to assess whether the decision may or may not be viable. In this chapter, two real case studies are presented: Mill A, whose project alternative to substitute bagasse indicates sugarcane integral harvesting as the best choice for straw recovery; and Mill B, which has the baling system as its best alternative.

3.6.1 A CUSTOM EVALUATION USING THE VIRTUAL SUGARCANE BIOREFINERY (VSB)

The VSB framework has been developed and updated over the last decade by the Brazilian Biorenewables National Laboratory (LNBR), a research facility that integrates the Brazilian Center for Research in Energy and Materials (CNPEM). In SUCRE Project, agricultural and industrial phases were assessed in an integrated model, considering the positive and negative aspects of the entire sugarcane bioelectricity production chain. Given the wide variety of sugarcane mills participating in the SUCRE Project, understanding the best way to handle and take advantage of the available straw was not an easy task. There are several factors that have an impact on the cost and quality of the straw recovered, from the yield of the cane to the operational productivity of the machinery used. In addition, there are a variety of factors at the industrial stage related to the impact of straw on the plant's industrial processes.

To evaluate the cost of recovering straw, the VSB uses CanaSoft, a tool designed by the LNBR/CNPEM team. It is a computational model that encompasses all agricultural operations of sugarcane production, from the systematization of the area, preparation of the soil, and including the transportation of straw and procedures for recovery straw, while accounting for labor, required machinery and tools, as well as the raw materials used. The CanaSoft agricultural model allows technologies that are in use and under development to be assessed, making it possible to identify the critical points and technological bottlenecks in the process. Using CanaSoft, it is possible to determine the points that merit attention in agricultural operations based on the characteristics of each sugarcane mill examined. This is done to achieve better technical, economic and environmental results on the use of straw. In order to determine the cost of straw, CanaSoft looks at the cost difference between the scenario with recovery and a situation without recovery.

To assess the potential for generating electricity by the sugarcane mills, computer simulations need to be built that represent the operations for processing and burning straw. The excess electricity generated by the sugarcane mills can be increased by burning straw in the boilers. Using operation and equipment data from the mills that are participating in the Project, information from the sector and from published studies, and accounting for factors such as the amount of straw recovered and moisture levels, the industrial simulation is designed to generate results that will be used for environmental and economic analysis.

After running agricultural and industrial simulations, the next step is to assess whether the generation of bioelectricity from straw will be economically viable for the partner mills. This analysis is divided into three stages. The first involves using the information from the sugarcane mill to run agricultural and industrial simulations. In this stage, essential information includes the electricity prices, since all future revenue will depend on this amount. The second step requires a discounted cash flow analysis to be conducted, which includes investments in equipment and infrastructure, in addition to other costs for factors like labor, industrial inputs and maintenance. In the third and final stage, the responses that will reveal whether the decision was viable in economic terms are presented.

In SUCRE Project, the environmental impacts of sugarcane bioelectricity production are calculated using the Life Cycle Assessment (LCA) methodology. This methodology accounts for the impacts of the entire production chain such as the use of inputs and emissions to the air, water and soil. In other words, raw materials, fuels and machinery used in the sugarcane production stages, transportation, and electricity generation at the sugarcane mill are all accounted for in the LCA.

3.6.2 MAIN LESSONS LEARNED FROM SUCRE PROJECT

In SUCRE Project, 12 partner mills were assessed to provide insights to help their understanding whether the generation of electricity from sugarcane straw could yield satisfactory results in terms of sustainability. In the first stage, detailed data on the operational characteristics of four participating mills were collected, like operational bulletins, process diagrams, among others. As a result, the details of sugarcane production and straw recovery were assessed, with the calculations adjusted according to the characteristics of each participating mill. Similarly, processing in the industry was also detailed, with the simulations adjusted according to the information received.

The second stage was the assessment of eight mills incorporating the lessons learned from the previous stages of the Project and, along with eight new participating sugarcane mills, the Integration team defined the relevant scenarios for assessing the recovery and use of straw. The calculations performed in this stage were focused on the areas more impacted by straw, such as sugarcane juice extraction and cogeneration sectors of the sugarcane mills, while other industrial sectors were less detailed in the simulations. The assessments were conducted using the VSB, adjusted to the current situation of each plant.

The main lesson learned over the execution of SUCRE Project was that there is not a preferential technological pathway for straw recovery. Besides the agricultural operations and straw transportation to the industry, the potential of success in decision-making varied according each mill's situation regarding industrial scale, existing infrastructure, industrial efficiencies, electricity selling price, company's business model and even the definitions on regulatory framework for the electricity sector.

In the agricultural phase, studies showed that the baling technology enables compacted straw to be recovered with low moisture. This technology has lower costs for both situations of larger quantities of straw recovered per hectare and longer transport distances. On the other hand, baling machineries can be associated with potential damage on both sugarcane ratoons and soil structure. For the integral harvesting technology, on the other hand, straw and stalks are harvested simultaneously and no additional operations are required. A benefit from this technology is the reduction on sugarcane stalk losses which, in turn, decrease integral straw cost. On the other hand, this technology reduces load density and straw has a higher moisture; consequently, it increases the transport cost. A lesson learned from this technology is that integral harvest has lower costs for shorter transport distances and smaller amounts of straw recovered per hectare.

In the industrial phase, straw recovered through bales goes through processes of unbaling, cleaning and shredding before being used as fuel. The straw recovered through integral harvesting requires additional equipment to separate it from sugarcane stalks, such as dry-cleaning system (DCS), which still presents low efficiency, affecting sugarcane milling capacity and efficiency. Straw, either recovered through bales or separated by dry cleaning system, has different ash content, moisture, density and particle size distribution when compared to bagasse. Thus, straw use as fuel in boilers traditionally designed for bagasse is still limited due to difficulties on continuous feeding and operation.

Considering the positive and negative effects of straw on both agricultural and industrial phases, it is necessary to carry out an integrated assessment to reach a verdict on whether it is advantageous or not to recover straw, and on which route would be the most appropriate. Agricultural and industrial parameters must be considered to have a better understanding of how these parameters interact with each other and of the possible economic and environmental impacts for the selected route. Among the scenarios that were assessed in SUCRE Project, the answers related to economic viability of sugarcane straw bioelectricity varied a lot because they depended on many factors. *Figure 71* shows an example of results of the incremental economic analysis with the range of straw recovery costs (US$ 9-45/metric ton) and the minimum selling price of electricity (US$ 29-106/MWh) obtained in the assessed scenarios of SUCRE Project, considering an exchange rate of US$ = R$ 4.00.

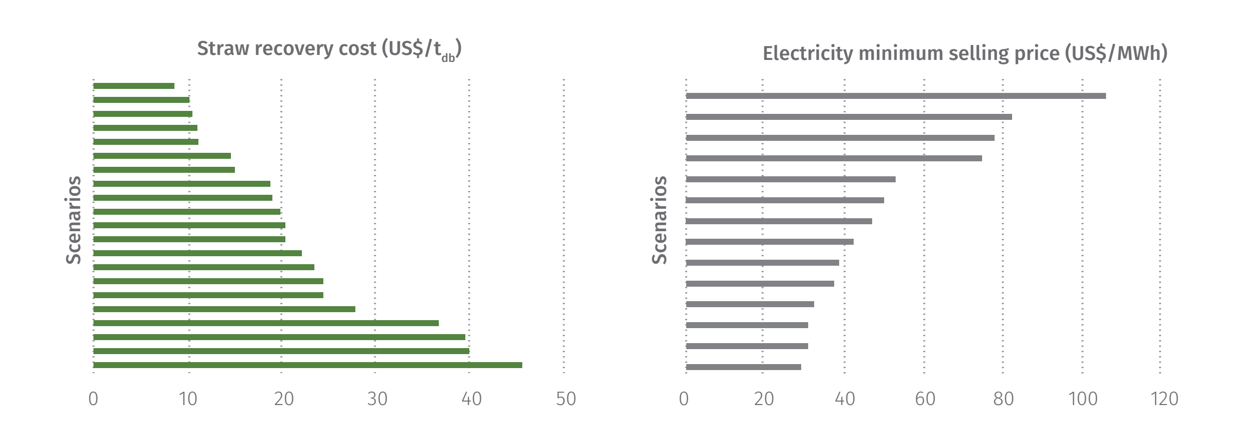

Figure 71: Example of results from partner mills in the context of SUCRE Project (t_{db}= metric ton of straw on dry basis).

3.6.3 TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF MILL A

DESCRIPTION OF MILL A

Mill A currently processes approximately 2 million metric tons of sugarcane per year and produces sugar, hydrated ethanol and electricity. The mill still does not recover straw and need to acquire additional bagasse from other units of the group for cogeneration in order to meet the contracted electricity export. Main agricultural and industrial parameters that describe current operation of this unit are shown in *Table 38*.

	Unit	Value/Description
Agricultural parameters		
Sugarcane yield	(TC/ha)*	49
Average transport distance	km	25
Recovery System	-	none
Industrial parameters		
Processed sugarcane	Mt/y	2.19
Effective season operating days	d	175
Offseason operating days	d	15
Boilers configuration	-	2 boilers (21 kgf/cm², 320 °C) and 1 boiler (65 kgf/cm², 500 °C)
Turbine types	-	Backpressure (30 MW) and condensing (16MW or 8MW, depending on pressure of inlet steam)

**TC: metric ton of stalks*

Table 38: Main agricultural and industrial parameters of the mill current operation.

For comparison, two scenarios with straw recovery through baling (Scenario 1) and integral harvesting (Scenario 2) were simulated with the aim of supplying all the biomass demand of mill for electricity generation. Initially, a recovery of 2.5 tons of straw (dry basis) per hectare was assumed for both scenarios.

The baling system allows the straw to be recovered with less moisture (15%) and compacted, which facilitates transport. The integral harvesting system increases the quantity of straw transported with the sugarcane, due to the speed reduction of the harvester primary extractor which, in turn, reduces stalk harvesting losses (HASSUANI et al., 2005; NEVES et al., 2006; OKUNO et al., 2019). The average moisture of recovered straw through integral harvest was 32%.

STRAW RECOVERY COSTS

Table 39 shows costs for both sugarcane stalks and straw in the evaluated scenarios. In these scenarios, the investment in machinery and implements, labor and inputs are considered. Besides, the costs include agricultural operations and transport to the mill. The calculation of straw recovery costs considers the additional costs per hectare of each straw recovery scenario in comparison with the scenario without straw recovery (Base Scenario). For Scenario 1, the additional costs are allocated to the straw recovered. For Scenario 2, the additional cost is divided between straw and extra stalks (stalks resulting from lower losses), proportionally to their masses on wet basis (DIAS et al., 2016; CARDOSO et al., 2018).

Table 39: Sugarcane production and straw recovery costs.

	Base Scenario	Scenario 1	Scenario 2
Sucarcane stalks (US$/TC)	29.91	29.91	29.38
Straw (US$/$t_{db}$)	-	40.58	10.79

In Scenario 2 the stalk cost is slightly lower due to sugarcane stalk losses reduction in the integral harvesting. Also, a sensitivity analysis was performed for straw recovery cost range varying the amount of straw recovered per hectare for both scenarios (see *Table 40*).

Table 40: Straw recovery cost varying amount of straw recovered per hectare.

	Amount of straw recovered		
	2 t_{db}/ha	2.5 t_{db}/ha	3.5 t_{db}/ha
Scenario 1	45.12	40.58	36.45
Scenario 2	9.55	10.79	12.10

In Scenario 1, as much as the straw quantity recovered increases, straw recovery cost decreases due to a more efficient use of agricultural machinery. On the other hand, Scenario 2 is related to increasing the straw recovery costs due higher amounts of straw which reduces the transport load density.

ELECTRICITY PRODUCTION

Without straw recovery, the current operation of the mill presents a deficit of 71.7 thousand tons of sugarcane bagasse per harvest (Base Scenario). As this mill has an annual contract for electricity export (approximately 110 GWh per year), this value was maintained in the evaluated scenarios (Scenario 1 and 2). The amount of required straw to meet this electricity export was calculated for each scenario (see *Table 41*).

	Base Scenario	**Scenario 1**	**Scenario 2**
Recovery System	-	Baling	Integral harvesting
Straw recovery (kt_{db}/y)	-	33	45

Table 41: Amount of straw recovered in each scenario.

The industrial results obtained for the scenarios are reported in *Table 42* as well as the investment needed to process the straw. In Scenario 1, investment is related to equipment to process straw bales, such as unbaling system, rotating screens, shredders, conveyor belts, among others. For Scenario 2, it was considered the investment on the dry-cleaning station that separates straw from sugarcane stalks (assuming a 35% efficiency). In both scenarios, investment was calculated based on cost-capacity correlations, considering data provided by partner mills of the project. As shown in *Table 44*, the sugar and ethanol production present a variation only when using the integral harvesting (Scenario 2), due to the additional straw that is crushed along with stalks, which increases the amount of fibers, resulting in a decrease in sugar extraction. For the calculations of the decrease on sugar extraction, it was assumed that the Pol (sucrose content) of the bagasse would be maintained for the scenario with integral harvesting, but that a higher amount of bagasse would be generated due to the increase in fibers on the material entering the milling tandem. It was not considered that additional crushing days would be necessary for Mill A, because the milling tandem is currently operating below its maximum capacity, as informed by the Mill. For both scenarios the electricity demand for straw processing was discounted from the total electricity generated to obtain the values reported on *Table 42* (electricity export). Additionally, it is observed that the amount of straw recovered in this scenario is higher than that from Scenario 1 (with baling) to meet the same electricity export. This is mostly because straw from integral harvesting has a higher moisture which results in a lower heating value of this fuel.

Table 42: Industrial results for scenarios with and without straw recovery and the necessary investment for straw processing.

	Base Scenario	**Scenario 1**	**Scenario 2**
Sugar production (kt/y)	210.67	210.67	210.39
Hydrated ethanol production (ML/y)	60.30	60.30	60.22
Electricity export (GWh/y)	110.25	110.25	110.25
Investment (million R$)	-	9.88	13.96

ECONOMIC VIABILITY

An incremental discounted cash flow analysis considers only the effects caused by the decision of recovering straw on the existing agro-industrial system of Mill A. In this analysis, the additional agricultural costs from straw are included in the industrial cash flows as the annual operating costs associated to biomass. In this agricultural cost, both operating and investment costs related to the baling system are included. Also, additional expenses (such as labor, maintenance and chemicals) as well as capital costs related to the extra industrial equipment are accounted for. The metric considered to compare alternatives was the net present value of the incremental project. The main assumptions used for the discounted cash flow analysis are described in *Table 43*.

Parameter	Value	Unit
Reference date	July/2019	-
Exchange rate	3.88	R$/US$
Project implementation	1	year
Project lifetime	20	years
Discount rate, real rate	12	% per year
Working capital	10	% of fixed capital investment
Average annual depreciation	10	% per year, linear
Total employee cost (w/ charges)	962	US$/month
Average maintenance cost	3	% of fixed capital investment
Income tax (IRPJ)	25	% of taxable income
Social contribution on net income (CSLL)	9	% of taxable income

Assessed products	Value	Unit
Electricity - average price	70	US$/MWh
Bagasse - price range	4-21	US$/ $_{\text{twet basis}}$
Bagasse - average price	10	US$/ $_{\text{twet basis}}$

Table 43: Main assumptions made in the discounted cash flow analysis.

Scenario 1 considers an additional straw recovery of about 33 thousand tons (dry basis) using bale system in relation to the current situation (Base Scenario). In this case, the expansion scenario considers that part of the purchase of bagasse from third parties is reduced due to the additional recovery of straw. For this decision-making, the industrial plant would need an additional US$ 2.54 million of investment in equipment for receiving, unbaling, shredding and transporting straw. Such data were estimated from the SUCRE Project database and correlated with the capacity required to process the straw. In addition, an investment in working capital of US$ 255 thousand was considered.

Table 44 shows that the main impact on operating costs of the agro-industrial system is agricultural costs with straw, industrial labor and additional maintenance. This table illustrates the case for a straw cost of US$ 40.66 per dry ton, but it is known that this value varies according to the premises, for example, the amount of straw recovered per hectare. A benefit computed as cost of bagasse avoided is based on the amount of US$ 10.31 per wet ton.

Parameter	Scenario 1
Additional CAPEX (US$)*	2,800,773
Additional OPEX (US$/year)	
Agricultural straw costs	1,342,268
Industrial labor costs	138,660
Maintenance costs	76,289
Avoided bagasse cost**	-1,478,608
Additional revenue (US$/year)	
Additional surplus electricity	-

**Fixed and working capital. ** Average bagasse price at US$ 10.31 per wet ton*

Table 44: Impacts on additional investment and operating costs of Scenario 1.

It is important to highlight that in the present analysis, the costs associated with indirect factors that may impact the agro-industrial system were not quantified, such as the impacts of straw on possible increase in the maintenance of industrial equipment (mainly in boilers) due to additional corrosion/erosion, deposits, shutdowns and reduction of useful life. In addition to these results requiring long-term studies, some project partners report that, based on their observations, straw and bagasse are likely to incur similar maintenance costs.

Table 45 shows the deterministic result of the agro-industrial system in terms of internal rate of return - IRR (real rate) and net present value (NPV). Due to the cash flows not showing a sign reversal, the IRR calculation was not possible. The obtained value shows that the agro-industrial system would not be viable (negative NPV), showing that the investment made is not remunerated at this discount rate, being better to continue buying bagasse instead of removing baled straw. It is important to highlight that bagasse price is very low in the region of Mill A, fact that contributed to achieve these results.

Parameter	Scenario 1
Incremental IRR (per year)	-
Incremental NPV (US$)	-3,326,109

Table 45: Results of discounted cash flow analysis.

However, considering the possibilities of variation in the cost of straw, a sensitivity analysis was performed to understand the impacts of variations in the cost of straw – considering the assumptions of variable straw removal in tons per hectare – would impact the Net Present Value of the agro-industrial project. At the same time, *Table 46* shows how the price of the avoided bagasse available in the region could impact the NPV if it was sold at a variable price, between US$ 4-21 per ton on wet basis.

Table 46: Sensitivity analysis of NPV (US$ million) when varying the price of bagasse and the straw cost in Scenario 1.

		Straw agricultural cost (US$/$t_{db}$)*			
		37	39	42	45
Price of the avoided bagasse (US$/$t_{wb}$)	4	-8.87	-9.54	-10.21	-10.88
	8	-4.64	-5.31	-5.98	-6.65
	12	-0.59	-1.08	-1.75	-2.42
	16	2.37	1.91	1.44	0.95
	21	5.34	4.87	4.41	3.92

** Considering variations in the quantities of straw recovered per hectare.*

Table 46 shows the regions of economic feasibility (green, with positive NPVs) and non-viability (red cells, with negative NPVs) for the agro-industrial system, considering the straw recovery via baling system. As it is possible to observe, there are possibilities of achieving project viability. As indicated in the green regions, the decision may be viable if the price of avoided bagasse reached values above the average (US$ 10/ t_{wb}); in the case of the highest straw cost, the decision is viable with bagasse with a price equal to or above US$ 15 per ton on wet basis; in the case of the lowest straw cost, for a price equal to or above US$ 13/t_{wb}.

Considering the unfavorable results for Scenario 1, an alternative scenario (Scenario 2) considers the recovery of 45 thousand tons of straw on a dry basis by the integral sugarcane harvest, also acting in the replacement of all the quantity of bagasse purchased from third parties. In this scenario, additional 30,385 MWh are generated. Analogously to the previous scenario, the deterministic impacts for this case were computed. In this case, the incremental investment in the industry (mostly the dry-cleaning system) was estimated at US$ 3.59 million, according to the amount of straw recovered and delivered to the industry. A peculiarity of this route is that the agricultural cost of straw is benefited by the reduction of stalk loss in the harvest, as explained in the agricultural modelling section. The net effect is a negative operating cost with biomass, that is, a cash flow benefit. Losses of revenue from hydrated ethanol and sugar were also computed due to the entry of straw into the juice extraction system. For the calculations presented in *Table 47*, an average bagasse price of US$ 10 / t_{wb} was considered.

Parameter	Scenario 2
Additional CAPEX (US$)*	3,956,701*
Additional OPEX (US$/year)	
Agricultural straw costs	-678,093**
Chemical inputs	11,031
Industrial labor costs	23,112
Maintenance costs	107,990
Avoided bagasse cost**	-1,478,608
Additional revenue (US$/year)	
Additional surplus electricity	-
Hydrous ethanol	-35,309***
Sugar	-96,392***

Table 47: Impacts on additional investment and operating costs of Scenario 2

**Includes equipment, infrastructure and working capital **Annual agricultural cost of straw of US$ 0.49 million, deducted from the benefit of US$ 1.16 million in the reduction of stalk loss. ***Losses in revenue due to reduced extraction at the mill considering the price of hydrated ethanol at US$ 0.44/ L and sugar at US$ 0.34 / kg (CEPEA, 2019).*

Table 48 presents the deterministic result of the agro-industrial system choosing the integral harvest, in terms of internal rate of return - IRR (real rate) and net present value (NPV). The deterministic value shows that the scenario with straw recovery would be viable against the use of sugarcane bagasse (IRR above the discount rate of 12% per year), showing that the investment made is remunerated at a rate of 34.33% per year, in this specific case.

Parameter	Scenario 2
Incremental IRR (per year)	34.33%
Incremental NPV (US$)	6,124,226

Table 48: Results of discounted cash flow analysis.

Table 49 shows the NPV sensitivity analysis to represent the case of Scenario 2, when the amount of straw recovered per hectare varies, impacting the operating cost with straw. As the quantity recovered increases, the agricultural cost of straw transported to the mill is also increased. However, as can be seen in the NPV sensitivity graph, the higher the cost of whole straw, the greater the project's viability. This is because there is a simultaneous benefit of reducing stalk losses and stalk costs (which decrease from US$ 29.53 to US$ 29.28 per ton when the cost of straw increase from US$ 9.57 to 12.12 per ton). The table below shows, therefore, that the incremental project to recover whole straw to replace bagasse would be a viable alternative in the avoided bagasse price ranges evaluated in the study.

Table 49: Sensitivity analysis of NPV (US$ million) to the price of bagasse and the straw cost in Scenario 2 (integral harvesting system).

Price of the avoided bagasse (US$/$t_{wb}$)	Straw agricultural cost (US$/$t_{db}$)*: 9.55	10.40	11.25	12.10
4	0.8	1.5	2.2	2.9
8	3.7	4.5	5.2	5.9
12	6.7	7.4	8.1	8.8
16	9.7	10.4	11.1	11.8
21	12.6	13.3	14.0	14.7

** Considering variations in the quantities of straw recovered per hectare.*

As a main specific conclusion of this case study, it is possible to observe that both baling (Scenario 1) and integral harvesting (Scenario 2) systems can achieve economic feasibility. However, when considering the agricultural and industrial characteristics of this project, integral harvest has an advantage, mainly because of the negative operating costs in the agricultural stage caused by stalk reduction losses.

ENVIRONMENTAL ASSESSMENT

The objective of this session was to assess how the recovery of straw impacts the GHG emissions of ethanol and electricity production from Mill A. In this assessment energetic allocation (*Table 50*) was considered to obtain the GHG emissions associated to the production of 1 MJ of ethanol and 1 kWh of electricity for the assessed mills.

Table 50: Parameters considered for energetic allocation.

Product	Energy content	
Anhydrous ethanol	22.35[a]	MJ/L
Hydrous ethanol	21.34[a]	MJ/L
Sugar	16.20[b]	MJ/kg
Electricity	3.60	MJ/kWh

[a] ANP (2019); [b] NEPA (2011)

The objective of the environmental assessment for this mill was to estimate the GHG emissions when replacing purchased bagasse with recovered straw by bales (Scenario 1), and with integral harvesting (Scenario 2). The parameters from *Tables 50* and *51* were used to allocate total emissions to the products.

Table 51: Products from Mill A.

Product	Base Scenario	Scenario 1	Scenario 2
Hydrous ethanol (L/TC)	27.59	27.59	27.55
Sugar (kg/TC)	96.37	96.37	96.25
Electricity (kWh/TC)	50.43	50.43	50.43

In *Table 52*, we present the emissions of CO_2eq per ton of sugarcane for each production stage (agricultural and industrial), before allocation among products.

Table 52: GHG emissions for stage of production (kg CO_2eq/TC).

	Base Scenario	Scenario 1	Scenario 2
Total	62.30	62.22	61.02
Agricultural	56.19	56.18	54.83
Industrial	6.11	6.03	6.18
Purchased bagasse	0.04	-	-

Emissions from Scenario 1 and 2 are lower than Base Scenario, because there is less straw decomposing on the field, and in the case of scenario 2, also because there is less diesel consumption in agricultural operations. Regarding industrial emissions, there is a decrease from Base Scenario to Scenario 1, due to higher lower heating value (LHV) of straw compared to bagasse, for instance, it is necessary less straw to produce the same amount of electricity produced by bagasse. On the other hand, from Scenario 1 to Scenario 2, such emissions increase because there is more lignocellulosic material burnt in the boilers (increased straw recovery), since it is necessary more straw recovered by integral harvest to generate the same amount of electricity from straw recovered by bales. In general, there is a reduction in GHG emissions per ton of processed sugarcane when recovering straw.

Finally, after allocation of total emission among the products, the emissions per MJ of ethanol and kWh electricity decrease as more straw is recovered. This happens because more electricity is produced, consequently, total emissions are allocated to more products. In all the situations assessed, the ethanol and electricity produced from this mill has more than 50% emissions reduction when compared to their fossil counterparts (gasoline and natural gas) (*Figure 72*).

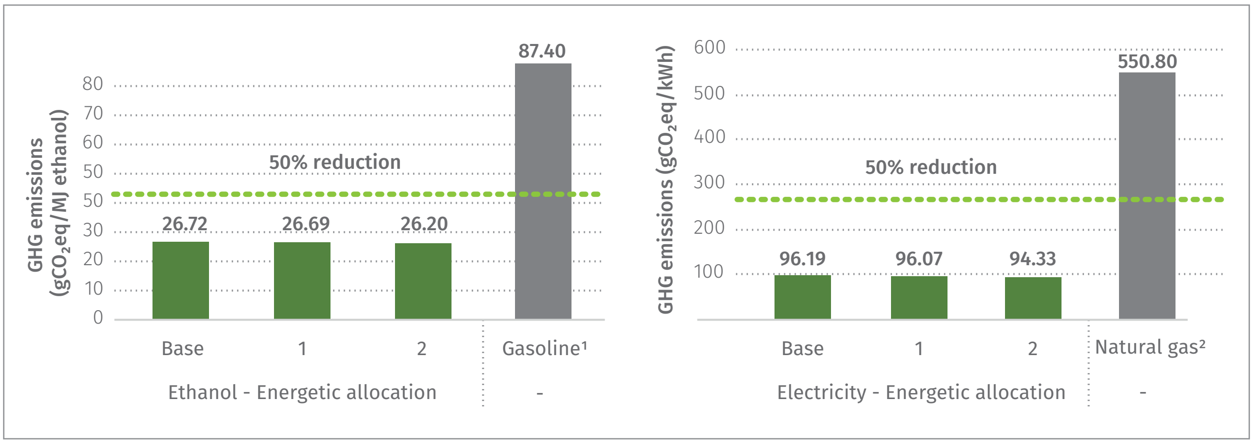

Figure 72: GHG emissions for ethanol and electricity produced in Mill A – energetic allocation. [1]Matsuura et al. (2018). [2]Ecoinvent (n.d.)

3.6.4 TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF MILL B

DESCRIPTION OF MILL B

Mill B currently processes approximately 2 million metric tons of sugarcane per year and produces sugar, anhydrous and hydrated ethanol and electricity. The mill recovers straw through baling system and has plans to expand this operation to increase electricity export. The mill assesses the alternative to purchase eucalyptus chips as a complementary fuel. Some agricultural and industrial parameters that describe current operation of this unit are shown in *Table 53*.

Table 53: Main agricultural and industrial parameters of the mill current operation.

	Unit	Value/Description
Agricultural parameters		
Sugarcane yield	(TC/ha)*	68
Average transport distance (straw)	km	40
Straw recovery	t_{db}/ha	4.6
Straw moisture	%	14
Recovery System	-	Baling
Industrial parameters		
Processed sugarcane	Mt/y	1.93
Effective season operating days	d	200
Processed straw per year (db)	t	43,518
Boilers configuration	-	1 boiler (42 kgf/cm², 450 °C) 1 boiler (67 kgf/cm², 520 °C)
Turbine types	-	2 Backpressure turbines (15MW each) and 1 Extraction-condensing turbine (32 MW, but on average operating at 18 MW)

**TC: metric ton of stalks*

A simulation of the current operation (Base Scenario) was carried out for the 2018/2019 harvest, resulting in an electricity export of about 130 GWh per year. In addition, the following scenarios were evaluated: Scenario 1, whose expansion of straw recovery through the baling system from 43,518 to 80,000 tons per harvest is made to increase electricity export; and Scenario 2, with maintenance of the current straw recovery (43,518 tons) and with the purchase of eucalyptus chips achieves the same electricity export of Scenario 1. In this scenario the agricultural phase considers the Base Scenario parameters for straw recovery.

STRAW RECOVERY COSTS

Scenario 1 considers an increase of mechanized harvesting area, thus increasing the amount of straw recovery in the season. However, Scenario 1 considers the same amount of straw recovered per hectare as the Base Scenario, as well the transport distance (*Table 53*).

The costs for sugarcane stalks and straw recovery in the evaluated scenarios are presented in *Table 54*.

	Base Scenario	Scenario 1
Sugarcane stalk (US$/TC)	20.23	20.59
Straw (US$/$t_{db}$)	27.44	24.91

Table 54: Sugarcane production and straw recovery costs.

The sugarcane stalk cost increases in Scenario 1 due to the variation in the both harvested area and harvest efficiency. The straw recovery cost, on the other hand, decreases due to the greater efficiency of the machinery use.

Straw recovery cost is affected mainly by the quantity of straw recovered and the transport distance. However, the baling allows the straw to be recovered with less moisture and compacted, which reduces transport cost.

A sensitivity analysis was performed for straw recovery cost range varying the amount of straw recovered per hectare and transport distance (*Table 55*).

Table 55: Straw recovery cost varying the amount of straw recovered per hectare and transport distance.

	Transport distance			
	40 km		45 km	50 km
Straw recovered (t_{db}/ha)	3.2	4.6	4.6	4.6
Straw recovery cost (US$/$t_{db}$)	28.23	24.91	25.53	26.26

As expected, *Table 48* shows that straw recovery cost with bales are more sensitive to variations in straw recovery quantities than transport distance. Smaller amount of straw recovered presents higher cost due to reduced machineries operational efficiency, mainly of baler.

ELECTRICITY PRODUCTION

The additional fuels in Scenarios 1 and 2 are burnt in the offseason period, considering the capacity of one of the boilers (67 kgf/cm², 520 °C) and an extraction-condensing turbine, resulting in 63 operating days.

For Scenario 2, the demand of eucalyptus chips was calculated so that the electricity export would be equal to that of Scenario 1 (approximately 160 GWh per year). The calculated amount was 56.5 thousand tons of eucalyptus chips per year, considering a lower heating value of 10,042 kJ / kg and a moisture of 40%.

The industrial results obtained for the scenarios are reported in *Table 58*. There was an increase of 24% in the electricity export in Scenarios 1 and 2, compared to base case, due to the increase in biomass processing for steam generation and, consequently, electricity. In this case, additional investments in the industrial unit were not considered since no extra equipment would be required, since the project of this mill was originally conceived to process more straw than was being processed on the Base Scenario. The existing equipment (boilers, conveyor belts) would also be sufficient to process the eucalyptus chips (Scenario 2). For both scenarios, the electricity demand for the additional straw or eucalyptus chips processing was discounted from the total electricity generated to obtain the values reported on *Table 56* (electricity export).

It is worth mentioning that sugar and ethanol production was maintained the same as in Base Scenario, since straw bales and eucalyptus chips are processed in the cogeneration system, without any impact on the sugarcane processing.

Table 56: Industrial results for the simulated scenarios.

	Base Scenario	**Scenario 1**	**Scenario 2**
Straw recovered (kt/y)	43.52	80. 00	43.52
Eucalyptus chips purchased (kt/y)	-	-	56.54
Electricity export (GWh/y)	129.76	160.60	160.60

ECONOMIC VIABILITY

The technical and economic feasibility assessment of mill B considers similar system boundaries of mill A, with an incremental cash flow analysis for a project using the baling system as an alternative to generate additional electricity surplus to the grid. Also, a comparison with eucalyptus chips is performed considering the location of this mill in relation to eucalyptus plantations. The assumptions related main prices, expenses and others used for this assessment are described in *Table 57*.

Parameter	Value	Unit
Reference date	July/2019	-
Exchange rate	**3.88**	**R$/US$**
Project implementation	1	year
Project lifetime	20	years
Discount rate, real rate	12	% per year
Average annual depreciation	10	% per year, linear
Total employee cost (w/ charges)	773	US$/month
Income tax (IRPJ)	25	% of taxable income
Social contribution on net income (CSLL)	9	% of taxable income
Assessed products	**Value**	**Unit**
Electricity – average price	51	US$/MWh
Electricity – price range	36-82	US$/ MWh
Eucalyptus chips – average price	41	US$/ twet basis
Eucalyptus chips – price range	36-46	US$/ twet basis

Table 57: Main assumptions made in the discounted cash flow analysis.

Considering the additional straw harvested in the order of 31.4 thousand tons of dry straw using the baling system, the economic feasibility of Scenario 1 of expanding straw recovery in relation to the current situation was evaluated (Base Scenario). This case study presents a particularity which is the industrial equipment and infrastructure for (processing and moving straw that have already been installed in the past. Therefore, in the present case, the additional CAPEX of the present analysis was null, since the invested structure is currently idle (capacity to process up to 80 thousand tons of straw per year).

The deterministic results of Scenario 1 were assessed, considering a fixed straw recovery cost of US$ 25.50 per dry ton. Also, this scenario has a different harvesting system when compared to the base case, i.e., the situation of no straw recovery. As a result, an additional cost of US$ 0.36 per ton of processed sugarcane stalk is added into the operating costs associated with this project. The estimated additional maintenance and labor costs were US$ 24.74 thousand and US$ 27.81 thousand, respectively. The additional revenue with electricity was estimated at US$ 1.59 million per year. As a result, a positive net present value (NPV) of US$ 257 thousand was obtained, indicating the economic viability of the baling system as an alternative to provide additional electricity.

Considering the possibilities of changes in the main assumptions, a sensitivity analysis of NPV to straw costs and price electricity was performed. *Table 58* shows a sensitivity analysis to variations in the cost of straw, where the range obtained shows the influence of greater transport distances (up to 50 km) and variations in the amount of straw recovered per hectare. At the same time, the table shows how the price of electricity sold at a variable price, between US$ 36-82/ MWh.

Table 58: Sensitivity analysis of NPV (US$ million) to the price of electricity and straw cost in scenario 1 (baling system).

		Straw agricultural cost (US$/$t_{db}$)*			
		25	26	27	28
Electricity price (US$/MWh)	36	-2.99	-3.22	-3.48	-3.71
	48	-0.46	-0.72	-0.95	-1.21
	59	1.44	1.26	1.08	0.93
	71	3.20	3.02	2.86	2.68
	82	4.95	4.79	4.61	4.43

**Considering changes in transport distance and amount of recovered straw per hectare.*

Table 60 shows the regions of economic feasibility (green) and unfeasibility (red) for the agro-industrial system. As it is possible to observe, there is a region of viability predominant in the intervals chosen for the sensitivity. As shown at the electricity price level at US$ 59/MWh, all simulated straw costs would imply on viable projects. The decision shows the viability threshold (NPV = 0) with a minimum electricity selling price of US$ 49.74/MWh for the case of lower straw costs; for the highest straw cost, the minimum price would be at US$ 53.35/MWh.

An alternative incremental project (Scenario 2) assesses electricity generated from eucalyptus chips as an alternative for the additional sugarcane straw. This possibility is explored due to the availability of such biomass in the context of the sugarcane mill. In this case study, the industrial plant would not require additional industrial investment, as the purchased chips are suitable as fuel for the available boilers. Therefore, it was estimated that 56,537 tons of eucalyptus chips (40% of moisture) were purchased to supply the same 30,385 MWh of Scenario 1.

In the deterministic scenario, the main impact on operating costs of this alternative project are the agricultural costs with the chips of US$ 2.33 million (US$ 41/ t_{wb}), delivered at the gate. Labor costs were estimated at US$ 27.8 thousand per year. The additional maintenance cost was assumed to be zero since there is no need for additional processing and conditioning the eucalyptus chip, which is already ready for combustion in the boiler. The additional revenue with electricity is approximately US$ 1.59 million per year.

The result of the deterministic cash flow analysis presents a negative NPV (-US$5.59 million), indicating that using eucalyptus chips would not be economically viable in this context, considering an electricity selling price of US$51/MWh.

Considering the possibilities of changes in the cost of the eucalyptus chips and electricity price, a sensitivity analysis was carried out. *Table 59* shows that economic unfeasibility is predominant in the intervals chosen for the sensitivity. If the eucalyptus chip reaches lower costs, for example US$ 36/ t_{wb}, the decision would be viable at the minimum electricity selling price of US$ 68/MWh. In the case of chips at US$ 46/ t_{wb}, the minimum sale price would be at about US$ 77/MWh.

Table 59: Sensitivity analysis of NPV (US$ million) to the prices of electricity and eucalyptus chips in scenario 2.

		Eucalyptus chips (US$/$t_{Wb}$)*				
		36	39	41	44	46
Electricity price (US$/MWh)	36	-6.91	-7.91	-8.94	-9.97	-11.01
	48	-4.38	-5.41	-6.42	-7.45	-8.48
	59	-1.86	-2.89	-3.92	-4.95	-5.95
	71	0.46	-0.36	-1.39	-2.42	-3.45
	82	2.22	1.49	0.77	0.08	-0.93

**Changes in chips prices estimated at the gate, in wet basis.*

In general terms, comparing the results of Scenario 1 with those of Scenario 2, the use of straw baling system for the expansion of electricity generation has an economic advantage over the use of eucalyptus chips as fuel.

ENVIRONMENTAL ASSESSMENT

For the Mill B, the objective was to assess the impacts of electricity expansion on GHG emissions per MJ of ethanol and kWh of electricity. Such expansion of electricity generation happened by recovering straw from sugarcane fields (Scenario 1) and from purchase of eucalyptus chips (Scenario 2). The parameters from *Tables 60* and *61* were used to allocate total emissions to the products.

Product	Base Scenario	Scenario 1	Scenario 2
Anhydrous ethanol (L/TC)	11.70	11.70	11.70
Hydrous ethanol (L/TC)	20.93	20.93	20.93
Sugar (kg/TC)	70.93	70.93	70.93
Electricity (kWh/TC)	67.23	83.21	83.21

Table 60: Products from Mill B.

In *Table 61*, the emissions of CO_2eq per ton of sugarcane for each production stage (agricultural and industrial) before allocation among products are presented; it also contains emissions for the purchased eucalyptus chips that consider production and transportation until Mill B location.

	Base Scenario	Scenario 1	Scenario 2
Total	47.10	47.81	48.89
Agricultural	40.39	40.65	40.65
Industrial	6.71	7.16	7.17
Purchased chips	-	-	1.07

Table 61: GHG emissions for stages of production (kg CO_2eq/TC).

The best alternative to produce electricity considering GHG emissions is to recover straw instead of purchased eucalyptus chips. Scenario 2 (electricity from eucalyptus chips) presents higher emissions per MJ of ethanol and kWh of electricity compared to Scenario 1 (electricity from sugarcane straw). In all the situations assessed, the ethanol produced from this mill has more than 50% emissions reduction (approximately 75%) when compared to gasoline. In the case of electricity, the reductions are of approximately 85% (*Figure 73*).

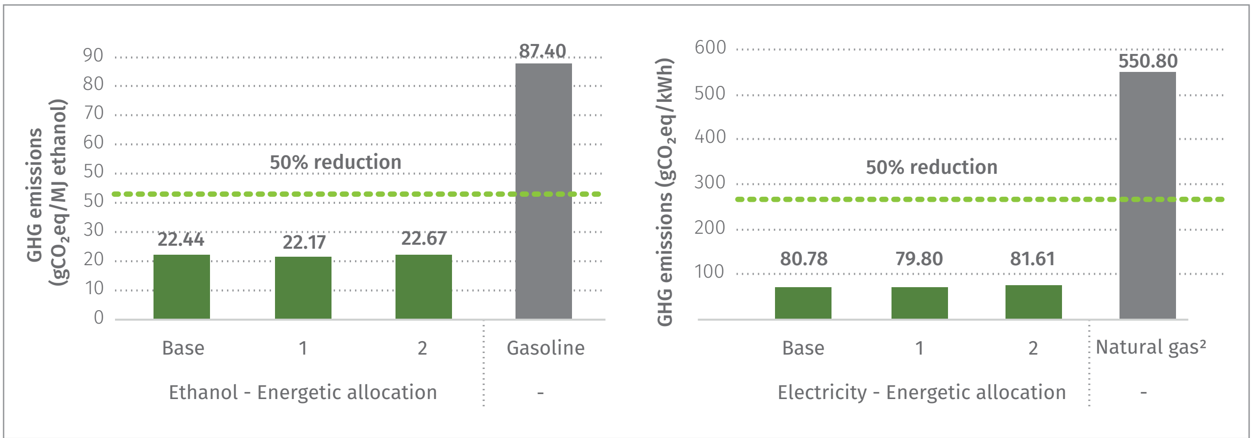

Figure 73: GHG emissions for ethanol and electricity produced in Mill B – energetic allocation. [1]Matsuura et al. (2018), [2]Ecoinvent (n.d.)

As conclusion, ethanol and electricity from sugarcane have huge potential to mitigate GHG emissions when compared to gasoline and electricity from natural gas. The recovery of straw does not increase emissions of electricity produced. In fact, electricity from bagasse or mixed bagasse and straw presents huge potential for GHG mitigation and presents a feasible alternative for the activation of natural gas thermoelectrical plants during dry season in Brazil.

3.7 COUNTRY LEVEL ENVIRONMENTAL AND SOCIAL IMPACTS

Authors: *Alexandre Monteiro Souza, Nariê Rinke Dias de Souza,*
Thayse Aparecida Dourado Hernandes

3.7.1 SUGARCANE ELECTRICITY: POTENTIAL MITIGATION OF GHG EMISSIONS

During dry periods in Brazil, the level of water in reservoirs decreases, necessitating electricity production through other methods such as the activation of thermoelectric plants driven by natural gas (Romeiro et al., 2020). Similarly, sugarcane bioelectricity is considered a reliable energy source during such dry periods and has the advantage of low greenhouse gas (GHG) emissions when compared to natural gas electricity (Sampaio et al., 2019; Souza et al., 2019).

Currently, the sugarcane sector produces bioelectricity mostly from bagasse, although sugarcane straw (sugarcane tops and leaves) possess a huge potential for additional electricity production (Sampaio et al., 2019; Souza et al., 2019). Moreover, the recently approved RenovaBio program is expected to be an impetus for the expansion of the sugarcane sector, which may enhance sugarcane bioelectricity production.

In 2018, approximately 620 million tons of sugarcane were harvested in Brazil, from which approximately 22 TWh of bioelectricity was exported to the grid (UNICA, 2019), representing approximately 16% of residential electricity consumption, presented in *Figure 74* as "Bagasse current system" scenario. With the optimization of energy utilization in the mills (cogeneration and process steam consumption), more than 40 TWh of extra bioelectricity could be exported, giving a total of 62 TWh, and this could supply 46% of the residential electricity demand and mitigate 7% of energy sector emissions (bagasse optimized system). This optimized plant configuration is characterized by efficient boilers, reduction of steam consumption, extraction-condensation turbines, electric mill drives, and 100 kWh of energy surplus per ton of sugarcane processed (Bonomi et al., 2016; Cardoso et al., 2018).

Sugarcane electricity generation in Brazil can be increased from the current 22 TWh to 104 TWh, by only recovering 50% of the current produced straw and improving the cogeneration system (Bagasse + 50% straw) with no additional land requirement. This electricity could potentially supply 78% of household electricity demand and mitigate 11% of energy sector GHG emissions, considering that the bioelectricity would be replacing electricity generated from natural gas.

According to RenovaBio expectations (MME, 2020), the expansion of the sugarcane growing area in Brazil by 3 million ha to meet the demand for 50 billion L of ethanol could mitigate approximately 15% of the energy sector emissions and result in the distribution of up to 141 TWh of surplus electricity to the grid per year (Bagasse + 50% straw + RenovaBio).

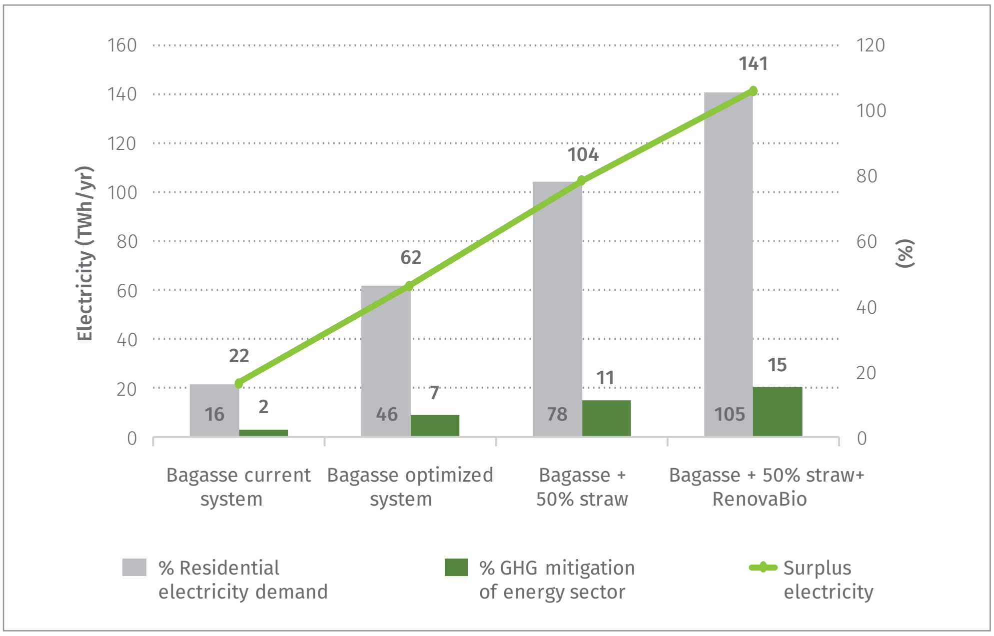

Figure 74: Potential of surplus sugarcane electricity generation for the mitigation of energy sector GHG emission and supply of residential electricity demand | Source: (SUCRE, 2020).

The parameters presented in *Table 62* were utilized to estimate the potential for surplus electricity generation, residential electricity demand, and mitigation of GHG emissions from the energy sector.

Table 62: Parameters for bioelectricity potentials.

Parameters	Unit	Value
Net electricity generated from straw (15% moisture)[a]	MWh/t	0.8
Impact of natural gas-based electricity in Brazil[b]	gCO_2eq/kWh	551
Impact of bioelectricity from sugarcane biomass in Brazil[c]	gCO_2eq/kWh	69
Total residential electricity consumption in Brazil[d]	TWh/year	134
Brazilian energy sector emissions in 2015[e]	Mt CO_2eq	449

[a]CTC (2015); [b]Ecoinvent (n.d.); [c]Calculated – Brazilian average; [d]EPE (2018); [e]SIRENE, MCTIC (n.d.).

It is extremely important to evaluate the GHG mitigation potential of sugarcane bioelectricity, particularly considering the global objective of reducing these emissions and the Sustainable Development Goals (SDG). In addition, emissions from the Brazilian energy sector increased by 42% from 2005 to 2015, as shown in *Figure 75* below.

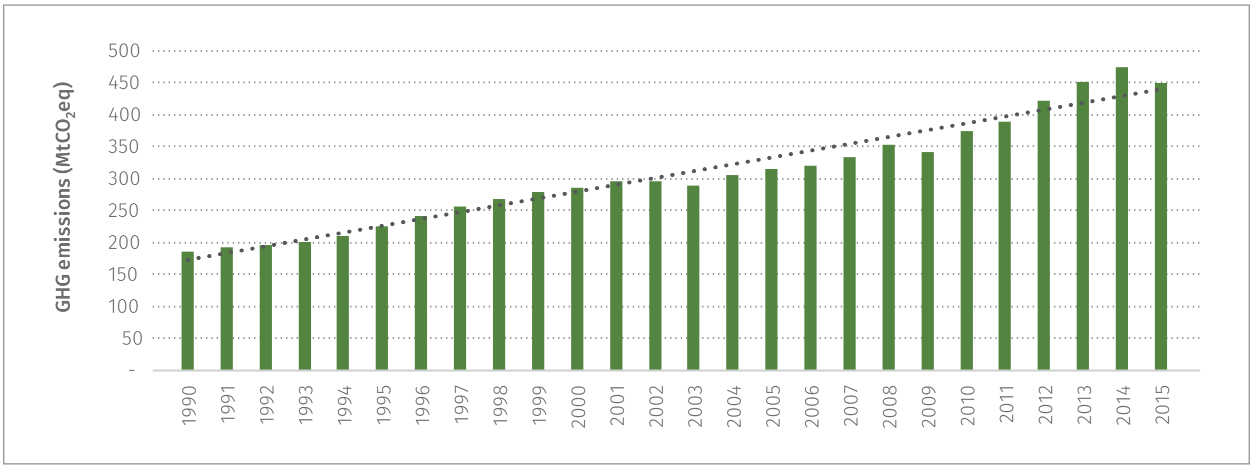

Figure 75: GHG emissions from Brazilian energy sector | Source: SIRENE, MCTIC (n.d.).

Brazil has a huge potential for expanding electricity production by recovering sugarcane straw from the fields. Sugarcane bioelectricity is more environment-friendly compared to fossil sources of electricity and also fits within the contemporary context of an energy transition towards low carbon-intensive sources and maximizing the use of feedstocks.

The recovery of straw has a huge potential to increase bioelectricity production and to mitigate energy sector emissions in Brazil, which may help the country to meet the established targets for the Paris Agreement (37% of GHG emissions by 2025 and 43% by 2030, compared to the 2005 national emissions).

3.7.2 SOCIAL EFFECTS OF SUGARCANE ELECTRICITY: POTENTIAL FOR STRAW RECOVERY AND USE

The recovery and use of sugarcane straw can increase electricity production, increasing the supply to meet the increasing demand for electricity, and simultaneously contributing to the mitigation of energy sector emissions in Brazil. However, it is also important to evaluate the potential social effects of the additional technologies and processes required for straw recovery and electricity production.

The SUCRE Project examined the potential positive and negative social effects of electricity production using sugarcane straw. The main technological configurations applied in Brazil for straw recovery are the integral harvesting and baling systems. *Table 63* shows a comparison of the social effects of two electricity production scenarios (Bales and Integral) on workers, considering 50% of straw recovery using integral harvesting and a baling system (SUCRE, 2019). The social effects associated with straw recovery and electricity production are defined by the difference (Δ) between the scenarios with straw recovery (Bales and Integral) and a basic scenario (without straw recovery). The results are related to the social effects throughout the production chain.

Table 63: Social metrics of electricity production using straw recovery for different recovery technologies.

Metrics	Δ Integral [a,b]	Δ Bales [a,c]
Jobs/million tons of stalks	9	18.5
Occupational accidents/million tons of stalk	0.15	0.25
Occupational accidents/1000 workers	0.04	0.05
Annual average wage (USD)	55	64
Average years of formal education	0.1	0.1
% women	0.3%	0.4%

[a] *50% of straw recovery*
[b] *Difference between Integral harvesting and Basic scenarios*
[c] *Difference between Bales and Basic scenarios*

The contribution of electricity production from sugarcane straw to the social metrics related to the workers' profile (annual average wage, average years of formal education, and percentage of women), was slightly positive. In the number of jobs/million tons of stalks metric, a potential of over 12 thousand jobs could be achieved under the application of the Bales scenario to Brazilian sugarcane production of 665 million tons as in 2015 (CONAB, 2017), even though the contribution seems small.

The electricity from sugarcane biomass has the maximum potential for job creation in comparison with the electricity produced using other sources in Brazil (*Figure 76*). When comparing sugarcane electricity with the electricity production using natural gas, which is a fossil energy source, the sugarcane electricity can double the potential for job creation. Additionally, a substantial proportion of the jobs created in sugarcane electricity production are in the sugarcane growing sector, which is advantageous as it increases job opportunities in rural areas.

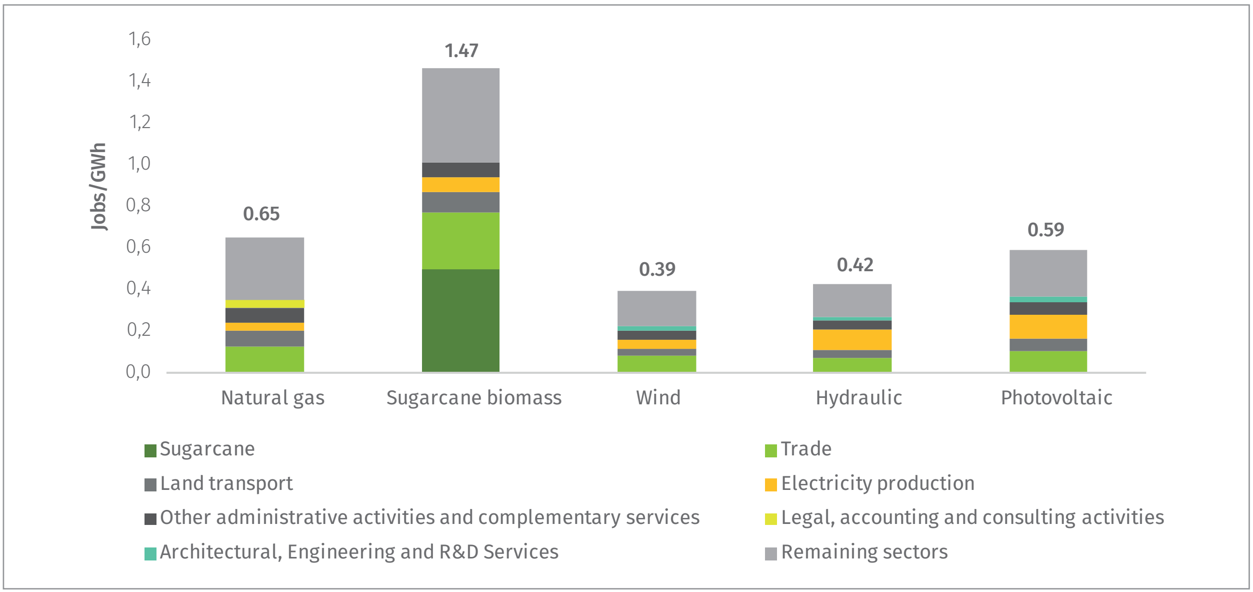

Figure 76: Comparison of electricity generation from renewable and fossil sources in Brazil.

3.7.3 ENVIRONMENTAL ASSESSMENT: BEYOND GHG MITIGATION

The main objective of the SUCRE Project was to increase the supply of clean and affordable energy (**SDG #7: Affordable and Clean Energy**) while reducing GHG emissions and thus contributing to the mitigation of climate change (**SDG #13: Climate Action**). However, the reduction in GHG emissions must, in the best possible way, be accompanied by other environmental benefits to ensure that this energy source does not increase the pressure on important natural resources, such as land and water. Thus, studies related to the impacts of land use change due to the expansion of sugarcane production and its possible consequences on water resources and deforestation were conducted. Furthermore, the effect of straw removal on the availability of water resources was evaluated in a basin located in an expansion area for sugarcane cultivation.

By considering the dynamics of land use changes in sugarcane cultivation from 2002 to 2016, studies based on the processing and analysis of satellite images showed that the vast majority of sugarcane areas are within the Sugarcane Agroecological Zoning (SAZ) (Leal et al., 2018; Manzato et al., 2009). This means that the bulk of expansion that occurred in the evaluated years (approximately 4 million ha) did not displace native vegetation and instead occupied areas that were already deforested before the evaluation period. The data showed that 96% of the new sugarcane areas in the evaluated period did not cause direct deforestation.

In this study, evaluations carried out in hydrographic basins over the same period show significant regional differences in the dynamics of land use changes driven by sugarcane expansion. In the southern region of the state of Goiás, the results showed significant expansion of annual crop areas such as soybeans and corn, with these crops being responsible for most of the deforestation that occurred in the period. In western São Paulo state, the evaluation showed that the expansion of sugarcane zones led to reforestation and recovery of riparian and permanent preservation areas; most likely for producers to gain access to rural credit lines, and to do so, they must comply with the rules of the Forest Code.

Other studies evaluated the expansion of sugarcane cultivation in two basins and their possible impacts on basin flow (Hernandes et al., 2018a, b). The results showed that as a replacement for pasture areas and/or annual crops, sugarcane cultivation tends to increase water availability in dry seasons by approximately 15% of the reference flow in one of the basins evaluated. Another study considering one of these two former basins showed that the total removal of straw left on the ground after sugarcane harvest had a slight negative impact on the flow of the basins occupied by large areas of sugarcane (Henzler et al., 2019). However, the simulations showed that the partial removal of straw does not change the flow pattern of the basin; part of the biomass can be removed from the ground for energy purposes without impairing the water availability in the basin.

3.8 ELECTRIC SECTOR LEGAL AND REGULATORY FRAMEWORK

Author: *Zilmar José de Souza*

In 2004, two possible environments were established to conclude purchase and sale contracts in terms of the commercialization of bioelectricity in the Brazilian electric sector:

Regulated Contracting Environment (RCE)

in which energy generation and distribution agents participate (in response to so-called captive consumers); and

Free Contracting Environment (FCE)

which includes generation agents, traders, importers and exporters of energy, and free and special consumers of electricity.

Energy consumption in the free market was 18,754 MW (average) in February 2020, representing 29% of all electricity consumed in the country, a 1.9% increase in consumption in the last 12 months. In February 2020, 82% of the country's industrial electricity consumption was served through the free market. Producers deliver and receive energy to the system, in their center of gravity, assumed part of the losses between the point of generation and this center of gravity. Consumers, in an analogous way, deliver and receive energy to the system, in its center of gravity, assuming part of the losses between this center of gravity and the point of consumption.

Since 2017, some initiatives have been implemented to make possible a comprehensive reform of the energy sector, with emphasis on its modernization, sustainability, and legal certainty. Among these initiatives, it is worth mentioning Public Consultation No. 33, opened in 2017 by the Ministry of Mines and Energy (MME), which presented proposals for the modernization of the energy sector, having received several contributions from the agents that resulted in a proposal for a bill of law. With a partnership with UNICA (Brazilian Sugarcane Industry Association) and a consulting company (Excelência Energética), SUCRE Project has contributed to this public consultation by highlighting the benefits of sugarcane bioelectricity for the Brazilian energy sector.

In addition, in April 2019, already within the context of the new government, the MME enacted Ordinance MME No. 187 establishing a working group to evaluate measures for the modernization of the energy sector, aiming at a sustainable expansion by promoting the opening of the market and an efficient costs and risks allocation.

The Modernization Measures seek development of proposals that deal with the following topics in an integrated manner: rationalization of charges and subsidies; introducing a mechanism to allow for the internalization of environmental externalities; increasing the granularity of wholesale-market price formation, with intraday price differentiation; and how to finance an expansion of the grid and supply security, with market opening being one of the main guidelines of this sectorial reform.

The Brazilian – and even the global – electric energy industry faces pressure for changes in its regulatory, commercial and operational framework, requiring a modernization of its institutional environment, because there has been a lot of friction in today's demanding business models, often leading to sector judicialization. For sugarcane bioelectricity, it is important that the modernization process of the electric sector addresses the main regulatory barriers that bioelectricity has faced, among other things:

Lack of long-term planning | The lack of a long-term planning for contracting biomass energy, with annual targets, represents an impediment to stimulating the virtuous cycle in the bioenergy production chain, since there is no predictability for the sector's agents as to the amounts of energy contracting and the corresponding, thereby deterring investments throughout the chain.

Distance to consumption centers poorly priced | The fact that the sugarcane plantation is primarily located in the Southeast/Center-West submarket means that the biomass generation plants are located close to the consumer centers, reducing the need to build large transmission lines and respective power transmission losses.

At the auctions for procuring electricity, the costs for distribution and transmission systems are not properly priced. The location of the power generating plant is not effectively compared from an economic point of view, nor are the differences in price risks between submarkets.

Insufficient pricing of the benefit of generation concentrated in the dry season | In 2019, 91% of the total sugarcane bioelectricity to the grid was supplied in the dry season, between April and November, with bioelectricity saving the equivalent of 15% of the total energy stored in the reservoirs of the hydroelectric plants of the Southeast/Center-West submarket (UNICA, 2020). In addition, 75% of the bioelectricity for the Brazilian Electricity Sector in 2019 was concentrated on the months when the Tariff Flag System was in yellow or red (UNICA, 2020).

Simulations reveal that there is more freedom in operating the system with the use of sugarcane biomass in the energy matrix. That is, the bioenergy generation profile allows greater efficiency in leveraging resources, reallocating energy dispatching throughout the period and resulting in a reduction of the risk of deficit without aggravating water reservoir conditions. In short, the operation of the system becomes more efficient with bioenergy. This benefit of biomass to the National Interconnected System seeks to be represented by Expected Short-Term Economic Cost (ESTEC, or CEC in Portuguese) variable of the Expected Cost Benefit Index (ICB) and projects are ranked by increasing ICB given in R$/MWh and contracted by auctioneer in that order. However, the methodology for calculating the Marginal Operating Cost (CMO) used by the Energy Research Office (EPE), which ultimately determines the variables Expected Operation Cost (COP) and ESTEC, does not properly quantify the benefit of energy production from bagasse and straw during the dry season, distorting the ICB principle. This is because the simulations carried out by EPE, up to then, did not include the actual procedures used by the ONS in operating the system.

Economic infeasibility of adding new fuels | The current mechanism for participating in auctions already provides for the possibility of a thermoelectric plant using more than one fuel in the generation. However, the rules for electricity supply auctions do not allow for different treatments among fuels. In other words, it does not consider specific situation of each fuel, and a distinct price cannot be linked to the generation with straw compared to the generation with bagasse, although these biomasses have different costs for the generator.

In 2019, sugarcane bioelectricity offered to the grid represented 5% of all electricity consumed in Brazil. The total generated by biomass was 22.4 thousand GWh to the national system. It is almost equivalent to the annual consumption of electricity in a country like Ireland, for example.

Despite this performance, only 15% of the potential of sugarcane bioelectricity is used. If bioelectricity were to be fully utilized in sugarcane sector, bioelectricity would have the technical potential to reach almost seven times the volume offered in 2019, which would account for more than 30% of electricity consumption in Brazil.

Combining the conditions of RenovaBio, a government program to spur the production of biofuels, and a positive business environment in the electricity sector, sugarcane bioelectricity has the potential to grow by over 50% by 2030 – from the 22.4 thousand GWh produced in 2019 to 34 thousand GWh in 2030. Nevertheless, we would begin to take advantage of less than 20% of the technical potential of this generation source in 2030, demonstrating the possibility of a positive response that bioelectricity can provide to the expected expansion of the free market.

Furthermore, the expected growth for the free market and pricing models that incorporate externalities in regulated auctions should stimulate the commercialization of bioelectricity projects, due to the huge potential "dormancy" of this source in Brazil.

The challenge is posed for both public and private entities: to stimulate (and accelerate) the inclusion of bioelectricity in the electric matrix, a fact that will undoubtedly also assist in creating the conditions needed for expanding ethanol in the fuel matrix and the effectiveness of RenovaBio.

3.9 DISSEMINATION OF INFORMATION

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3.9.1 CALCULATOR: THE SUCRE PROJECT'S LEGACY IN A FREE ONLINE TOOL

The SUCRE calculator is a free, virtual simulation platform available on the Project's website and is one of SUCRE's primary legacies. The calculator is based on an integrated assessment of project results and can be used as an exploratory tool for the sugar-energy sector, and can answer environmental and economic feasibility questions regarding the recovery and use of sugarcane straw for bioelectricity production, such as the minimum recommended sale price of the electricity generated, generation capacity of a plant, and amount of greenhouse gas emissions prevented with the bioelectricity produced.

The responses are generated based on the information provided by the user, i.e., the amount of straw that the mill plans to recover and the recovery method, as well as a standard series of agricultural and industrial parameters. These data, which must represent the conditions of the mill or the variables that the user wishes to simulate as closely as possible, are applied in simulation models and reproduce results previously obtained and validated that consider lessons learned from Project studies and knowledge acquired from simulation software.

This tool allows the user to generate a report providing data that permits them to understand and assimilate the main assumptions for agricultural, industrial, economic evaluation, equipment use, and costs considered in the simulations. The results generated by the simulation platform will not necessarily represent the conditions of all mills. The outputs should be used as a first step toward data refinement and customized results, as bioelectricity generation involves high investments.

The differential of such a platform is that, in addition to being free, it was being developed based on all the scientific and technological knowledge developed during the five years of the SUCRE Project.

3.9.2 DATA STORAGE AND TRACEABILITY

The use of databases is essential for storing information in a structured way, ensuring long-term data traceability, allowing for later statistical analysis, and favoring the production of results in the research performed, as well as providing more professional information management, with greater security and confidentiality of the results.

The “Data Management Plan of the SUCRE Project” aims to use and connect different data management and storage platforms, according to their specificities.

The “e-LN LIMS” system is the customization of an Enterprise Laboratory Platform, which will provide for the different needs of the Project. The technological solution of the software includes the functionalities of Laboratory Information Management System (LIMS) and Electronic Laboratory Notebook (ELN). The objective of this initiative is to digitize and standardize information related to the execution of experiments in the LNBR/ CNPEM laboratories and to facilitate professionals' access to experimental data.

The “Agricultural Experiment Database” (BDAgro) was developed with open source software. It relies on PostgreSQL, a relational object database management system; with pgAdmin, a database administrator and development platform; with R, which is a language and an integrated development environment for statistical and graphical calculations; and with Phyton, an auxiliary programming language for SQL scripts. The objective of BDAgro is to store data from agricultural experiments in a structured way, ensuring the legitimacy of data in the long term, in addition to performing statistical analysis and exploitation of the results integrated into the database.

The “Geographic Database” (BDGeo) was developed with open access software. It relies on PostGIS, a spatial extension built on the PostgreSQL relational object database management system, which allows the use of GIS objects to be stored in a database. BDGeo is a strategic tool that ensures that all assessments with a spatial character within the project are correctly stored and easily accessed by the team, in addition to being integrated with BDAgro information.

The “Mobile Agricultural Application” was developed with open access software and is intended for use with the Android operating system version 4.1 or higher. It is an offline application that streamlines the registration and availability of data obtained through experiments or collections carried out in the field. The application highlights the reading of barcodes previously printed by the e-LN LIMS system, plus the device's geolocation feature georeferences the location of the experiment or collection and the synchronization mechanism of data saved in the application to BDAgro.

The "Agricultural WEB Interface" was developed in Java and HTML and aims to facilitate employees' access to data stored in our databases. Its restricted access allows consultation and downloading of BDAgro's event data and more data obtained through APPAgro.

3.9.3 DISSEMINATION MATERIAL

The dissemination of advances and results of studies carried out in the SUCRE Project has always gone side by side with research and development. The entire content of the SUCRE Project is available on LNBR's website, ranging from basic information about the Project and work, to news and downloadable documents, covering events, presentations, papers, references, and tools.

A **mailing list** was created when the Project began and was updated along its course. It is composed of approximately 1,200 e-mail addresses from companies and entities in the sugarcane and energy sector; government agencies; universities, institutes, and research centers in areas such as engineering, agronomy, chemistry, energy, economics, and technology; as well as the media.

Since the beginning of the Project, dissemination of information through **newsletters** was one of the main ways of sharing the progress and results obtained in SUCRE. Over the five years of the Project, 28 newsletters were published. According to MailChimp, the platform used to launch the newsletters, on average, 26% of those receiving the newsletters have opened them. Access the newsletters: *https://lnbr.cnpem.br/en/research/technological-challenges/sucre-project/sucre-newslettes/*.

The first printed promotional material for the Project were **flyers** which contained a brief presentation of its main objective, focuses, stages, relation with the Sustainable Development Goals (SDG), and key points. The Project produced 6,300 flyers, with a circulation of around 3,000, distributed at events and meetings for the sugarcane mills, the public, sugar-energy sector institutions, government agencies, universities, and research institutions. The SUCRE Project flyer can be downloaded here: *https://lnbr.cnpem.br/wp-content/uploads/2020/04/Flyer2019-EN.pdf*.

From the second semester of 2019, five **Booklets** were created referring to the five work fronts of the Project, with versions in Portuguese and in English: "*Sugarcane Straw Recovery Routes*"; "*Sugarcane Straw Processing and Burning*"; "*Guidelines for Sugarcane Straw Removal to Produce Electricity*"; "*Sustainable Bioelectricity*"; and "*Sugarcane Bioelectricity*". The purpose of this material was to disseminate SUCRE's main results in easily understood language, guiding the sugarcane industry to understand strategies to best recover and process straw. This material provided information on ways to commercialize energy from biomass, with suggestions to adapt the regulatory framework of the electricity sector, in addition to giving information that allowed the assessment of the economic, environmental, and social viability of using straw to generate energy. About 800 copies of each Booklet were distributed at events and gatherings of the sugarcane sector. Access all Booklets: *https://lnbr.cnpem.br/en/research/technological-challenges/sucre-project/dissemination/booklets/*.

In the first semester of 2020, the Project's **issue papers** were developed. This is one more legacy of the SUCRE Project, available to those interested. The issue papers provide an even more summarized content than the Booklets, but in a very technical language. There are total of five issue papers. SUCRE's issue papers can be found at *https://lnbr.cnpem.br/en/research/technological-challenges/sucre-project/dissemination/issue-papers-sucre-project/*.

A total of 14 **videos** were created throughout the lifetime of the Project. In addition to recordings of SUCRE events, all of these are available online. Three of those contain testimonials from sugarcane mills regarding the necessity of using straw to generate electricity and the importance of results obtained from SUCRE's team studies. The other 11 videos present details on the Project, discuss the studies carried out, and its outputs. Some of those videos were shared by the United Nations Development Program (UNDP) on Facebook, had a high impact, and gathered 148 likes and 145 shares.

The Project was the topic of just over 200 **articles in the press**. The vast majority were in specialized media, although some were in wide-reaching media. SUCRE was the subject of press content published by important sector entities, such as UNICA (Brazilian Sugarcane Industry Association), UDOP (União Nacional da Bioenergia, in Portuguese, or the National Union of Bioenergy in a free translation), and CEISE (Centro Nacional das Indústrias do Setor Sucroenergético e Biocombustíveis, in Portuguese), as well as important segmented vehicles in the sugarcane industry, such as novaCana, RPAnews, and JornalCana. In the mainstream media, the Valor Econômico newspaper stands out, with a publication about the bioelectricity potential of growth using straw. There were also publications in important vehicles such as Fapesp (São Paulo Research Foundation), EBC (Brazilian Communication Corporation), and on the UNDP Brazilian website.

The Project also maintained an active Facebook page. Since the page was launched in May 2016, it has achieved 444 likes, 455 followers, and around 130 publications, with an additional 25,000 users till June 2020. SUCRE was the subject of 16 CNPEM Facebook posts, reaching a total of 28,000 people and 1,830 engagements. The Project received mention in 12 publications on the Facebook profile of the UNDP, the Project's managing body along with LNBR/CNPEM. Together, these publications gathered 288 likes, 9 comments and 211 shares. CNPEM's LinkedIn posted 7 publications from the SUCRE Project, gathering a total of 307 likes, 3 comments, and 22,000 organic impressions, a term used for the number of times the post was exposed to LinkedIn members. In CNPEM's Instagram profile, the Project appeared in 9 posts, gathering a total of 732 likes and 10 comments.

4. FINAL COMMENTS AND CONCLUSIONS

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The SUCRE Project was well structured since its conception by focusing on the identification and overcoming the barriers that are holding the growth of the use of sugarcane straw to increase the surplus power generation for sale by the mills. Working directly with partners mills in testing the different technologies in use in the recovery, processing and using the straw as boiler fuel has brought the experiments and studies developed in the project to the real world and the solutions appointed were based on tested technologies at commercial scale.

Starting by trying to answer the question "how much straw exists in the field and how much we have to leave on the ground to assure its agronomic benefits" SUCRE team was able to develop a set of guidelines to achieve a strategic straw recovery and assess the real potential of straw availability. However, these are only indications for the mills to develop their own operational strategies on a case by case basis. Decisions can be made based on principles that allows a visualization of potential gains and losses in simulated cases. The test information will remain available for those interested to use, even after the end of the SUCRE, in the project website, including guidance for the mills to prepare straw recovery maps to be able to anticipate how much straw will be available during the harvesting season and the exact location of the plots.

With respect to the recovery route alternatives, the field tests in the partner mills permitted the SUCRE team to identify the two most developed commercial alternatives: Baling and Integral Cane (straw is brought together with cane and separated at the mill in a Dry Cleaning System). The results indicated the quality of the straw as delivered at the mill (ash content, particle size distribution, level of problematic mineral components), costs of straw, operating efficiency of the equipment in the routes, fossil fuel consumption and Greenhouse Gas (GHG) emissions. All technical and economic information generated in the tests were fed to the LNBR/CNPEM proprietary agronomic model CanaSoft (Cavalett et al., 2016), which is part of the broader model VSB – Virtual Sugarcane Biorefinery (Bonomi et al., 2016), that allowed the SUCRE team to perform sensitivity analyses and identify the main parameters affecting the economic and environmental impacts. Playing with different values for the routes parameters the team selected the straw recovery rate (in t straw/ha), transport distance and operational efficiency of the equipment (h of effective operation per day) as the main parameters affecting costs and environmental impacts and were decisive in the determination of the best straw recovery route for each case. In general, high recovery rates (t straw/ha) and longer transport distances favor the baling route and lower rates and shorter transport distances point to the integral cane route (Makoto et al., 2019).

The low quality of straw as delivered to the mill strongly suggests the need for straw processing at the mill to reduce the mineral impurities level (ash) and to adequate the particle size distribution to the existing boiler feeding valves. In the former, the preferred solution adopted by the mills that recover and use straw was the rotating drum sieve and for the latter was the straw shredder (either with knifes or hammers). The several units tested in the SUCRE revealed low efficiencies in the former that was related to the fact that around 70% of the mineral impurities in the straw was firmly adhered to the straw surface and not in the loose form. The straw shredders tested present a reasonable particle size distribution at the initial phase of operation, but that deteriorates very fast, in a matter of few days, after the knifes/hammers lose their sharpness due to erosion caused by the abrasiveness of straw, demanding frequent replacement of these components and the associated high maintenance costs; besides that, the high energy consumption is an additional significant operating cost item. The SUCRE team sought alternatives to overcome these two serious deficiencies in the most popular straw processing commercial systems and identified three mills washing the straw at the outlet of their Dry Cleaning Systems (DCSs): two of them used water in a channel to transport and wash the straw at the same time, and the third had a spray type washing system; all three used a cush-cush type screen to separate the water and straw. In the two with the channel transport option the washed straw was fed to the last (or to the one before the last) mill in the milling tandem where it was crushed together with bagasse, making a perfect blend between the two biomasses. The third mill used an independent mill to dry and shred the straw at the same time and direct the processed straw to the bagasse belt conveyor for mixing. The SUCRE team tested all three systems and considered the results of mineral impurities and critical mineral components (K, Cl, S and Si) reduction promising. Laboratory and bench scale tests confirmed this expectation and incentivized the elaboration of the basic design of a new straw processing system that is expected to reduce the mineral impurities and critical mineral elements (K, Cl, S, Si) contents to acceptable levels. IEA Bioenergy (Meesters et al, 2018) and the University of Hawaii (Turn et al, 1997) have also successfully tested leaching these elements from sugarcane straw with water. The SUCRE team prepared the basic designs for three alternatives that can be used by interested mills to develop their own detailed designs.

Burning straw in boilers designed for bagasse was not a concern among technical people of the sugar-energy sector in Brazil. There was a strong belief that it was essentially similar to bagasse and the only point of some concern was the high ash content. In the initial tests with straw/bagasse mixtures in bagasse boilers and discussions with the mill operators have indicated several problems related to choking in the fuel feeding valves, corrosion, deposits and slagging in several boiler parts, especially the superheater. Erosion was also identified as a critical problem. The SUCRE team made a comprehensive literature research on this topic that identified several research projects, many supported by the US Department of Energy, testing several types of herbaceous biomasses in different types of boilers and identifying the problems and studying the mechanisms of corrosion, deposits and slagging, indicating the importance of Alkali, Chlorine, Sulfur and Silicon (see Miles et al al., 1995).The SUCRE team collected and analyzed samples of corrosion, deposits and slagging in boilers of several mills using different proportions of straw in the biomass fed into the boilers and the results for different areas of the boiler were very much in line with the results from the literature for herbaceous biomasses.

The project results supported the advances to a new level the knowledge about sugarcane straw agricultural impacts, recovery routes, storing and processing at the mills and burning in boilers designed for bagasse. The field experiments in the partner mills provided plenty of data to allow the team to identify the main bottlenecks and to suggest alternative solutions to solve or, at least, mitigate the problems, and prepared complete mass, energy, GHG emissions and fossil fuel balances, and economic and social impacts evaluations. The main barriers in the present Legal and Regulatory Framework to the expansion of the surplus power generation in the sugar-energy sector were identified with the assistance of UNICA and contracted external specialists. The project data is stored in three specialized Databases and were used also to improve the LNBR/CNPEM models and Virtual Sugarcane Biorefinery (VSB) (Bonomi et al., 2016) thus permitting their use to simulate straw recovery, processing and use under different conditions from those in the field tests. The SUCRE Website will remain operational and with open access to the project information and documents after the project end.

Regarding specific results on GHG emissions balance by applying the Life Cycle Assessment (LCA) (considering the replacement of natural gas as an electricity source), in the last four years, only considering the partner mills, they already contributed to avoid emission of more than 2 million metric tons of CO_2 equivalent. By extrapolating the electricity generation to the potential of the sector in Brazil, regarding the use of all the produced bagasse plus 50% of the produced straw (which is actually lower than the 63% estimated in the above indicator) it is possible to generate more than 100 TWh of electricity in Brazil without expanding sugarcane areas. In this case, only biomass-based electricity can supply almost 80% of the residential electricity demand in the country and mitigate more than 50 million of metric tons of CO_2 equivalent per year, which corresponds to more than 10% of the total GHG emissions from Brazilian Energy Sector (Souza et al., 2019). Moreover, results from satellite images processing showed that 96% of the most recent sugarcane expansion (more than four million hectares) occurred within the Sugarcane Agroecological Zoning, which means that sugarcane expanded over other crops and pasture areas and did not directly contributed to deforestation. In the case of a new sugarcane expansion driven, for example, by new public policies such as the RenovaBio, project team is finishing an evaluation of the available land for future expansion by updating the Agroecological Zoning and avoiding expansion over Environmentally Relevant Areas. Results in this case showed that, even being very conservative, there are still more than 20 million hectares available for sugarcane expansion considering only the six states that produce most of the sugarcane in Brazilian Center-South (São Paulo, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais e Paraná) (Hernandes et al., in review).

Some additional work is still required in some areas such as improvements in the efficiency of the Dry Cleaning Systems, reduction of the negative impacts of straw in the cane load density in the Integral Cane recovery route, more knowledge about the impacts of additional machine traffic on the cane fields in the Baling route and testing improved straw washing systems at a commercial scale. There are boilers designed and built to operate with agricultural residues like straw, but they are more expensive than those designed for bagasse firing. Besides, there are more than a thousand bagasse boilers installed and operating in the Brazilian mills and many are new and efficient units, therefore the SUCRE team sees that it is wiser to try to make straw more similar to bagasse meaning similar contents of ash, K, Cl, S, similar particle size distribution, maybe even in terms of moisture content. The SUCRE team has proposed alternative processing systems to achieve this goal, but more tests are required to demonstrate their efficiency, investment and operating costs. UNICA must continue its effort toward the improvements in the Brazilian energy sector Legal and Regulatory Framework, that is, maybe, the most critical bottleneck to the expansion of renewable electricity generation by the Brazilian sugar-energy mills.

On the Legal and Regulatory Framework of the Brazilian Electric Energy Sector, several bottlenecks have been identified by the SUCRE Team working in close cooperation with UNICA and the consulting company Excelência Energética, contracted to help in this endeavor (Excelência Energética, 2017). The Ministry of Mines and Energy (MME) issued a Public Consultation MME nº 33/2017 and both LNBR/CNPEM and UNICA presented suggestions for the improvement of the Legal and Regulatory Framework of the Electric Energy Sector. Among the several bottlenecks identified four were considered the most important (see Chapter 3):

1. Lack of long-term planning for contracting bioelectricity on the Government side;
2. Distance to consumption centers inadequately priced;
3. Insufficient recognition of the benefits of generating electricity concentrated on the dry period;
4. Difficulties in operating with more than one type of biofuel with different costs, under the same contract.

In April 2019 MME created a working group to develop a proposal to modernize this regulation. Now UNICA is leading the effort on the sugar-energy sector side, following up the progress.

Now it is up to the sugar-energy sector to continue to improve the recovery and use of sugarcane straw to make it a fully viable alternative, and actively participate in the revision of the Legal And Regulatory Framework of the Electric Sector and develop new business models for electricity sales, taking all the advantages that biomass power has over the intermittent renewable and fossil sources.

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Project BRA/10/G31
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Print run: 200 copies

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