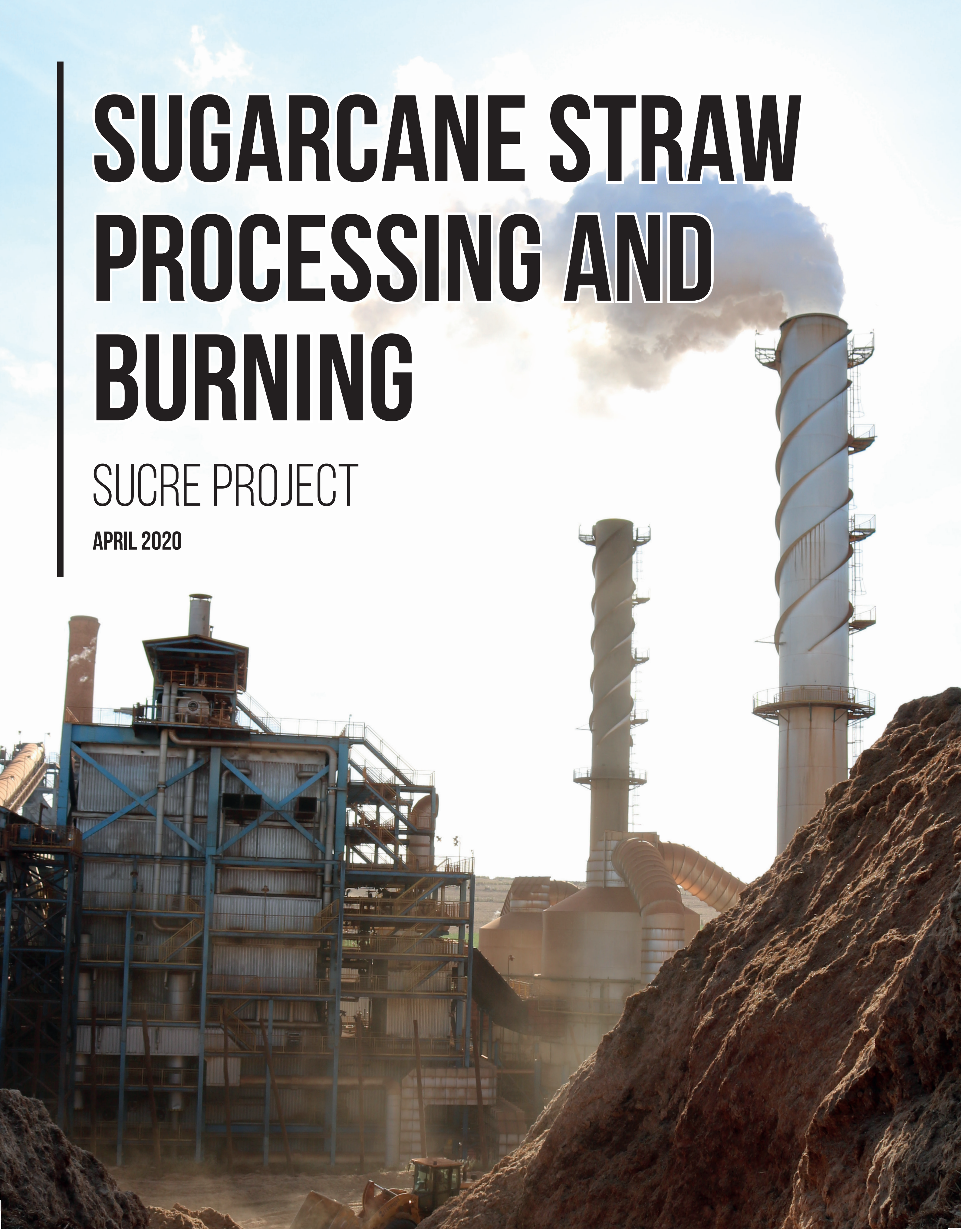

SUGARCANE STRAW PROCESSING AND BURNING

SUCRE PROJECT

APRIL 2020

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ABOUT SUCRE PROJECT

The SUCRE (Sugarcane Renewable Electricity) Project is primarily designed to **increase the production of electricity with low greenhouse gases (GHG) emission using the sugarcane straw** made available during the crop harvest. SUCRE team has been working on identifying and solving issues that hinder partner mills from fully and systematically generating electricity. Beginning in June 2015, it is a total five years of Project, with funding of around US$ 7.5 million from Global Environment Facility (GEF) and a counterpart from the Brazilian Center for Research in Energy and Materials (CNPEM) of over US$ 3 million. The recovery and use of straw for electricity production in the private sector triggered an investment of approximately US$ 160 million by partner plants (a major part of which has already been done through the installation of dry cleaning systems, refurbishment or purchase of boilers, turbogenerators, balers and other pieces of equipment). The initiative is managed through a partnership with the United Nations Development Programme (UNDP) and is carried out by the Brazilian Biorenewables National Laboratory (LNBR), which is part of CNPEM.

ABOUT LNBR

The Brazilian Biorenewables National Laboratory (LNBR) is part of the Brazilian Center for Research in Energy and Materials (CNPEM), a non-profit private organization that operates under Contract Management with the Brazilian Ministry of Science, Technology, Innovations and Communications (MCTIC). LNBR uses Brazilian biomass and biodiversity to solve key scientific and technological challenges by employing high-performance biological platforms of industrial relevance for the sustainable development of advanced biofuels, biochemicals and biomaterials. The Laboratory has a history of technology development in partnership with companies, including start-ups. Among LNBR open-access facilities one finds a Pilot Plant for Process Development, a unique facility for scaling up of technologies.

ABOUT CNPEM

The Brazilian Center for Research in Energy and Materials (CNPEM) is a non-profit private organization under supervision of the Brazilian Ministry of Science, Technology, Innovation and Communications (MCTIC). Located in Campinas, São Paulo, the Center is comprised of four laboratories, worldwide references in their fields, which are open to the scientific and business communities. The Brazilian Synchrotron Light Laboratory (LNLS) is currently assembling Sirius, the new Brazilian electron accelerator. The Brazilian Biosciences National Laboratory (LNBio) is dedicated to solving challenges in the areas of health. The Brazilian Biorenewables National Laboratory (LNBR) is focused on biotechnological solutions for the sustainable development of advanced biofuels, biochemicals and biomaterials, using biomass and the Brazilian biodiversity. Finally, the Brazilian Nanotechnology National Laboratory (LNNano) conducts scientific research and technologic development into solutions based on nanotechnology. The four Laboratories also have their own research projects and participate in the transversal research agenda coordinated by CNPEM, which articulates scientific facilities and capabilities around strategic themes.

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PRESENTATION

This booklet deals with the main straw processing systems in operation at sugarcane mills, highlighting the alternatives that make straw more like bagasse, aiming to overcome the challenges associated with burning this biomass in boilers.

This document aims to present in a clear and explanatory way how straw is processed in the plants, what equipment is used, identify the main process bottlenecks, show the challenges associated with burning straw in boilers originally designed for bagasse and, finally, alternatives propose to overcome quality and processing issues. Thus, finding ways to overcome existing barriers, contributing to the bioelectricity cogeneration expansion from straw in the Brazilian context.

This material was prepared by the Sugarcane Renewable Electricity (SUCRE) Project team based on information, data and results obtained from the experiments carried out at the partners' plants and in LNBR/CNPEM laboratories.

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SUCRE PROJECT

THE USE OF SUGARCANE STRAW FOR BIOENERGY COGENERATION

THE MECHANIZED GREEN CANE HARVESTING

The mechanization of sugarcane harvesting, besides the improvements in working conditions and productivity gains, made it possible for sugarcane fields to be harvested without burning, with significant environmental benefits in the emissions-reduction. The cane burning elimination and the increasing mechanization process contributed to the increased straw availability in the field after harvest. Maintaining part of the straw in the field to ensure soil and crop benefits (read the "Guide on the Best Practices for Removing Sugarcane Straw") opens the opportunity to use the remaining straw as fuel for bioenergy production.

STRAW: A NEW BIOMASS

The presence of straw in the crop generated profound changes in the entire sugarcane agroindustry productive chain. In addition to creating many opportunities, these changes have brought major challenges for the sugarcane industry. When used as a raw material for energy generation some aspects of straw should be considered, such as quality and quantity and availability factor. The use of bagasse and straw allows the generation, under current conditions of existing biomass boilers in the Brazilian sugar-energy sector, of about 0.4 MWh per ton of bagasse at 50% (w/w) of moisture and 0.7 MWh per ton of sugarcane straw, with moisture around 15% (w/w).

QUALITY AND AVAILABILITY MUST BE CONSIDERED TO THE ELECTRICITY PRODUCTION

STRAW COLLECTION AND PROCESSING

Quality and availability aspects depend mainly on how the straw is collected, transported and processed in the industry before being sent for burning in the boilers. There are three systems used for the recovery of straw for energy cogeneration in Brazilian sugar mills plants: hay harvester straw collection route and processing, baling and full or partial harvesting with straw separation by Dry Cleaning Systems (DCS).

Bagasse and straw mixture and boilers chimney in the background

STORAGE STRAW COLLECTION AND PROCESSING

The straw collection and processing by hay harvester machines has as its main feature the fact that they need low investments in the industrial area. As the straw is shredded in the field, the straw arriving at the plant does not need to be shredded to reduce particle size before sending to the boilers. Upon arrival in the industry, the straw is discharged directly into the bagasse pile and mixed with the aid of wheel loaders. However, it should be noted that since the load density of straw harvested by hay harvester machine is very low, about 70 to 120 kg/m³, its application depends on the transport distance. This option is usually justified for short distances in areas located around the industrial plant, with an average radius between 5 and 10 kilometers.

Among the main challenges found in the studies carried out by the SUCRE Project, we highlight the highest content of mineral part of extraneous materials (mineral impurities) present in the straw (9 to 25%) and the high cost of maintaining the shredding knives, which wear out on average every 150 hours of operation. The condition of the knives directly affects the straw particle size and its density. The results indicated that, in the first hours of use of the knives, the straw particle size distribution was very close to the bagasse, with 90% (w/w) of the particles smaller than 12.5 mm.

The SUCRE Project identified only one plant in Brazil that used this route, however, the collection operations by this way were interrupted in 2017. There are currently no reports or records indicating the use of hay harvesters in Brazil for sugarcane straw collection.

Hay harvester machine harvesting sugarcane straw

BALED STRAW PROCESSING IN THE MILLS

Upon arriving at the industrial unit, the baled straw must be processed in various unit operations before it can be used as fuel in the biomass boilers. There are different configurations in the bale processing systems in operation at Brazilian sugar/ethanol mills. The simplest systems rely only on the presence of equipment that simultaneously performs the unbaling and shredding steps (made by Vermeer). Since they do not contemplate important unitary operations, such as the screening for mineral impurities removal, these systems have limitations. The most modern unit of baled straw-processing in operation in Brazil can process up to 25 tons of baled straw per hour, what is considered to be in the state of the art for this application. This system has a covered bale storage area for the 600 bales, an automatic weighing crane capable of moving 10 bales at a time, unbaling machine with low-speed

Unloading Straw Bales

hammers (made by Metso), string remover, rotary screen (made by Vibromaq) and knife shredder (made by Demuth), and efficient dust control system. It is important to point out that both knives and hammers of the straw shredders have an operating life rarely exceeding 15 days.

Storage of straw bales for 250,000 tonnes (GranBio Sugar Mill, São Miguel dos Campos, Alagoas)

For the system evaluated, considered the state of the art, SUCRE calculated the energy consumption and processing cost of baled straw, covering all necessary unit operations and data provided by the partner mill. The results indicated an average consumption of 25.6 kWh per tonne of straw and the cost of the energy consumed in processing about US$ 1.34 (2018) per tonne of straw processed (considering the price of energy in Brazil at US$ 50/MWh).

During the 2016/2017 and 2017/2018 harvest seasons, SUCRE Project evaluated the bale processing systems of three plants located in São Paulo state. Results indicated that the systems operate relatively well, but some deficiencies have been identified along the straw processing unit operations.

Bale storage, in addition to requiring very complex logistics both outside and inside the plant, also requires facilities and care to prevent fires.

Straw hammer shredder

Appearance of straw from hammer shredder

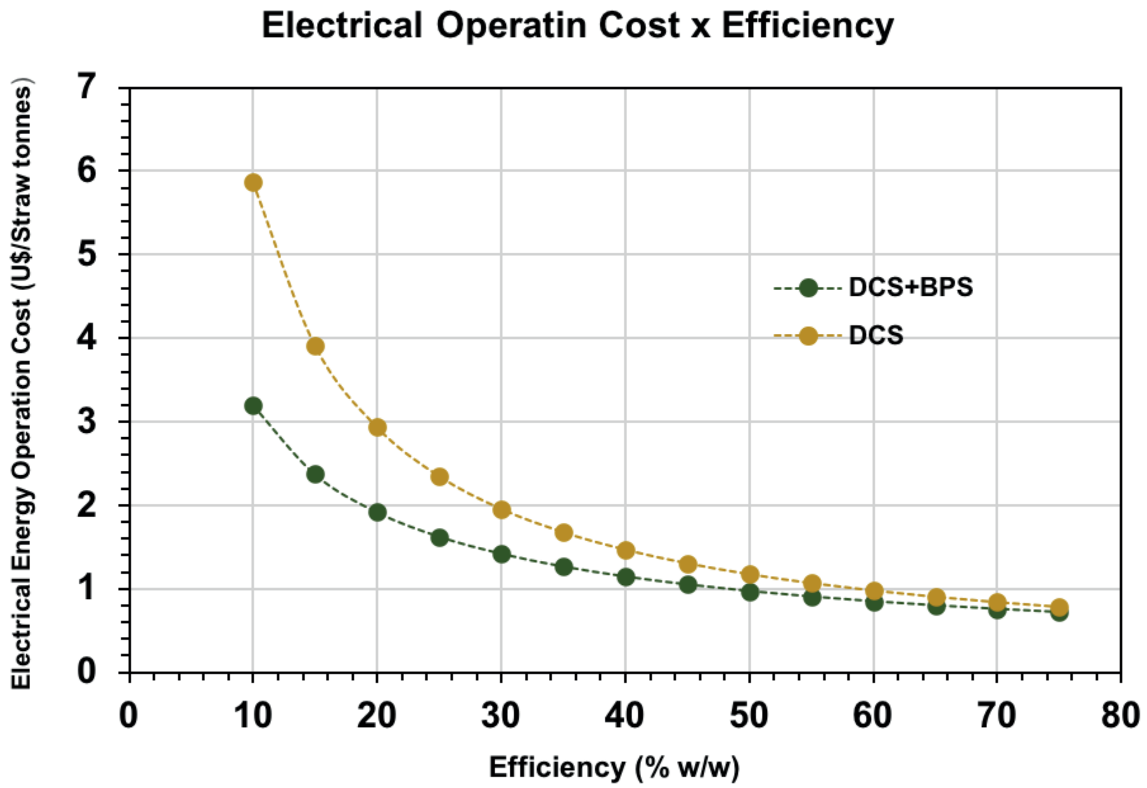
The processing rate of the baling machine is limited by the moisture content of the straw, which must be less than 15% (m/m). Deficiencies in the string removal process were also identified, which may cause problems in later steps. Among the alternatives evaluated for the removal of mineral part of extraneous materials (mineral impurities) from the straw, the rotating screen presented low efficiency (average 33%). In short, shredding can be considered a process bottleneck, as shredders require frequent maintenance shutdowns due to the severe wear caused by the straw and the mineral impurities present. Among the evaluated shredders (knives and hammers), it was found that the performance of the hammers is more regular than that of knives, however, it was found that there is a limitation in the suitability of straw to the desired particle size distribution, regardless of type. About 70% of the mass of straw samples prepared by conventional shredders had similar particle size distribution to that found for bagasse (<12.5 mm), with the remaining 30% (w/w) consisting of larger particles that can cause clogging in the bagasse boiler feeders.

Rotary sieve straw screening

DRY CANE CLEANING SYSTEMS (DCS)

Dry Cleaning Systems (DCS)w play a fundamental role in full or partial harvesting straw collection systems, as they are responsible for cleaning and separating straw from sugarcane stalks in the industry, reducing losses in juice extraction process and the negative impacts on cane sugar and ethanol production, as well as allowing the use of separated straw for power generation in the plants. DCS reduces vegetal and mineral impurities without the use of water that would lead to significant sugar losses in billeted cane. However, there is a need for additional investments in equipment that generate additional operating and maintenance costs and consumes energy.

SUCRE Project has evaluated 5 different dry-cleaning systems using the same methodology. This study was done in 7 plants located in the states of São Paulo (5 units) and Goiás (2 units). The evaluations were carried out between October 2017 and August 2018, comprising the 2017/2018 and 2018/2019 harvest seasons.



DCS: Dry Cleaning System
BPS: Bale Processing System
Data: Considering Electrical Energy Price US$ 50/MWh

Straw separation efficiencies (dry and green leaves) determined for systems operating at full ventilation capacity ranged from 17% to 49% (w/w) straw separation on wet basis. The efficiencies of separation of the mineral part of extraneous materials (mineral impurities, MI) ranged from 18% to 78% (w/w) of MI fed in the DCS along with cane, on wet basis. The efficiencies obtained are lower than those reported by manufacturers and previous studies, but it is important to note that there are differences between evaluation methods, processing capabilities, and the fact that many systems are not operating under optimal conditions. Deficiencies were identified during the trials, involving DCS design, operation and maintenance parameters.

Modeling the data from a partner mill that has a hybrid straw processing system, which can operate concurrently with DCS and bale processing system (BPS), SUCRE has found that DCS efficiency has an important impact on electrical operation processing costs.

The operating costs corresponding to the energy consumed by the systems (DCS and Bales) operating under current conditions (DCS with 18% efficiency and 28,000 tonnes of baled straw per crop) is US$ 2.07 per ton of sugarcane straw. Considering the operation under ideal conditions, with the equipment running at full capacity (DCS with about 65% efficiency and 28,000 tons of baled straw per crop), the operating cost of energy would be US$ 0.80 per ton sugarcane straw processed, that is about 2.6 times smaller.

Dry Cleaning System with air blowing in up flow

EVALUATION OF STRAW AND BAGASSE BURNING IMPACTS ON THE BIOMASS BOILERS

BAGASSE AND MIXTURE OF BAGASSE AND STRAW

With the increased availability of straw in the field after mechanized harvesting and the stages of collection and processing, this biomass was added to the bagasse and the mixture fed in the boilers, enabling the increase of production and exportation of electricity.

The evaluations performed by SUCRE revealed that straw has physicochemical properties different from those found in bagasse. Raw straw (prior to processing) has marked variations in humidity, depending on the collection system employed. These differences cause the straw to present a wide range of lower calorific value (LCV). Straw has a higher ash content when compared to bagasse, and different elemental composition, with higher concentrations of alkali metals such as potassium (K) and sodium (Na), as well as of sulfur (S), chlorine (Cl) and silicon (Si).These elements can increase the occurrence of fouling, slagging and corrosion and, besides that erosion wear on the boiler heat exchange surfaces. The particle size distribution and density of straw, when not processed properly, can have a quite different behavior from those found in bagasse in the boiler furnace. Thus, the addition of straw to the bagasse can cause adverse effects such as boiler feeding system problems, resulting in increased combustion instability. Bearing in mind, the differences between the properties and the behavior of bagasse and straw and that the great majority of biomass boilers in operation in Brazil where designed for operation with bagasse, the solution found was to adapt the burning to operate with balanced mixtures of bagasse and straw.

The high ash content in the straw, mainly due to the mineral impurities content, contributes to the reduction of its higher calorific value (HCV) as well as to the increase in the wear in the equipment that is in contact with the flue gas ashes. For the use of sugarcane straw as fuel for the boilers, it is highly recommended to determine and analyze its physical-chemical properties, in order to better understand the characteristics of the fuel fed in the boilers and their possible effect in relation to formation of the fouling, slag and corrosion. From these analyses the goal is to create parameters that allow us to predict the tendency to occur such phenomena from the fuel analysis. In the table beside is presented an example of the elemental analysis of sugarcane bagasse and straw.

Sugarcane bagasse and straw physical-chemical properties

Biomass	Humidity (%)	Ashes (% b.s.)	Particle size	HCV (MJ/kg)	LCV (MJ/kg)
Bagasse	48 - 52	2 - 8	99% < 12,5 mm	18 - 19	7 - 8
Straw*	12 - 45	6 - 20	90% > 90 mm	16 - 18	6 - 15

**Not processed straw*

Elemental analysis of sugarcane bagasse and straw

Element (m% d.b.)	Bagasse	Straw*
Carbon (C)	40 – 44	38 – 42
Hydrogen (H)	6.0 – 7.0	5.5 – 7.0
Nitrogen (N)	0.3	0.5 – 0.6
Sulfur (S)	0.09 – 0.11	0.12 – 0.2
Chlorine (Cl)	0.02 – 0.05	0.2 – 0.4

**Not processed straw*

The chlorine and sulfur concentrations in the sugarcane straw available for burning in boilers are much higher than that found in bagasse, being on average 10 and 2 times higher, respectively.

In addition to chlorine and sulfur, straw has higher levels of potassium and silicon. These elements, when fed into the boilers, in the presence of high temperature gas and severe turbulence, are volatilized and react to produce components with lower temperature of eutectic point , favoring the formation of deposits (fouling and slagging) that condense on the tube surfaces, reducing the heat exchange efficiency.

STRAW BURNING IMPACTS ON THE BIOMASS BOILERS OPERATION

The SUCRE Project carried out evaluations on boilers operating with bagasse-straw mixtures in 5 partner mills located in the states of Alagoas (1), Goiás (1) and São Paulo (3).

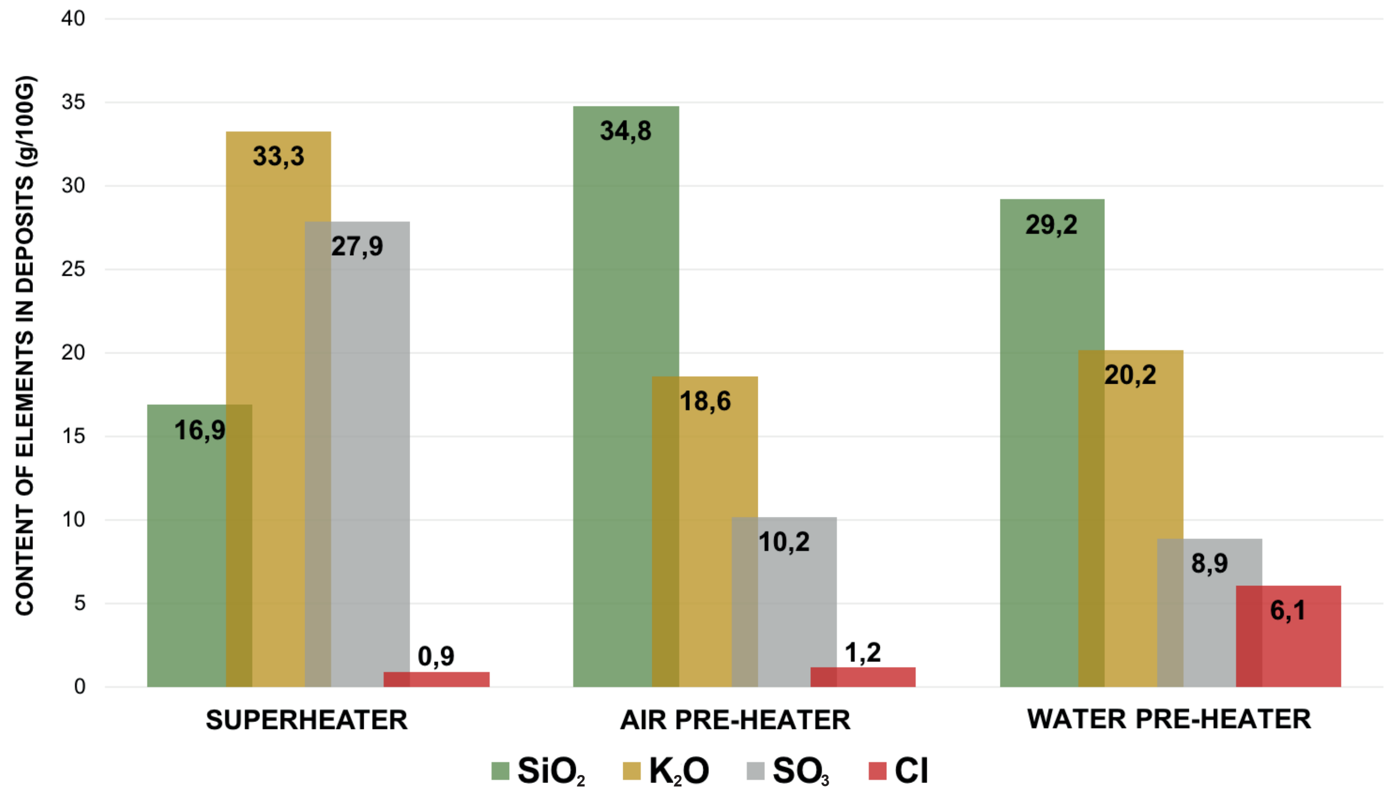
The boilers in operation were originally designed for burning bagasse with 30 to 60% humidity. With the burning bagasse-straw mixtures introduction, negative impacts were observed, such as combustion instability, increased fouling and corrosion, thermal exchange efficiency decreased and increased maintenance frequency and, consequently, impacts on the associated costs. Evaluations revealed that these impacts have restricted the use of straw mixed with bagasse at low concentrations, ranging from 5 to 16% by mass (dry basis). in the Figure 12 below it is presented a summary of the main problems in the biomass boilers and the affected parts are indicated.

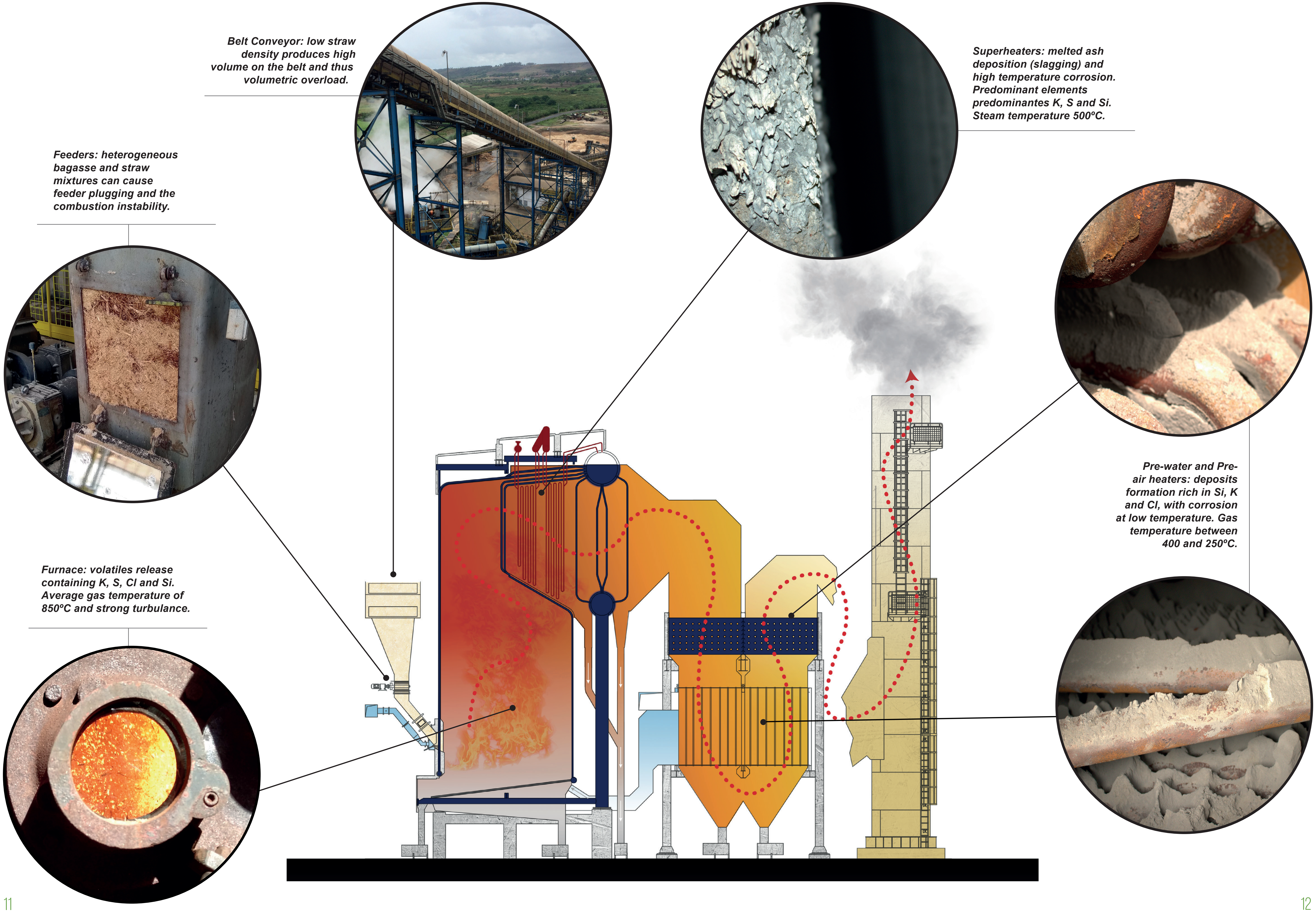
DEPOSIT AND SCALE FORMATION IN BIOMASS BOILERS

SUCRE analyzed the chemical composition of the fouling and slagging in the several parts of boilers that have operated along the season with mixtures of the bagasse and straw.

The Figure 13 show the different concentration of the chemical elements present in the deposits along of boiler elements. In accord with this Figure, can observed that there were differences in the chemical composition of the deposits, depending on the boiler region and associated with the operating temperatures. Following the flue gas flow along the different boiler regions, it was observed that potassium and sulfur concentrations are higher in the deposits found in the superheater and decrease in regions where the flue gas is cooler. The silicon concentration in the deposits is apparently a function of the gas velocity, since it was detected that its deposition was significantly increased in the low-velocity regions. Chlorine concentrations were higher in colder boiler heat exchange surfaces, such as the water pre-heater (economizer) and air pre-heater, with a more pronounced corrosion process in these regions.

DEPOSITS COMPOSITION IN SEVERAL BOILERS SURFACES




Belt Conveyor: low straw density produces high volume on the belt and thus volumetric overload.
Superheaters: melted ash deposition (slagging) and high temperature corrosion. Predominant elements predominantes K, S and Si. Steam temperature 500ºC.
Feeders: heterogeneous bagasse and straw mixtures can cause feeder plugging and the combustion instability.
Pre-water and Pre-air heaters: deposits formation rich in Si, K and Cl, with corrosion at low temperature. Gas temperature between 400 and 250ºC.
Furnace: volatiles release containing K, S, Cl and Si. Average gas temperature of 850ºC and strong turbulance.

ALTERNATIVE STRAW PROCESSING SYSTEMS

STRAW WASHING AND DRAINING SYSTEMS

Some Brazilian mills are using straw washing systems coupled with DCS cane cleaning systems. In this configuration, the sugarcane is cleaned in a DCS and the separated straw is processed by washing with water, before being mixed with the bagasse to be fed in the boilers. The Figures 14 and 15 show the circuit used comprising of washing and transporting straw in a water channel and the cush-cush straw drainage process.

The SUCRE Project performed assessments on these systems in 3 different plants located in the state of São Paulo during 2016-2017, 2017-2018 and 2018-2019 harvests. The studies were designed to evaluate the effectiveness of removing mineral impurities and leaching unwanted chemical elements found in the straw during the washing process.

Although the systems that were examined are not optimized, the results proved to be rather promising, given that the average efficiency for removing mineral impurities for the tested plants varied from 49% to 62%. In addition to this, washing has shown to be able to foster the leaching of chemical elements that are critical for burning in boilers, including silicon (Si), potassium (K), sulfur (S) and chlorine (Cl). Lastly, it was noted that leaching efficiencies can reach greater values in optimized washing processes.

USE OF CONVENTIONAL MILL FOR SUGARCANE STRAW SHREDDING

After being washed and drained, the straw can go two ways: be fed in the last mill (figures circled on the next page) of the milling tandem to produce a bagasse-straw mixture, or send to be milled in an independent mill (figure of page 14) and then sent to be added to the bagasse on the belt conveyors.

The evaluation of the straw grinding processes in the mills to reduce the particle size distribution presented very interesting results. After the straw passed through the mill, it was observed that on average 90% of the straw mass refers to particles smaller than 12.5 mm, very close to the value found

Straw washing into the channel

Washed straw drainage in the cush-cush

Straw feeding into the last extraction mill

Detail of feeding straw into the last extraction mill

Independent mill for straw shredding

for the bagasse particle size distribution. In addition, the mill had higher operational regularity, producing straw with greater homogeneity, with 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% by mass smaller than 12.5 mm). On the other hand, adding straw to the bagasse on belt conveyors produce more heterogeneous mixtures.

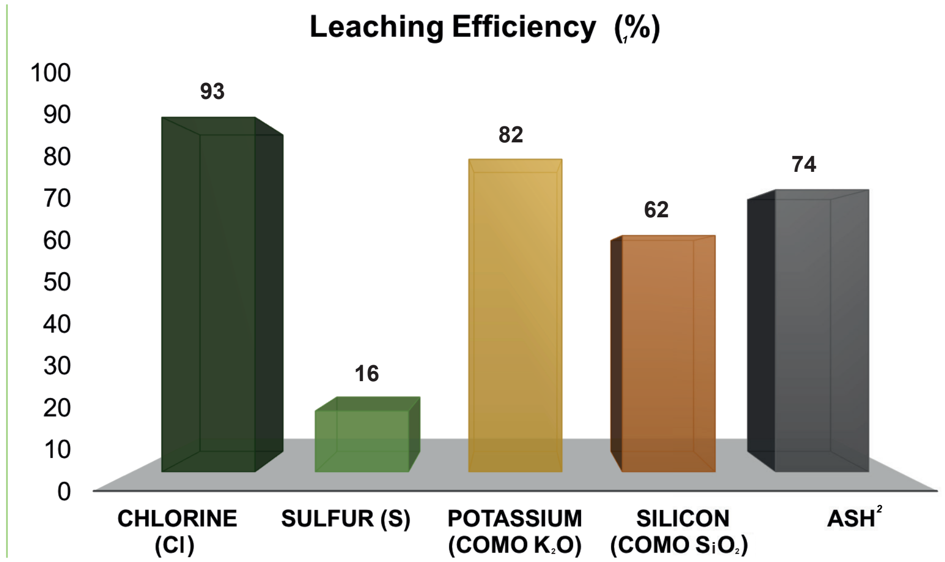
In short, mills have proven to be more efficient than shredders because they better match straw particle size distribution to the desired standard, with lower energy consumption, lower maintenance costs and lower investment for the installation.

Shredded straw aspect from the independent mill

Crushed straw and bagasse mixture aspect from the last mill in the tandem

LEACHING STUDY OF UNDESIRABLE CHEMICAL COMPONENTS IN SUGARCANE STRAW

To better understand the straw leaching process, SUCRE Project's team conducted bench-scale tests under controlled conditions. The experiments were conducted in a shaker and bench-scale extractor, using a dry and shredded straw. They evaluated the influence of process variables (such as temperature, time, straw/water ratio, agitation efficiency and number of washing stages) on the leaching efficiency. The extractor study showed the highest leaching efficiencies. From these studies, we identified parameters that can be optimized on an industrial scale system, such as agitation efficiency, contact time, temperature and wash water quality.



Conditions: 20°C, 1,500 rpm, 1:75 (m_{straw}:m_{water}), 3 min., 3 times (changing water between stages).

1 Relative leaching efficiency calculated as the difference between element concentrations in samples collected before and after the washing process.

2 Represents the relative reduction in the ash content in the straw before and after the washing process.

SUCRE PROPOSALS FOR STRAW PROCESSING

After 4 years of testing and evaluating partner mills, testing and laboratory analysis, SUCRE 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.

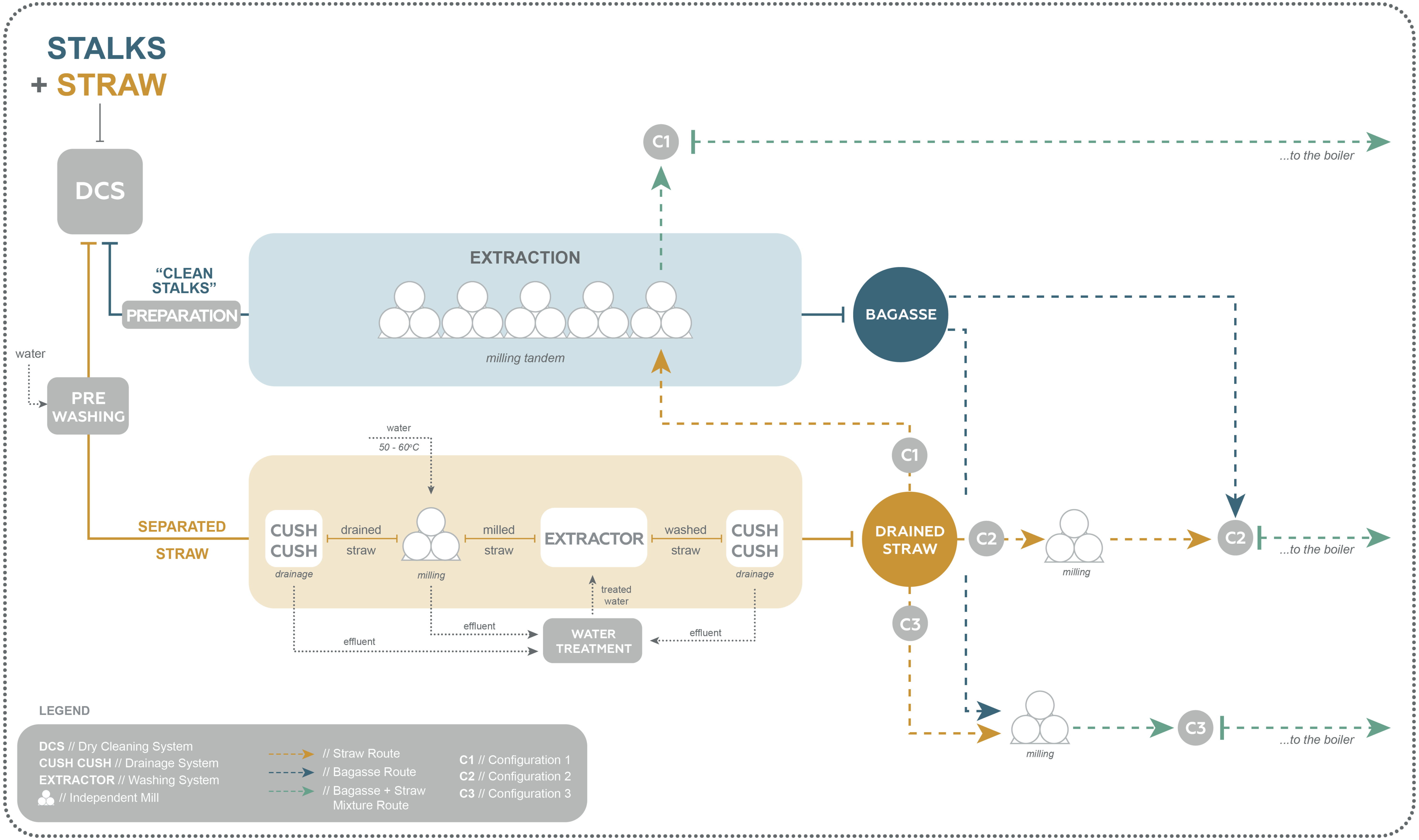
The Project proposals allow for the conditioning of separate straw by the Dry Cleaning System or unbaled sugarcane straw. In the graphic above is showed the simplified flowsheet of the proposed process. The first step involves pre-washing the straw, followed by cush-cush drainage and grinding in an independent mill with soaking water added between 50 °C and 60 °C, which removes part of the impurities and improves the particle size distribution of the straw. Then the straw is washed in an external mineral part of extraneous materials (mineral impurities) extractor, drained again in a cush-cush, and from this step, SUCRE proposes three possible configurations.

In the first, for those with milling spare capacity, the straw is fed in the last mill of the milling tandem and mixed with the bagasse; in the second, the straw is shredded in an independent mill and is added to the bagasse on the belt conveyors; and in the third, the straw is milled and mixed with a part of the bagasse produced using an independent mill. For a more conscious consumption, all water used in the process should be treated and reused, allowing low replacement rates of this resource.

With this proposals, SUCRE expects to enable the use of higher concentrations of straw in the mixture with bagasse, such as 25% by mass (dry basis).

SUCRE PROJECT PROPOSALS FOR SUGARCANE STRAW PROCESSING

Three possible configurations



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