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Sugarcane – unlocking its potential as an ‘electricity crop’

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Abstract This paper summarises and synthesises information on the utilisation of sugarcane residues as an energy source presented at the ISSCT Agronomy and Agricultural Engineering workshop in 2015. The magnitude of the potential resource, the relative value, and potential issues relating to the utilisation of the different residue components as a boiler fuel are addressed. On this basis, it is argued that brown leaf is the most valuable component as an energy source, and that tops and green leaf offer most value as an agronomic resource, to be left in the field. Strategies for residue recovery include a separate post-harvest operation or as an integral part of the harvesting operation, with the residues being separated from the cane prior to milling. The key associated issues relating to both machine harvesting and manual harvesting are discussed, along with the potential synergies offered by integrated trash collection. Many manual and machine harvesting challenges are addressed if neither machines nor people have to separate brown leaf from cane stalks in the field. The paper concludes that sugarcane residues are potentially a highly abundant, cost effective, reliable and sustainable fuel source, and the utilisation of brown leaf in conjunction with bagasse can potentially nearly double the electricity generation capacity relative to bagasse alone. Relative to coal, sugarcane residues are lower cost and more environmentally benign.

Key words Co-generation, fuel, sugarcane residues, energy crop, electricity

INTRODUCTION

Historically, in most sugar Industries, the focus in both agriculture and at the factory has been largely on efficient sucrose recovery for sugar production rather than on the utilisation of fibre for energy. In the mills, boilers, turbo-alternators and sugar-production processes were designed to meet only ‘internal’ energy demands whilst ‘using up’ available bagasse; thereby alleviating a potential bagasse disposal or storage problem. The cost of electricity purchased from the national supplier was often similar to self-generation, so there was little incentive to focus on the potential use of fibre as a fuel. Changing environmental, political and financial considerations mean that the use of sugarcane fibre as a fuel to generate electricity may offer an excellent option to boost profitability and reinvigorate mature sugar industries (Field and Sarir 2015).

The demand for electricity outstrips supply in many countries, particularly in southern Africa. The flow-on effects to industry of the resulting frequent power cuts and load-shedding in Zambia, Zimbabwe and South Africa have been negative, further depressing already struggling economies. Electricity has a very high ‘opportunity cost’, i.e. such as water, when electricity is not available the costs in terms of lost productivity can be very high. Furthermore, international concern about the negative impacts of climate change means that diversifying present and future power generation capabilities away from coal should be encouraged. As history has shown, using a non-renewable resource such as coal can expose users to substantial price spikes carrying substantial environmental risks, and one day economically viable deposits of the resource will be exhausted.

The thesis defended in this paper is that there is huge and often untapped potential to use sugarcane brown-leaf to supplement bagasse as a fuel to generate electricity to the benefit of local economies and at the same time improve and adapt milling, farming and research programs and systems accordingly. The objectives are to highlight and synthesise relevant knowledge so that there is a better understanding of the potential opportunity and constraints. We base this on a distillation of research reported mainly at the International Society of Sugar Cane Technologists (ISSCT) Agronomy and Agricultural Engineering workshop in 2015 and in associated ‘workshop’ discussions. Information to define the magnitude of the potential resource is given, issues regarding the suitability of the various residue components as a fuel are addressed, and systems to harvest, process and transport brown leaves efficiently are discussed.
THE POTENTIAL RESOURCE

Sugars represent only approximately one-third of the total energy captured by the sugarcane plant, with total energy contained in stalk fibre and leaf material each being similar to sugars in magnitude (Nastari 2005; Leal 2007). In traditional sugar industries, some fraction of the energy present in the stalk fibre (bagasse) is used as a fuel source for heat and power to process the sugarcane. The energy in leaf is generally not recovered.

Hassuanini (2013) notes that utilising 100 bar 520°C boilers and associated equipment, mills in Brazil are now achieving generation capacity of 74 kWh/t cane, using bagasse only. By utilising only 50% of the crop residues, the generating capacity can be increased to 126 kWh/t cane, under typical Brazilian conditions.

The actual size of the residue resource varies significantly with variety, age at harvest, yield and other factors (Norris and Eastwood 2004). Depending on these considerations, utilising all or part of the cane residues can increase the nominally available energy at the sugar mill substantially. Despite the variability in resource size, generalised assumptions can be made relating to the relative composition of residues and their potential heat values, based on ‘average’ component composition. Nominal component masses, moisture contents and energy values of the fresh components derived from a range of datasets (Norris and Eastwood 2004) are given in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial mass (t/ha)</th>
<th>Initial moisture content (%)</th>
<th>Energy content LHV* (MJ/kg)</th>
<th>Total energy (GJ/ha)</th>
<th>Dry matter (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk</td>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tops</td>
<td>9.2</td>
<td>80</td>
<td>1.4</td>
<td>13</td>
<td>1.8</td>
</tr>
<tr>
<td>Green leaf</td>
<td>14.0</td>
<td>66</td>
<td>4.</td>
<td>59</td>
<td>4.7</td>
</tr>
<tr>
<td>Brown leaf</td>
<td>10.8</td>
<td>12</td>
<td>15.1</td>
<td>162</td>
<td>9.5</td>
</tr>
<tr>
<td>Total leaf</td>
<td>24.8</td>
<td></td>
<td>19.3</td>
<td>221</td>
<td>14.2</td>
</tr>
<tr>
<td>Total leaf and tops</td>
<td>33.9</td>
<td>52.5</td>
<td>6.9</td>
<td>234</td>
<td>16.1</td>
</tr>
<tr>
<td>Bagasse</td>
<td>3.15</td>
<td>51</td>
<td>7.2</td>
<td>226</td>
<td>15.4</td>
</tr>
</tbody>
</table>

*Lower heating value - the total energy released as heat when a substance undergoes complete combustion with oxygen.

The data in Table 1 reinforces the observation recorded by Nastari (2005) and Leal (2007) relating to the relative amounts of energy available from bagasse and crop residues. It also indicates that the primary source of energy in the non-cane components of a freshly harvested crop is in the brown leaf (69% of the total energy), despite its relatively low fresh weight. Field drying to an aggregate moisture content of 25% results in a doubling of the recoverable energy from tops and a 30% increase in the recoverable energy from green leaf, however, the total energy increase is typically modest, averaging 11-15%. Recovery after field drying also requires an additional field operation.

Whilst highly dependent on yield, growing conditions and variety, an assumption of 162 GJ/ha in dry leaf alone is equivalent to approximately 6 t of coal per hectare. It is likely that fibre yields (and hence coal-equivalent yields) could be increased significantly with appropriate ‘high-fibre’ breeding strategies and optimised agronomic practices (Matsuoka et al. 2014).

The availability of additional energy from cane residues can potentially allow very significant increases in the potential to export electricity; however, the suitability of cane residues as a fuel source, particularly for ‘conventional’ boiler designs, is often queried. Whilst there are valid concerns there are also solutions.

**Millers’ concerns**

The high alkali levels (primarily potassium and chlorine) can result in ‘slagging’, ‘fouling’ and accelerated corrosion of super-heater tubes in conventional boilers. Work by Jenkins et al. (1998) indicated that alkali levels below 0.17 mg/MJ seldom result in fouling or slagging problems, whereas levels above 0.34 mg/MJ almost always result in these problems.

There are large differences in potassium levels in the different components of sugarcane (Table 2) - data derived from Hassuanini et al. (2013) and other sources. Thus, using composite crop residues can be problematical with respect to alkali levels, potentially resulting in boiler problems. Use of dry leaf alone as a boiler fuel would appear to be within the slagging limit reported by Jenkins et al. (1998).
Table 2. Potassium levels in components of sugarcane.

<table>
<thead>
<tr>
<th>Component</th>
<th>Potassium (g/kg FW*)</th>
<th>Moisture content (%)</th>
<th>Dry matter (%)</th>
<th>Potassium (g/kg DM)</th>
<th>LHV** (FW*) (MJ/kg)</th>
<th>Potassium (mg/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry leaf</td>
<td>2.38</td>
<td>12</td>
<td>88</td>
<td>2.7</td>
<td>15.5</td>
<td>0.15</td>
</tr>
<tr>
<td>Green leaves</td>
<td>4.52</td>
<td>66</td>
<td>34</td>
<td>13.3</td>
<td>4.3</td>
<td>1.04</td>
</tr>
<tr>
<td>Cane stalk</td>
<td>0.39</td>
<td>70</td>
<td>30</td>
<td>1.3</td>
<td>3.5</td>
<td>0.11</td>
</tr>
<tr>
<td>Tops</td>
<td>5.90</td>
<td>80</td>
<td>20</td>
<td>29.5</td>
<td>1.4</td>
<td>4.12</td>
</tr>
<tr>
<td>Bagasse</td>
<td>0.85</td>
<td>50</td>
<td>50</td>
<td>1.7</td>
<td>7.6</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*FW – fresh weight.
**Lower heating value - the total energy released as heat when a substance undergoes complete combustion with oxygen.

The higher moisture content reduces lower heat value (LHV) of cane tops and green leaf, and thus accentuates the issue with the higher potassium content on a DM basis. This increase in slagging potential (mg K/MJ) of green leaf and tops, as compared to brown leaf, make these components much less desirable as a fuel. Any strategy to utilise the residues as a fuel source must take into account the aggregate slagging potential of the fuel mix. Much greater proportions of brown leaf are potentially viable compared to green leaf and tops. Despite these concerns, Leal (1995) reported a mill in Brazil running on baled sugarcane residues (including all components) for an extended period without any problems.

Whilst bagasse has a very moderate energy content due to its high moisture content, the milling process removes many of the potentially problematic components. This makes it a very useful fuel.

A further concern to millers is that many Industries that currently harvest unburned crops are finding it difficult to maintain acceptable levels (low levels) of crop residues in the product delivered to the mill. This increase in extraneous matter, and associated increase in fibre and impurities invariably results in reduced extraction, reduced recovery and negatively impacts on sugar quality.

Agricultural concerns

Burned-cane harvesting and associated agricultural practices result in minimal crop residues being returned to the soil, and researchers generally agree with strategies which would facilitate an increase in residues being left in the field. Agriculturalists have therefore raised concerns, particularly relating to using all cane residues as a fuel. Residues, particularly the green leaf and tops, provide many agronomic benefits, including: to the water balance in terms of improved infiltration and reduced evaporation losses; a reduction in herbicide usage; recycling of nutrients (over time); development of ecologically balanced populations of predators to keep pests in check (over time); and improvements to soil health and productive capacity (over time), especially under zero-tillage and controlled-traffic farming systems (van Antwerpen et al. 2001; Hassuani et al. 2005; Kingston et al. 2005; Purchase et al. 2008).

Potential solutions

Fortuitously most of the agronomic ‘goodness’ in cane residues is in the tops and green leaves (Thompson 1991; Mitchell et al. 2000). If only the green leaves and tops are left in the field, the bulk of the agronomic benefits will accrue and indeed in many industries the chances of incurring negative impacts by having too much residue will likely be alleviated, i.e. the residue blanket is unlikely to be excessive if only the tops and green leaves are left in the field and the brown leaves are removed.

With the bulk of the energy content, especially per unit weight, being in the brown leaf (Table 1), it is, therefore, sensible to leave tops and green leaves in the field to accrue agronomic benefits and take brown leaves to the mill for use as a fuel, especially when considering the slagging problems that are likely to arise if green leaves and tops are used as a fuel source.
HARVESTING CANE AND RESIDUES: CHALLENGES AND SOLUTIONS

Different strategies for harvesting sugarcane and collection of residues were defined by Hassuani et al. (2005), with the ‘whole-stalk’ options being:

- hand-cut and top, and manually strip the brown leaf from the stalk. This is followed by immediate collection of cane and separate collection of residues after a period of field drying;
- hand-cut and top, with little or no attempt to remove brown leaf. Cane and brown leaf are forwarded to the factory. Trash separation is optional prior to milling. This option is also viable with whole-stalk machine-harvesting technologies.

The trash collection options for chopper harvested cane nominated were:

- machine harvest and load (chopper harvesting) with topping where possible and trash extraction systems operational. Separate collection of residues after field drying;
- machine harvest with topping where possible, with the use of the extractor system to modulate the proportion of residues left in the field and the proportion taken to the factory. Optional trash separation prior to milling.

Residue collection strategies: hand-cut whole-stalk

Hand-cutting in unburned crops is a widely used strategy in many South-East Asian industries and the residue resource is separated from the cane stalk as part of the process. After field drying of the residues, the collection process can be mechanical or manual. Mechanical collection is typically seen as the most potentially viable option. This strategy results in additional in-field traffic with associated field compaction and potential to damage the crop stool and, hence, to the ratoon crop.

Furthermore, no attempt is normally made to separate the different residue components, i.e. tops, lost stalks, green leaf and brown leaf. Observations in the Philippines indicate that cane stalk can compose over 20% of the total weight of the field-dried product that is retrieved. The high potassium (and other alkali metals) in baled cane trash seriously degrade the potential to use it in conventional boilers. Options are available for the separation of cane stalk and tops (with/without green leaf still attached), and potentially this approach can be utilised to upgrade the quality of collected trash (NorrisECT work with clients).

Increasing labour costs and labour availability issues are driving these South-East Asian industries towards mechanisation (Lawson 2016). Whist the level of full mechanisation will increase dramatically, alternative strategies are potentially available. Meyer et al. (2005) noted that in unburned crops the productivity for cutting stripping and windrowing was approximately 30% lower than cutting and windrowing in burned cane, with the work expended by a cane-cutter in the cutting and topping process being similar to that associated with stripping the brown leaf from the stalk. Their productivity can be maintained to close to burnt cane productivities if brown leaves are left on the cane stalks and there are likely to be fewer respiratory complaints compared to when they cut burnt cane.

In Mauritius, where the goal has been to both increase the recovery of crop residues for cogeneration whilst managing the impact on the mills of high levels of extraneous matter, growers are paid to partially trash the cane prior to loading. In Okinawa (Japan), cane cleaning facilities at sugar mills remove the trash prior to milling (Koh et al. 2010). This allows the growers to minimise harvesting costs by sending much of the residues to the mill with the cane. This strategy both reduces harvesting costs and supplies an additional brown leaf product to the mill maximising leaf available for power generation and other opportunities.

In burned-cane hand-cut Industries, the option of moving to green-cane cutting and manual stripping of the brown-leaf residues may not be economically viable if residues are subsequently removed from the field. The reduction in cutter productivity typically substantially increases cutting costs. The value of the crop residues seldom covers the increase in harvesting costs as well as the residue collection costs.

The strategy of hand-cutting and not stripping the trash reduces the negative impact on cutter productivity, thereby mitigating increases in cutting costs. Whilst loading and transport costs increase, these increases can usually be well below the value of the residues recovered. Residue separation at the mill can then maximise the quality of the cane to be milled, whilst also supplying predominantly brown leaf as an additional energy source. Benefits due to reduced kill to crush delays compared with burnt cane can also be substantial. Green leaves and tops would remain in the field to accrue agronomic benefits. Economic models to assess options have been developed (Wynne and van Antwerpen 2004; Purchase et al. 2008; Rees et al. 2015).
Residue collection strategies: machine harvesting (chopper)

The Brazilian Industry clearly leads the world with respect to both the annual tonnage machine (chopper) harvested and the tonnage of residues recovered annually. Much of this residue recovery is achieved via post-harvest collection of field dried residues, with baling being the method of choice, although other systems such as forage harvesters are also used. The option of using the chopper harvesters to clean cane and then collecting residues in a subsequent operation has some serious disadvantages relating primarily to sucrose losses and to the quality of the collected residues as a suitable boiler fuel. Additional concerns are the potential compaction damage from additional in-field traffic and the costs of the baling operations.

Sucrose losses

The traditional green-cane machine-harvesting operation, where the harvester is used to clean the cane, is a conundrum:
- extraneous matter (EM) targets and work-rate targets demand higher extractor fan speeds that result in significant sucrose losses – typically 10-20%;
- reducing extractor fan speeds to reduce sucrose losses, increases EM levels and can reduce harvester and transport system productivity, increasing costs;
- higher EM levels associated with reduced extractor fan speeds and reduced sucrose losses in the field adversely impact performance and extraction in the mill, often negating any in-field sucrose gains.

Therefore, managing both cane loss and composition of the product being delivered by the harvester in order to optimise outcomes is difficult.

To manage this issue, the Cuban Industry installed post-harvest cane cleaning facilities at rail sidings. The harvesters were then able to operate at ‘low loss’ settings, whilst cleaned cane was forwarded via the transport system to the mills. Whilst harvester technology has improved, the increases in pour rate required mean that post-harvest cleaning can still be a very viable option to address the chopper harvesting conundrum (Table 3) (Norris et al. 2015). Trials under a range of conditions demonstrated that recoverable sugar/ha (t CCS/ha) was increased by 10-30% by ‘low loss’ harvesting and post-harvest cleaning. Recovering residue (primarily brown leaf) with the cane actually increased the value of the primary value chain by in the order of USD100/ha, after increased harvest and haulage costs. Furthermore, if the cane is erect and topping by the harvester is effective, the green leaf and tops will be left in the field as an ideal mulch allowing the bulk of the potential agronomic benefits to accrue.

**Table 3.** Impact of ‘low loss’ harvesting and post-harvest cleaning on crop delivered and recovery with a current model harvester.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>t cane/ha delivered to mill</th>
<th>CCS of product delivered</th>
<th>t sugar/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>100</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Low loss</td>
<td>120.5</td>
<td>12.8</td>
<td>15.4</td>
</tr>
<tr>
<td>Low loss + cleaning</td>
<td>110.4</td>
<td>15.4</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Another potential concern over the use of chopper harvesters is the potential compaction damage they and the associated haul-out vehicles can do. However, GPS/GLONASS guidance technologies and associated controlled-traffic farming systems (CTFS) and surface irrigation innovations with appropriate row spacing can be adopted to minimise compaction damage (Lecler 2015; Tweddle 2015).

**DISCUSSION AND CONCLUSIONS**

There are apparently many stakeholders in the sugarcane world who do not adequately distinguish the difference between brown (dead) leaf and green leaves and cane tops in terms of their agronomic and energy characteristics. It is apparent that green leaf and tops are much less suitable as a fuel source, due largely to their potential to cause problems with conventional boilers. Fortuitously, brown leaf is of far better quality as a boiler fuel and is relatively energy dense compared
with green leaves and tops. Thus, it appears eminently sensible to leave green leaf and tops in the field to accrue the bulk of potential agronomic benefits and use brown leaves as an additional and substantial fuel source.

Post-harvest separation of dry brown leaves and cane stalks appears to be a very important aspect of any strategy to use brown leaf as a fuel source, as it facilitates very high levels of cane quality (low EM), while avoiding the losses associated with trying to ‘clean’ cane on the harvester or issues of low cutter productivity if cane is cut and cleaned by hand. The increase in sugar recovery under this strategy, through reduced cane loss during chopper harvesting and increased mill recovery due to improved cane quality, outweigh the costs associated with the cleaning process and this makes the incremental cost of brown leaf recovery low, or in some cases negative.

Despite a reduction in load densities associated with leaving dry leaf on cane and separating them at the mill or zone in a post-harvest separation facility, the overall economic gains appear favourable. Models to help assess the economics are available. Furthermore, in South Africa, for example, efforts to have performance-based vehicle standards that allow relatively higher-volume trailers on public roads are in progress. Higher-volume trailers could provide a solution to the challenge of having lower densities if brown leaf is transported together with cane stalks. In many sugarcane industries the haulage routes are on private estate roads and using higher-volume trailers could be implemented without major legal concerns. Technologies such as torrefaction and pelleting are among options that can also be considered to address transport costs (Rees et al. 2015).

Significant drivers for adopting mechanised harvesting throughout the world have been environmental restrictions on pre-harvest burning and the collection of residues for value-adding opportunities. In many countries where hand-cutting green cane has been the industry standard, increasing labour costs and reduced availability of people to cut cane are also driving a move to mechanisation. Appropriate controlled-traffic farming systems, post-harvest residue separation, coupled with reduced cut to crush delays and strategies to capitalise on the potential energy value of brown leaf, may make the change relatively painless and profitable.

In many countries there appears to be a great opportunity to focus on fibre and fuel in addition to sugar. Sugarcane industries could contribute substantial renewable energy; the supply of which is likely to boost local economies whilst at the same time reviving mature and sometimes struggling sugar industries. The groundwork has been laid and the challenge is for millers, growers, researchers and politicians to take further advantage of the opportunity.

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**La canne à sucre – ‘déblocage’ de son potentiel en tant que ‘ressource électrique’**

Résumé. Ce papier résume et synthétise les informations présentées au workshop Agronomie et Mécanisation en 2015 sur l'utilisation des résidus de la canne à sucre en tant que ressource énergétique. L’importance du potentiel de la ressource, sa valeur relative, les questionnements concernant l’utilisation des différents composants des résidus à brûler dans les chaudières sont abordés. Sur cette base, il a été précisé que les feuilles sèches constituent la meilleure ressource énergétique, tandis que les parties sommitales de la canne ainsi que les feuilles vertes sont mieux valorisées agronomiquement quand elles sont laissées au champ. Les stratégies pour la valorisation des résidus portent sur une séparation des éléments après récolte ou comme pratique intégrée à la récolte, avec des résidus séparés de la canne avant l’usinage. Les difficultés majeures liées aux deux méthodes de récolte, mécanique et manuelle, sont discutées, ainsi que les synergies potentielles offertes par une collecte de paille intégrée. Beaucoup de défis relatifs à la récolte mécanique et manuelle sont présentés dans le cas où ni les machines ni les hommes ne peuvent séparer les feuilles sèches des tiges dans le champ. Le papier conclut que les résidus de canne à sucre constituent une ressource énergétique potentiellement très abondante, rentable, fiable et durable, et que l’utilisation des feuilles sèches simultanément à la bagasse peut presque doubler la production d’électricité par rapport à la bagasse seule. En comparaison avec le charbon, les résidus de canne sont moins coûteux et ont un impact environnemental moins négatif.

Mots-clés: Co-génération, carburant, résidus canne à sucre, culture énergie, électricité

**La caña de azúcar - desbloqueando su potencial como un ‘cultivo de electricidad’**

Resumen. Este documento resume y sintetiza la información sobre el uso de residuos de caña de azúcar como fuente de energía presentada en el taller ISSCT de Agronomía e Ingeniería Agrícola en 2015. Se aborda la magnitud del recurso potencial, el valor relativo, y problemas potenciales relacionados con la utilización de los diferentes componentes de residuos como combustible de calderas. Sobre esta base, se argumenta que la hoja marrón es el componente más valioso como fuente de energía, y que los cogollos y la hoja verde tienen más valor como recurso agrícola, para ser dejados en el campo. Las estrategias para la recuperación de residuos incluyen una operación post-cosecha aparte o como una parte integral de la operación de cosecha, separando los residuos de la caña antes de la molíenda. Se tratan los temas clave relacionados tanto con la cosecha mecanizada y la cosecha manual, junto con las sinergias potenciales que ofrece la recolección integrada de residuos. Muchos de los retos de la cosecha manual y mecanizada se abordan sí ni las máquinas ni las personas tienen que separar la hoja marrón de los tallos de caña en el campo. El documento concluye que los residuos de caña de azúcar son potencialmente una fuente de combustible muy abundante, rentable, fiable y sostenible, así como que el uso de la hoja marrón junto con el bagazo puede potencialmente casi duplicar la capacidad de generación de electricidad en relación con el uso de bagazo solo. En relación con el carbón, los residuos de caña de azúcar son de menor costo y más benéficos para el medio ambiente.

Palabras clave: Cogeneración, combustible, residuos de caña de azúcar, cultivo energético, electricidad