FAPESP BIOENERGY RESEARCH PROGRAM BIOEN:
SCIENCE FOR A BIO-BASED SOCIETY

By

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KEYWORDS: Bioenergy, Biomass, Biofuels Technologies, Biorefineries, Sustainability.

Abstract

BIOEN IS THE STATE of São Paulo Bioenergy Research Program led by the state’s research funding agency FAPESP. The BIOEN Program aims to integrate comprehensive studies on sugarcane and other plants that can be used as biofuel sources, thus assuring Brazil’s position among the leaders in Bioenergy Research. Research includes from biomass production and processing to biofuel production and its impacts. The BIOEN Program is built on a solid core of academic exploratory research. It is expected that these exploratory activities will generate new knowledge and human resources, which are essential for advancing industry capacity in biofuel-related technologies. The program includes partnerships with industry for cooperative R&D activities between industrial and academic laboratories and themes are specified according to the interest of the private partners and to FAPESP’s commitment to fostering research. Other research agencies in Brazil and abroad participate in the Program through partnerships. The program has 90 projects underway in 12 institutions in the State of São Paulo in collaboration with other institutions in Brazil and in 15 countries. The program is built with five divisions: Biomass, Biofuel Technologies, Biorefineries, Engines (and Impacts and Sustainability. Overall, the Program is being conducted by over 300 researchers with funds in the order of US$ 200 million. A recent development was the creation of the State of São Paulo Bioenergy Research Centre funded by the State of São Paulo Government, FAPESP and the three state universities USP, UNICAMP and UNESP. The centre will consolidate efforts and create research facilities for the community as well as hire new bioenergy researchers to build capacity and expand research goals.

Introduction

Sugarcane is grown in more than 90 countries (FAOSTAT, 2011), mostly between 33°N and 33°S, covering an area of about 25 million hectares and with a yield of approximately 1.7 Gt of cane. This represents 0.52% of the world’s agricultural area, about 1.8% of the arable area, with Brazil, India, China, Thailand, Pakistan and Mexico topping the list of major producers. Data from 2011 show that these countries account for about 82% of the world’s sugarcane production; the
corresponding figure for Brazil alone is 43%. In the last 20 years, sugarcane production grew approximately 61% worldwide. In Brazil, the sugarcane production reached 559 Mt in 2011/12.

Sugarcane is nowadays a source of food, feed, biofuels, bioelectricity and biopolymers. In the last couple of decades, ethanol has been blended with gasoline in several countries in order to decrease dependency on oil (Nass et al., 2007). The use of sugarcane bioethanol as a substitute for gasoline decreases greenhouse-gas emissions by 80% (Macedo et al., 2008) and the positive energy balance of its production has contributed to its recommendation as an advanced fuel (Goldemberg, 2007).

The recent increase in flex-fuel cars, which can run on gasoline and ethanol, has further stimulated the use of sugarcane for biofuel production (Waclawovsky et al., 2010). First-generation bioethanol production from sugarcane sucrose may be considered very robust and does not compete with the food chain since, in most of the industrial units, the bioethanol is produced with depleted syrup with simultaneous sugar production.

More recently, a new scenario has emerged where some of the sugarcane bagasse is used for bioethanol production through cellulosic degradation and the establishment of new biorefineries.

These systems could aggregate value by including other products in the chain such as biodiesel, CO$_2$, biogas, biokerosene and new uses for the vinasse to mention a few. Such new pathways need research and development efforts, the generation of human resources and a thorough investigation of the social, economic and environmental impacts of an expanding sugarcane and biofuel industry.

In 2008, to meet the increasing demand for fundamental knowledge in Bioenergy and to keep Brazil leading the establishment of a bio-based economy, the State of São Paulo Research Funding Agency created BIOEN, a Bioenergy Research Program. This paper describes its organisation, mission, results and future directions.

**BIOEN overview**

BIOEN is the State of São Paulo Bioenergy Research Program led by the state’s research funding agency FAPESP. The BIOEN Program aims to integrate comprehensive studies on sugarcane and other plants that can be used as biofuel sources, thus assuring Brazil’s position among the leaders in Bioenergy Research. Research spans from biomass production and processing to biofuel production and its impacts.

BIOEN aims to link public and private R&D, using academic research institutions, and industrial laboratories to advance and apply knowledge in fields related to ethanol production.

Research goals are specified in accordance with the interests of private partners and FAPESP’s commitment to support high-quality research in the State of São Paulo. Research agencies from federal and other state government agencies, such as CNPq and FAPEMIG, respectively, participate in the BIOEN Program, and other agencies are expected to join.

The Program comprises five divisions, each of them with their specific aims:

**Biomass Research** – Focus on sugarcane, including genomics, biochemistry, cell biology, physiology, plant breeding and sugarcane farming technologies.

**Biofuel Technologies** – Focus on processing and engineering,

**Biorefineries** – Integrated focus on sugar chemistry, alcohol chemistry and bio-products.

**Engines** – Focus on ethanol applications for motor vehicles: Otto cycle engines and fuel cells.

**Impacts and Sustainability** – Focus on social, economic and environmental studies, land use, and intellectual property associated with the biofuel industry.

BIOEN is led by researchers from 12 State of São Paulo Institutions with collaborators in 15 countries.
Table 1 shows the number of projects per institution. Most of the projects are conducted under the Biomass Division (Figure 1). The program has yielded over 460 articles that can be found at [http://www.researcherid.com/rid/H-6149-2012](http://www.researcherid.com/rid/H-6149-2012).

BIOEN articles have been increasingly cited over the years, as depicted in Figure 2, and the combined production has an h-index of 17. BIOEN has also produced Master’s and Doctoral graduates, patents and software (Table 2).

**Table 1**—Number of BIOEN projects per institution.

<table>
<thead>
<tr>
<th>Participating Institutions</th>
<th>Number of projects</th>
</tr>
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<tbody>
<tr>
<td>Universidade de São Paulo (USP)</td>
<td>41</td>
</tr>
<tr>
<td>Universidade Estadual de Campinas (UNICAMP)</td>
<td>15</td>
</tr>
<tr>
<td>Secretaria Estadual de Agricultura, Pecuária e Abastecimento de São Paulo</td>
<td>9</td>
</tr>
<tr>
<td>Universidade Estadual Paulista Julio de Mesquita Filho (UNESP)</td>
<td>7</td>
</tr>
<tr>
<td>Ministério da Ciência, Tecnologia e Inovação</td>
<td>6</td>
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<tr>
<td>Universidade Federal de São Carlos (UFSCar)</td>
<td>3</td>
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<tr>
<td>Universidade Federal do ABC (UFABC)</td>
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<tr>
<td>Instituto de Estudos do Comércio e Negociações Internacionais</td>
<td>2</td>
</tr>
<tr>
<td>Secretaria de Desenvolvimento Econômico, Ciência e Tecnologia do Estado de São Paulo</td>
<td>1</td>
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<tr>
<td>Ministério da Aeronáutica</td>
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<tr>
<td>Fundação Getúlio Vargas São Paulo (FGV)</td>
<td>1</td>
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<tr>
<td>Ministério da Agricultura, Pecuária e Abastecimento</td>
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</table>

**Table 2**—BIOEN production as of November, 2012.

<table>
<thead>
<tr>
<th>Type of production</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Articles</td>
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<td>Book chapters</td>
<td>56</td>
</tr>
<tr>
<td>Books</td>
<td>3</td>
</tr>
<tr>
<td>Doctoral theses</td>
<td>56</td>
</tr>
<tr>
<td>Master’s dissertations</td>
<td>117</td>
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<tr>
<td>Abstracts</td>
<td>365</td>
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<tr>
<td>Awards</td>
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</tr>
<tr>
<td>Patents</td>
<td>17</td>
</tr>
<tr>
<td>Software</td>
<td>1</td>
</tr>
</tbody>
</table>
Main challenges and recent developments

Biomass Division: increasing biomass yields, adaptation to the environment, and the development of biotechnological tools for breeding

Sugarcane studies under the Biomass Division are mainly aimed at increasing yield in a sustainable manner in the current cultivated areas and in the expansion areas where climate and soil conditions are limiting factors.

In addition, there is fundamental research to extend the basic knowledge of physiology and environmental responses as well as genetics and genomics that could contribute to further develop biotechnological routes.

This division has contributions from groups from the three state universities (USP, UNICAMP and UNESP), the sugarcane breeding programs from the federal universities (RIDESZA), the Campinas Agronomic Institute (IAC) and the private sector. One target in the division is to envisage other uses for sugarcane as feedstock in the chemical industry as well as high-value liquid fuels such as ethane.

C4 photosynthesis, discovered in sugarcane, can be impacted by global climate change and studies towards understanding sugarcane responses to increased atmospheric CO₂ and drought are central questions in the Biomass Division.

Joint efforts between the group of Dr Buckeridge and Dr Long have compared sugarcane and Miscanthus responses and contrasting results were obtained, suggesting that sugarcane can more efficiently adapt to changes in climate and maintain efficient carbon storage (de Souza et al., 2008, 2013).

Water availability defines regions where sugarcane can be grown without irrigation. Conversely, sugarcane growth under drought conditions is a challenge to be explored. Water balance and sugar content are highly interrelated, while increases in fibre accumulation are less affected by water availability.

The work from the groups of Dr Souza and Dr Menossi have identified molecular markers, responsive genes and potential regulatory circuit changes associated with current sugarcane cultivars in response to drought conditions (Lembke et al., 2012; Ferreira et al., 2012). Begcy et al. (2012) have demonstrated that a previously identified stress induced gene actually confers drought and salt tolerance in transgenic plants and Dr Souza has discovered a possible role for antisense gene expression in the regulation of stress responses.
A thorough study of Brazilian sugarcane cultivars has confirmed the concept of narrow genetic diversity in the current breeding populations (Dal-Bianco et al., 2012). Efforts to generate genetic maps to identify resistance genes and metabolic and environmental QTLs are in progress (Palhares et al., 2012, Pastina et al., 2012).

A concerted program to predict allelic contribution to phenotypes using mathematical models of the sugarcane polyploid genome has encouraged new avenues for genetic prediction (Serang et al., 2012). Sugarcane breeding is yet to benefit from genomic tools, but several groups are contributing using complementary approaches to build the infrastructure to interpret the consolidated sugarcane genome sequence derived from BAC-based and shotgun strategies. Regulatory small RNAs and repetitive sequences such as microsatellites and transposable elements will enable stronger gene prediction (Vicentini et al., 2012; Domingues et al., 2012; de Jesus et al., 2012). Deciphering the sugarcane genome will open new avenues for breeders, geneticists and plant physiologists.

Transformation of the current breeding of sugarcane towards energy canes is one of the goals of the program. Progress towards the energy cane may benefit from a better understanding of the sugarcane cell-wall structure and its glycomic code (De Souza et al., 2012). Cesarino et al. (2012) have described the activity of peroxidases during sugarcane stem growth and the group of Dr Silva-Filho has done extensive work on genes that have an antiborer activity (Medeiros et al., 2012; Dinardo-Miranda et al., 2012; Rafikov et al., 2012). Sugarcane genetic transformation is under intensive development and will soon validate several of the genes identified in the published studies.

**Biofuels Technologies and Biorefineries Divisions: more efficient production of biofuels and bio-based chemicals**

A significant part of the BIOEN program is devoted to studies in the areas of Biofuel Technologies and Biorefineries. These are broad areas, with a large potential for application that requires investment and specialised human resources. The BIOEN program has contributed to the development of processes and products. Typically, it may be said that bioethanol from sugarcane is a potential substitute for gasoline for light engines, whereas biodiesel is for heavy engines. Efforts have also been made for the development of biofuels for aircraft, filling an important niche for biofuels as liquid fuels for transportation.

Bioethanol programs are generally thought of in terms of first, second and third generation production. First generation covers the fermentation of the sugarcane juice (molasses) in autonomous (only producing bioethanol) and integrated (producing bioethanol and sugar) processes. In both scenarios, the co-generation of electricity may be part of the factory production.

The second generation program make use of the sugarcane bagasse and, to some extent, the tops and leaves as a feedstock to produce bioethanol. Third generation, or thermochemical, processes involve the pyrolysis and gasification of sugarcane bagasse and part of the tops and leaves to produce either bio-oil or syngas (Ardila et al., 2012), which may be converted chemically to biofuels and chemicals.

It is worthwhile mentioning that any type of agricultural residues and even specific cellulosic crops may be used as feedstock for second and thermochemical routes. In addition, the use of CO₂ for micro-algae growth as an alternative way to produce biodiesel has been considered as third generation and some fundamental studies have been carried out on the production of micro-algae (Chia et al., 2013) and alternative photo bioreactors to provide improved processes (Jesus et al., 2012) and biodiesel production (Santana et al., 2012).

First-generation bioethanol is worldwide considered a cost-effective model and has worked since the Pro-alcool program in the early 1980s. Although it has been considered a suitable economic activity, many research projects are focusing on process improvements, covering aspects
such as better feedstock management for processing, sugar extraction and juice treatment, fermentation, and alternative or combined ethanol grade fuel purification processes. Several BIOEN projects focus on such questions and results have shown that it is possible to improve overall process efficiency (Furlan et al., 2012). Process heat integration and the development of more efficient energy systems, including the steps of sugar production and first generation optimisation with electricity co-generation, are important to increase bagasse surplus and, hence, the conditions for production of second-generation fuels.

Studies on ethanol dehydration have shown that energy can be reduced significantly (Dias et al., 2011a; Batista et al., 2012). Research results have shown that there exists a significant opportunity for process improvement which leads to lower production costs and a larger sugarcane bagasse surplus (Dias et al., 2012). Aims of this Division cover experimental large-scale factory data collection and evaluation, as well as development of a representative simulation platform that is crucial to speed up the evaluation of different scenarios.

The concept of second-generation ethanol coupled with first-generation production has led to the investigation of several scenarios for different pre-treatments (Dias et al., 2011b) – these show the potential of such an approach to increase ethanol production and still have an electricity surplus. Evaluation of different second-generation configurations (Dias et al., 2013) show the impact this may have on factory performance.

An important part of the second-generation process is the hydrolysis, which is done sustainably using an enzyme cocktail to liberate fermentable sugar. The BIOEN program has provided one of the fundamental studies in this area (Rosseto et al., 2013). Experimental data from pre-treatment and hydrolysis of sugarcane bagasse (Andrade et al., 2012) are necessary to propose and evaluate possible configurations and enzyme loads in the early design stages.

Many projects cover the most critical areas for process development of bioethanol and chemicals from renewable sources using the biorefinery approach (Mariano et al., 2012). A full list of contributions can be found at http://www.researcherid.com/rid/H-6149-2012.

**Impacts and Sustainability Division: social, environmental and economic consequences of the expansion of bioenergy production**

Several studies are focusing on nitrogen nutrition in sugarcane and its environmental interactions. There is evidence that biological N-fixation (BNF) in sugarcane supplies part of the N requirement of this crop. Many species of N-fixing bacteria associated with sugarcane have been isolated and their plant growth-promoting capacities characterised, indicating that they can stimulate the development of both roots and shoots, especially in the early stages of plant growth (Sala et al., 2011; Ferrara et al., 2012).

An inoculant for sugarcane containing five species of bacteria has been launched, but no significant yield responses have been obtained in a series of field experiments (Cantarella et al., 2012). It is possible that the effect of BNF is already built into sugarcane production systems with the native microbiota.

The challenge is to extend the benefits of this wide range of N-fixing microorganisms that are being found by selecting or breeding plant varieties that are more responsive to the interaction with them.

The area of sugarcane harvested without burning is increasing rapidly in Brazil. Currently, trash is preserved in almost 70% of the plantations in the southwest region, and the consequences of such management changes are being studied in several BIOEN projects. Results obtained by Rossetto et al. (2010) in a set of field experiments indicate that optimum N fertilisation is around 120 kg/ha, which is slightly higher than that of previous studies in burnt fields.

However, the combination of sugarcane trash, fertilisation and vinasse application has more than doubled the emission of N$_2$O due to N fertilisation (Carmo et al., 2012). However, that study
also showed that, on average, the emission factor for N₂O was below 1% of the fertiliser N applied to sugarcane and that it was little affected by levels of up to 14 t/ha of trash dry matter. Vargas et al. (2012) also reported a N₂O emission factor below 1% in two plant-cane field experiments.

The consequences of trash preservation for the balance of CO₂ emission from soil are discussed by Figueiredo and La Scala (2011) and Bordonal et al. (2012). They have shown a net gain of CO₂ in the system when plant residues are not burnt: conversion to green cane could save the equivalent of 311 kg CO₂/ha/yr or 1484 kg CO₂/ha/yr if soil C sequestration is taken into account.

The expansion of ethanol production has sharply increased the production of vinasse, a liquid residue generated at an average rate of 10 to 13 L/L ethanol. Rossetto et al. (2012a,b) have examined the impact of vinasse application on soil properties and nutrient losses in sugarcane and found little or no deleterious effect on soil but, rather, an increase in available plant nutrients. If concentrated vinasse is used instead of regular vinasse, N mineralisation becomes slower, which indicates that this nutrient may be available for plants for a longer period (Rossetto et al., 2012b).

The consequences of land use change for sugarcane expansion – a highly sensitive matter in Brazil – was studied by Nassar et al. (2011a, b). A model that takes into account the specificities of Brazilian agriculture was developed. Their results show how land is being displaced for sugarcane expansion and that very little forest or natural vegetation is being occupied by the new sugarcane crops. At the same time, Rudorff et al. (2010) have used satellite images to characterise the expansion of sugarcane cultivation. In this way, BIOEN projects are helping to evaluate the environmental impacts of sugarcane, important because society as a whole expects that Brazilian bioenergy is produced in a sustainable way.

Research networks and innovation for a bio-based economy

BIOEN was built with a strong core of fundamental research. In recent years, a growing number of companies have taken an interest in conducting R&D&I activities in Bioenergy in Brazil. Similarly, several foreign universities and research centres are seeking collaborations with Brazilian groups.

Due to its climate, extensive land availability and successful agribusiness, Brazil is playing an important role in the development of a global bio-based economy. We expect that a significant part of the research efforts will develop into sugarcane, biofuels and bio-based chemical innovations.

The BIOEN Research Program has a strong effort to connect its fundamental research to business-oriented applications. This is done through agreements with companies for the development of joint research. So far BIOEN has had research projects co-funded by Oxiteno (3 grants), Braskem (5 grants), Vale (3 grants), ETH (10 grants), Microsoft Research (1 grant) and Boeing (1 grant). New partnerships have been signed recently – and BP Biofuels BIOEN will gain two Engineering Research Centres (ERC) focusing on sustainability and the agriculture of sugarcane.

An open call for proposals is underway with Peugeot-Citroen do Brasil Automóveis (PSA) for an ERC devoted to the science and technology of ethanol Otto-cycle engines. In addition to these university-industry cooperative research projects, FAPESP also supports 10 grants in small businesses in themes associated with BIOEN. Of the 122 research grants already approved in the program, 33 are either jointly developed with companies or developed in small businesses.

Additional efforts include the creation of the State of São Paulo Bioenergy Research Centre, a joint initiative of FAPESP, USP, UNICAMP, UNESP and the State of São Paulo Government and the creation of a joint Bioenergy Graduate Program among those universities.

This effort includes the hiring of 80 researchers to start new laboratories, including an Engineering Centre at UFSCAR, a Plant Cell Biology Centre at ESALQ and a Biomass Systems and Synthetic Biology Centre in the São Paulo City campus of USP, as well as Labioen, a multi-
disciplined initiative at UNICAMP. We expect that, with such actions, we will be able to double the number of young researchers and students in Bioenergy in Brazil generating a critical mass to tackle the most challenging issues and innovate.

Finally, BIOEN labs participate in the research activities sponsored by the PAISS program of the Brazilian National Development Bank (BNDES) and FINEP that are currently funding initiatives in the order of US$700 million for the development, production and commercialisation of novel industrial technologies for sugarcane biomass processing. We believe that the combination of fundamental and applied research efforts, the high quality of its scientific production and the many examples of strong networks formed since the beginning of the program make BIOEN one of the leading Bioenergy Research Programs in the world.

Acknowledgements

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REFERENCES


LE PROGRAMME DE RECHERCHE BIOEN EN BIOÉNERGIE DE LA FAPESP: UNE SCIENCE POUR UNE SOCIÉTÉ DE BIO-INNOVATION

Par

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Résumé

BIOEN EST LE PROGRAMME de recherche en bioénergie de l’état de Sao Paulo, mené par la FAPESP, l’agence d’état pour le financement de la recherche. Le programme de BIOEN vise à intégrer les études approfondies sur la canne à sucre et autres cultures qui peuvent être utilisées comme sources de biocarburants, assurant ainsi la position du Brésil parmi les pionniers sur la recherche en bioénergie. Cette recherche va de la production de la biomasse, à sa transformation en biocarburants et ses impacts. Le programme de BIOEN est mené sur une base solide de recherche exploratoire académique. Il est prévu que ces activités exploratoires vont générer de nouvelles connaissances et ressources humaines, qui sont essentielles pour faire progresser la capacité de l'industrie dans les technologies liées aux biocarburants. Le programme comprend des partenariats avec l’industrie par des coopérations en R&D entre des laboratoires industriels et académiques et les thèmes sont définis en fonction de l'intérêt des partenaires privés et de l'engagement de la FAPESP à encourager la recherche. D’autres organisations de recherche au Brésil et à l'étranger participent aussi à ce programme à travers des partenariats. Quatre-vingt dix projets sont en cours dans 12 établissements de l'état de Sao Paulo et ils sont menés en collaboration avec d'autres institutions au Brésil et dans 15 pays. Le programme comprend cinq axes: la biomasse, les technologies de biocarburants, les bio-raffineries, les moteurs et les impacts et la durabilité. Dans l’ensemble, le programme est mené par plus de 300 chercheurs avec des fonds de l’ordre de US $ 200 millions. Un développement récent a été la création du centre de recherche en bioénergie de l’état de Sao Paolo, financé par le gouvernement de l'état de Sao Paulo la FAPESP et trois universités publiques notamment USP, UNICAMP et UNESP. Ce centre permettra de consolider les efforts et de créer des facilités de recherche pour la communauté ainsi que d’embaucher de nouveaux chercheurs en bioénergie pour renforcer les capacités et d'étendre les objectifs de la recherche.
EL PROGRAMA BIOEN DE INVESTIGACIÓN EN BIOENERGÍA DEL FAPESP:
CIENCIA PARA UNA SOCIEDAD SUSTENTADA EN BIOLOGÍA

Por

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PALABRAS CLAVE: Bioenergía, Biomasa, Tecnologías de Biocombustibles, Biorefinerías, Sustentabilidad.

Resumen

BIOEN ES EL PROGRAMA de Investigación en Bioenergía del Estado de São Paulo, liderado por el FAPESP, la agencia estatal de financiamiento para la investigación. El Programa BIOEN tiene como objetivo integrar estudios exhaustivos en caña de azúcar y otras plantas que puedan ser utilizadas como fuentes de biocombustibles, con lo que se asegura la posición del Brasil entre los líderes en Investigación en Bioenergía. La Investigación incluye desde la producción de biomasa y su procesamiento hasta la producción de biocombustible y sus impactos. El Programa BIOEN está construido sobre una base sólida de investigación académica exploratoria. Se espera que estas actividades exploratorias generen nuevo conocimiento y recursos humanos, esenciales para el avance de la capacidad de la industria en las tecnologías relacionadas con los biocombustibles. El programa incluye colaboraciones con la industria para establecer actividades de cooperación en Investigación y Desarrollo entre los laboratorios industriales y académicos, cuyos temas son establecidos en consonancia con los intereses de los socios de capital privado y con el compromiso del FAPESP en el avance de la investigación. Otras agencias de investigación en el Brasil y del exterior participan en el Programa a través de colaboraciones. El Programa comprende 90 proyectos en curso en 12 instituciones en el Estado de São Paulo, en colaboración con otras instituciones en el Brasil y en 15 países. El Programa está diseñado en cinco divisiones: Biomasa, Tecnologías de Biocombustibles, Biorefinerías, Motores, e Impactos y Sustentabilidad. En conjunto, el Programa está siendo conducido por 300 investigadores con recursos del orden de US$ 200 millones. Un reciente desarrollo es la creación del Centro de Investigación en Bioenergía del Estado de São Paulo, fundado por el Gobierno del Estado de São Paulo, el FAPESP y las tres universidades estatales: USP, UNICAMP y UNESP. El Centro consolidará esfuerzos y creará instalaciones de investigación para la comunidad, y contratará nuevos investigadores en bioenergía para incrementar la competitividad y expandir los objetivos de investigación.
PROGRAMA BIOEN FAPESP DE BIOENERGIA: CIÊNCIA PARA UMA SOCIEDADE SUSTENTÁVEL

Por

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PALAVRAS-CHAVE: Bioenergia, Biomassa, Tecnologias de Biocombustíveis, Biorrefinarias, Sustentabilidade.

Resumo

O PROGRAMA DE PESQUISA de Bioenergia do Estado de São Paulo (BIOEN) é liderado pela maior agência de financiamento do estado, a FAPESP. O Programa BIOEN pretende integrar estudos abrangentes sobre cana-de-açúcar e outras plantas que podem ser utilizadas como fontes de biocombustível, assim garantindo a posição do Brasil entre os líderes na Pesquisa em Bioenergia. A pesquisa inclui desde produção e processamento de biomassa a produção de biocombustível e seus impactos. O Programa BIOEN foi construído em uma base sólida de pesquisa exploratória acadêmica. Espera-se que essas atividades exploratórias gerem novos conhecimentos e recursos humanos, essenciais para avançar a capacidade da indústria em tecnologias relacionadas a biocombustíveis. O programa inclui parcerias com a indústria para cooperação em atividades de Pesquisa e Desenvolvimento entre laboratórios industriais e acadêmicos e os temas são especificados de acordo com o interesse de parceiros privados e o compromisso da FAPESP em fomentar a pesquisa. Outras agências de pesquisa no Brasil e no exterior participam do Programa por meio de parcerias. O programa possui 90 projetos em andamento em 12 instituições no Estado de São Paulo em colaboração com outras instituições no Brasil e em 15 países. O programa é constituído por cinco divisões: Biomassa, Tecnologias de Biocombustíveis, Biorrefinarias, Motores e Impactos e Sustentabilidade. De modo geral, o Programa está sendo conduzido por mais de 300 pesquisadores com fundos na ordem de US$ 200 milhões. Um desenvolvimento recente foi a criação do Centro de Pesquisas em Bioenergia do Estado de São Paulo com fundos do governo do Estado de São Paulo, da FAPESP de de três universidades estaduais USP, UNICAMP e UNESP. O centro consolidará esforços e criará instalações de pesquisa para a comunidade, além de contratar novos pesquisadores em bioenergia para aumentar sua capacidade e expandir os objetivos de pesquisa.
KNOWLEDGE, AN UNDEREXPLOITED INPUT FOR INCREASING NOT ONLY CANE PRODUCTIVITY

By

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KEYWORDS: Knowledge, Inputs, Productivity, Marginal Gains, Social Organisation.

Abstract

INCREASING CANE PRODUCTIVITY continues to be one of the greatest challenges in the sugar industry against the backdrop of yield stagnation. Expansion in cane production will largely have to come from increasing productivity as expanding current areas and or identifying suitable new cane-producing areas become less of an option. Unlike the sugar beet sector, particularly in the EU and USA where beet productivity rates at farms are on average around 30% less than those obtained at research stations, the probable divide between cane yield differences at a farm and research station, is markedly higher. This paper argues that one of the compelling reasons explaining the huge difference in yields in the cane sector is probably to do with under exploitation of knowledge as an input. Whereas in the USA and EU there are examples of effective collaborative structures among growers, factories and research stations facilitating knowledge transfer, with the exception of Australia and South Africa, the cane industry is bereft of such successful models. In countries where cane yields are hovering at around 50-70 t/ha, opportunities for significantly increasing yields through employing the concept of marginal gains, whereby each aspect of the value chain in the production of cane is addressed to the highest standard, are real.

Introduction

Several years ago, The New England Journal of Medicine featured an article where surgeons from best, average and poor performing heart-transplant units in the US visited each other’s units during actual surgery.

Subsequent to these exchanges, the mortality rates of transplantees from all the units went down significantly, particularly those from the poor performing units. It was apparent that the knowledge exchange and sharing that this initiative was instrumental in promoting, yielded a significant dividend performance-wise.

In agricultural production, the process of knowledge sharing and application of latest research products is a bit more complex, if not insurmountable, as it involves a collaborative structure that needs to be fluid among farmers, extension workers and researchers. In the sugar industry, complexity is added by the necessary involvement of sugar mills.

The main challenge for growers anywhere is to bridge the yield gap between that obtained at a research station with output obtained from the same cultivar at a farm.

In the beet sugar sector in Europe, as Table 1 suggests, yield differences between research stations and growers are on average around 30% (Jaggard et al., 2012). In the cane sugar sector, achieving similar levels of productivity would be something to marvel at.
Table 1—Average sugar yields (t/ha) from sugar beet in European countries and in the area contracted to American Crystal Sugar Co-operative: 2006–10.

<table>
<thead>
<tr>
<th>Country</th>
<th>Variety trials</th>
<th>Delivered</th>
<th>Mean gap</th>
<th>% achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>13.01</td>
<td>9.21</td>
<td>3.80</td>
<td>70.8</td>
</tr>
<tr>
<td>Denmark*</td>
<td>13.29</td>
<td>10.92</td>
<td>2.37</td>
<td>82.2</td>
</tr>
<tr>
<td>Netherlands</td>
<td>15.20</td>
<td>12.20</td>
<td>3.00</td>
<td>80.3</td>
</tr>
<tr>
<td>Belgium</td>
<td>16.02</td>
<td>12.28</td>
<td>3.74</td>
<td>76.7</td>
</tr>
<tr>
<td>England</td>
<td>14.94</td>
<td>9.39</td>
<td>5.55</td>
<td>62.9</td>
</tr>
<tr>
<td>France</td>
<td>15.99</td>
<td>13.32</td>
<td>2.67</td>
<td>83.3</td>
</tr>
<tr>
<td>Germany**</td>
<td>15.77</td>
<td>10.11</td>
<td>5.66</td>
<td>64.1</td>
</tr>
<tr>
<td>Austria</td>
<td>17.12</td>
<td>10.81</td>
<td>6.31</td>
<td>63.1</td>
</tr>
<tr>
<td>Italy</td>
<td>14.55</td>
<td>9.10</td>
<td>5.45</td>
<td>62.5</td>
</tr>
<tr>
<td>Spain</td>
<td>19.99</td>
<td>15.03</td>
<td>4.96</td>
<td>75.2</td>
</tr>
<tr>
<td>Red River Valley, USA</td>
<td>10.22</td>
<td>9.77</td>
<td>0.45</td>
<td>95.6</td>
</tr>
</tbody>
</table>

*2006–2009, **White sugar yield
Source: Jaggard et al. (2012)

The theoretical possible yield for sugarcane is about 280 t/ha per year. Very few sugarcane industries manage to achieve even half of this. Table 2 suggests that, at best, yields are some one-third or one-quarter of the potential.

Table 2—Cane yields for selected countries for 2011–12.

<table>
<thead>
<tr>
<th>Country</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colombia</td>
<td>120</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>61</td>
</tr>
<tr>
<td>Guatemala</td>
<td>90</td>
</tr>
<tr>
<td>Mexico</td>
<td>70</td>
</tr>
<tr>
<td>Mozambique</td>
<td>80</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>102</td>
</tr>
<tr>
<td>Peru</td>
<td>123 (53–190)*</td>
</tr>
<tr>
<td>South Africa</td>
<td>60</td>
</tr>
<tr>
<td>Swaziland</td>
<td>98</td>
</tr>
<tr>
<td>Thailand</td>
<td>77</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>85</td>
</tr>
</tbody>
</table>

Source: USDA; *Values in brackets depict range

Yield stagnation

It is apparent from the foregoing that cane productivity is a major issue in the cane sugar sector.

A recently published review (Ray et al., 2012) signposts the emerging issue of yield stagnation that is beginning to pressure on global agriculture. Agricultural output will have to roughly double by 2050 on the back of a rise in population, meat and dairy consumption and biofuel use.

For this to be realised, there has to be a significant rise in crop productivity. However, the review suggests that yield stagnation and collapse across 24–39% of maize-, rice-, wheat- and soybean-growing areas is countering yield advances in other areas. These four crops currently provide some 64% of agricultural calorie production.

While the review does not posit data on trends in sugarcane productivity in the leading producing countries, it is apparent that the picture is no different, if not bleaker. In the cane industry in the US over the period 1980–81 to 2012–13, the yields have practically remained the same – the yields for these two years are 83.8 t/ha and 81.4 t/ha, respectively.

During the recent past in Brazil, cane yields have tumbled from 89 t/ha to 69 t/ha. An extensive replanting campaign is helping yields to recover. In India, while the yields have increased...
over the period 1985–86 to 2010–11 from 60 t/ha to 70 t/ha, there have been significant fluctuations annually.

In Pakistan, a similar picture emerges over the period 1996–97 to 2010–11 when yields increased from 43.5 to 56.1 t/ha. In Australia, cane yields peaked at 100 t/ha during 1996–98, declining to around 80–90 t/ha currently. In Thailand, cane yields dropped from 77.3 t/ha last year to 70.7 t/ha this year. The Philippines situation is a tale of two halves that is doubtless repeated elsewhere in the global industry – productivity from large farms (>100 ha) is 73.4 t/ha while that from small farms (<5 ha) is 50.3 t/ha.

Knowledge as an input

Arguably, one of the central underlying factors for a wide gap in cane productivity, but a relatively short one with beet productivity, is probably to do with access to knowledge, and conversion of this knowledge into action.

Along with capital inputs such as fertilisers and crop protection chemicals, knowledge is a vital input in agricultural production. Indeed, it should be apparent that the dividend from productivity increases that come with applying relevant knowledge is, arguably, as much use as capital inputs.

It is no accident that, in the beet sugar sector in Europe, yield differences between research stations and growers are narrowing. Beet sugar processors such as Nordic Sugar, British Sugar and Sudzucker have developed solid and proactive links with both research stations and beet growers. This effective social organisation is conducive to knowledge sharing, resulting inevitably in an increase in output and production of quality beet.

A recently published study (Cock et al., 2011) based on research in the cane sugar sector in Colombia confirms that knowledge transfer to farmers is facilitated by social organisation that promotes sharing of information, and that farmers readily adopt the positive results that stem from their own experiences. The authors conclude that ‘strong social organisation appears to be essential for the development of effective operational research in agriculture’.

The converse is also true. Cock et al. (2011) cite a study of fruit growers in the Andes where ‘lack of strong social organisation led to a breakdown in the system of continually obtaining information on the effectiveness of innovative practices and, hence, continuous improvement of the production system’. The wide yield disparity between small holders and those farmers with significantly large cane area in the Philippines probably suggests a similar situation operating there.

The transition from an industrial economy to one that is knowledge-driven has brought in its wake a fundamental rethink in securing competitive advantages.

Instead of economies of scale, in the knowledge economy, competitive edge is informed by and based on economies of expertise derived by leveraging knowledge that resides in an organisation’s network through intra-organisational and inter-organisational relationships.

However, this idea that knowledge is a vital input in any areas of activity is not necessarily a recent discovery, but rather the understanding how it can be better exploited to serve a particular purpose, certainly appears to be.

Knowledge theory – a very brief introduction

It is worth stepping back here and to recall one of the fundamentals of knowledge management.

Some years ago, a former CEO of Hewlett Packard said to the effect ‘if we only knew what we now know, we would probably be three times as successful’. During the ’90s when there was a wave of downsizing in many large firms, little care was exercised to preserve valuable organisational knowledge gleaned over a long period when many senior staff were let go. In the case of one company, Ford, they had to rehire some of these staff as consultants to source their valuable knowledge that they simply could not duplicate overnight.
Knowledge process embraces the following truisms:

- I know what I know
- I know what I don’t know
- I don’t know what I know
- I don’t know what I don’t know

The most compelling of these is ‘I don’t know what I don’t know’.

If one is to review the history of knowledge management disasters, one of the candidates would surely be the Renaissance engineers whose innovations, while engineering marvels of the day, had one significant shortcoming which rendered their machines less effective (Anon., 2013). At the time, the concept of energy and power was not understood. Indeed, if these concepts were well understood, the industrial revolution would have probably taken place much earlier than the further 250 years that it subsequently took.

A few examples of these are noted in Figures 1a–c sourced from the travelling exhibition ‘The art of invention: Leonardo and the engineers of the Renaissance’ that passed through the Science Museum in London in October 1999.

Fig. 1a—Human-powered flying machine. (The invention has a wing spread of about 33 feet. The wings are driven by the back pedals, which the flier operates with an alternating leg motion. The effect of this thrust is amplified by the hand-operated crank. The machine incorporates complex gears and ingenious solutions for transmitting motion.)

Fig. 1b—Pile driver (This machine is used to drive poles into the ground in order to lay solid foundations for buildings. The ingenious mechanism, operated by a person on a tread-wheel, lifts and drops the weight automatically.)
Fig. 1c—Pump (This human-powered device features an intricate system of levers. They serve to control the travel of the crank's cylinder piston, which draws water from the spring, through the valves, into a collecting vessel.)

While the Renaissance engineers can be forgiven for designing and developing machines well ahead of their time, the wide gap in cane productivity must seriously be questioned. It is not as if there is no applicable knowledge for farmers to successfully utilise. In all probability, lack of an effective collaborative structure among growers, millers and research institutions is at play here.

Samuel Johnson, the celebrated English writer born in the 18th century, said ‘Knowledge is of two kinds. We know a subject ourselves, or we know where we can find information upon it.’ This distinction between knowledge and information is an important one, and worth exploring to glean insight into how knowledge can be productively employed. Too often, 'information' and 'knowledge' have been used fairly interchangeably to the detriment of knowledge transfer in particular.

**Distinction between knowledge and information**

Knowledge, essentially, is ‘organised information’ and the process of organising it is purely intellectual. Information is the product of processing, sorting and combining data (and data are raw, unconnected facts). Information per se cannot be visualised as a ‘brick’ that has some pre-defined intrinsic worth, but rather like clay that the user can mould for constructing his or her sense, and this construction is dependent on the individual’s knowledge base. That is, the ‘enabling value’ of information is contingent on the effectiveness with which it is applied by the user.

Examine the following:

- **Knowledge – Information = 1**

Rapid progress is limited under this circumstance where acquired knowledge is not regularly refreshed by new actionable information to expand this knowledge base to make an informed decision. In an agricultural context, this model is representative of situations where farmers' knowledge base is built up over a period of time mainly through their own 'informal' research on their farms and informal knowledge networks ...built around traditional channels of communication, such as the use of the ‘folk media', word-of- mouth, and example as in apprenticeships. This has certainly yielded the development of quality innovative practices: intercropping and agroforestry are just two of these examples. They represent good examples of the holistic approach to agricultural development. That is, they are a stage before the logical progression to the 'science of the abstract' when the use of products of dedicated research into input use, input intensification and input efficiency takes over.
• Knowledge + Information = 1+

Under this circumstance, there is a likelihood of much rapid progress where new relevant information adds to the existing knowledge base leading to its further development. The caveat here is that the level of information processing and use, and the quality of output from this use is contingent on users' knowledge base and cognitive abilities. Further, as the knowledge base expands, less and less information is required to refine it. The oft observation made is a testimony to this. Senior consultants generally rely mostly on their personal knowledge while their junior counterparts rely on a range of information sources to satisfy their information needs to support an informed decision. Secondly, the quality of the knowledge base impacts upon the ability to select information or be selective about what specific information is required to fill a particular information gap. This ability to utilise new knowledge effectively as a result of having the technical know-how is particularly illustrative of the differences between progress made in agricultural development in developing and emerging economies as opposed to developed countries.

One of the features of advances in new developments is that it not only involves understanding new knowledge and its application, it also involves the more difficult element of unlearning any past practices that have been counter intuitively superseded. One example is reduced inputs of fertilisers in beet production without seeing declines in yield.

• Information - Knowledge = 0

This scenario is self-explanatory. No amount of information, no matter its quality, is of use if there is no relevant knowledge base to action it. For example, I can give 'you' all the latest information on astrophysics, but if you have no grounding on the subject, you are not going to make sense of it. A study by ICRISAT in Kenya in one farming community revealed that farmers used the wrong chemical, at the wrong doses at the wrong time to control insect pests in pigeon peas. In one district, farmers used fungicides recommended for use on tomatoes to control insect pests of pigeon peas.

This lack of knowledge in differentiating between insecticides and fungicides was as much due to limited access to formal advice. The above expression suggests why the laudable aim of making information available is not necessarily going to move mountains. Indeed, the problem is not only about availability or accessibility to actionable information, but the end user having the capability to make sense of and use this information. Initiatives directed only at improving access to information are not enough.

A much more integrated approach that sets out to develop the technical knowledge base and skills through education and training, in tandem with information provision, is likely to lead to more effective exploitation of information that is made available.

Marginal gains, collectively significant

Prior to the Beijing Olympics in 2008, Great Britain’s cycling team was not world renowned. Soon after the 2004 Olympics, UK Sports appointed a Head of Marginal Gains. The purpose of this was to study in-depth accumulation of incremental improvement that would collectively contribute to significant advantage over their rivals. Every aspect of athlete preparation and lifestyle, equipment, clothing, training methods, nutrition and anything else which might produce a marginal gain was examined. Some of the strategies and tactics that were subsequently deployed included:

• never using an Olympic courtesy bus to avoid possible infections
• made-to-measure shoes with custom-made soles – this was considered a huge innovation
• Spraying alcohol on bike wheels to remove a layer of dirt and increase tackiness before a standing start
• The 'black box' or integrated performance measurement box – the size of a matchbox under a rider's saddle
• To establish actual distance raced down to the last millimetre – literally, videos of complete performances were made.

• Fish oil and Montmorency cherries, high in antioxidants were eaten in large quantities as they help muscles recover quicker.

In 2008, the British Cycling team came away with 8 gold medals compared with 2 in the 2004 Olympics. The team leveraged knowledge to the extent that its competitors did not, to secure the competitive advantage it subsequently demonstrated.

The concept of marginal gains is not new in agriculture either, but it is simply not fully exploited as it should. Australian industry has for some years been focusing cane production research into yield stability.

Eoin Wallis, the former CEO of BSES Limited, made a pertinent observation in the industry’s Canegrowers Magazine a few years ago. He pointed out that along the value chain from soil cultivation right through to harvesting, a grower can potentially increase cane yields by some 35 t/ha by adhering to best practice at all stages.

For example, an additional 15 t cane/ha can be had from forthright control of weeds, pests and diseases, another few more tonnes from appropriate fertiliser application, and so on. The point here is that there is knowledge in the industry that can be productively exploited - but it is not.

In a clear extension of seeking marginal gains along the value chain in sugar beet production to help maintain increased productivity, the British Beet Research Organisation (BBRO) (2013) produced a blueprint 4X4 Yield Initiative (Figure 2).

The aim of this initiative is to help growers to increase yields on average by 4% over the period 2012–15.

<table>
<thead>
<tr>
<th>Yield Component</th>
<th>What is the objective?</th>
<th>What is it worth?</th>
<th>What is the measure?</th>
<th>What has to be done?</th>
<th>Key Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seed treatment</strong></td>
<td>100% seed order with insecticide treated seed within 2 years.</td>
<td>Virus yellows can cause losses of 30% on 9% of the area currently not treated.</td>
<td>Seed Order</td>
<td>Target those growers not ordering treated seed. Technical mailing/AM visit</td>
<td>JUNE</td>
</tr>
<tr>
<td><strong>Drilling date</strong></td>
<td>Bring rolling three year average drilling date forward by three days without increasing bolting risk.</td>
<td>An average of 0.19% adjusted yield.</td>
<td>Crop Declaration</td>
<td>Pull out target lists from previous crop declarations for AM’s to target. Publications</td>
<td>FEB/MAR</td>
</tr>
<tr>
<td><strong>Soil management and Cultivations</strong></td>
<td>Ensure primary cultivation carried out when land is dry. Minimise secondary cultivations whilst still ensuring a good seedbed.</td>
<td>Poor cultivation can hit establishment and yield by 20%.</td>
<td>Difficult to measure as beet is rotated.</td>
<td>Background advice</td>
<td>AUGUST/SEPT and FEB/MARCH</td>
</tr>
<tr>
<td><strong>Fungicide strategy</strong></td>
<td>100% of crop to receive a full rate fungicide. Those crops to be harvested from Oct to receive a second application.</td>
<td>At least 5% on the 13% of the crop currently receiving no treatment. Further benefit from second applications</td>
<td>Crop Survey.</td>
<td>Produce advice and demonstrations. Target those people not currently using fungicides with personal visits.</td>
<td>JUNE</td>
</tr>
<tr>
<td><strong>Weed beet</strong></td>
<td>To double the level of weed beet control measures currently being applied to the crop.</td>
<td>1 tall weed / square metre costs 11% yield</td>
<td>Add a question to the field survey? What control measures have been undertaken?</td>
<td>Produce advice and demonstrations. Target those people not currently controlling weed beet with personal visits.</td>
<td>MAY and JULY</td>
</tr>
<tr>
<td><strong>Weed control</strong></td>
<td>More to no tall weeds surviving in the growing crop over the next three years.</td>
<td>1 tall weed / square metre costs 11% yield</td>
<td>Add a question to the field survey? What weeds, what level?</td>
<td>Horticide advice based on BBRO project. Advisor briefings.</td>
<td>FEB</td>
</tr>
</tbody>
</table>

Fig. 2—Template for increasing sugar beet productivity in UK during 2012–15.
To support growers adopt best practice and techniques to increase beet productivity, BBRO has a dedicated communications program ‘targeted at effective knowledge transfer’ via a variety of means, predominantly social interactions. This embraces: technical meetings, decision-maker training, field demonstrations, operator training courses, printed technical bulletins, electronic communications (e.g. internet portal, email and text messages), face-to-face advice, and plant clinic.

It is apparent that these initiatives help build a common shared background that facilitates communication between the parties and, invariably, knowledge transfer.

Concluding comment

With the increasing consolidation in the sugar industry, it is within the writ of the many large companies in the cane sugar industry to proactively develop an effective knowledge-transfer structure along the lines developed by the likes of BBRO. Yes, in some industries, there are enormous challenges. For example, on average a sugar mill in India deals with 40,000 cane growers.

This clearly is likely to put enormous strain on executing knowledge-transfer initiatives without significant investment. But these are not insurmountable. To restate, the dividend from applying knowledge is as great as any of the complementary capital inputs, if not more.

REFERENCES


LES CONNAISSANCES: UNE CONTRIBUTION SOUS-EXPLOITÉE POUR ACCROÎTRE PAS UNIQUEMENT LA PRODUCTIVITÉ CANNIÈRE

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MOTS CLÉS: Connaissance, Contribution, Productivité, Gains Marginaux, Organisation Sociale.

Résumé

L’AUGMENTATION DE LA PRODUCTIVITÉ cannière continue d’être l’un des plus grands défis de l’industrie sucrière avec, comme toile de fond, la stagnation des rendements. L’accroissement de la production de canne devra provenir en grande partie d’une augmentation de la productivité alors que l'extension des zones actuelles et ou l'identification de nouvelles régions appropriées à la production cannière ne représentent plus une option attrayante. Contrairement au secteur de la
betterave, en particulier dans l'Union européenne et aux Etats-Unis où les taux de productivité de la betterave dans les exploitations agricoles sont en moyenne autour de 30% inférieurs à ceux obtenus dans les stations de recherche, la répartition probable des différences de rendement canne entre une ferme et une station de recherche, est nettement plus élevée. Cet article soutient que l'une des raisons convaincantes expliquant l'enorme différence de rendement dans le secteur de la canne est probablement à voir avec la sous valorisation de la contribution des nouvelles connaissances. Alors qu’aux Etats-Unis et dans l'UE, il existe des exemples de structures de collaboration efficaces entre les producteurs, les usines et les stations de recherche facilitant le transfert des connaissances, à l'exception de l'Australie et de l'Afrique du Sud, l'industrie de la canne est dépourvue de ces modèles de réussite. Dans les pays où les rendements de canne oscillent autour de 50–70 t / ha, les possibilités d'accroître sensiblement les rendements sont réelles, grâce au recours au concept de gains marginaux, à travers lequel chaque aspect de la chaîne de valeur de la production de canne à sucre est traitée au plus haut niveau possible.

CONOCIMIENTO, UN INSUMO POCO EXPLOTADO PARA NO SOLAMENTE AUMENTAR LA PRODUCTIVIDAD DE CAÑA

Por

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PALABRAS CLAVE: Conocimiento, Insumo, Productividad, Ganancias Marginales, Organización Social.

Resumen

AUMENTAR LA PRODUCTIVIDAD de la caña de azúcar en un contexto de estancamiento de la producción sigue siendo uno de los mayores desafíos en la industria azucarera. Un incremento en la producción de caña, en gran medida, tendrá que provenir de un aumento de la productividad ya que una expansión de zonas actuales o identificar nuevas áreas productoras de caña es cada vez la opción menor. A diferencia del sector productivo de la remolacha azucarera, particularmente en la Unión Europea y Estados Unidos, donde las tasas de productividad de remolacha en granjas son en promedio alrededor 30% menos que los obtenidos en las estaciones de investigación, la diferencia probable entre el rendimiento de la caña en una granja comparada con la estación de investigación es marcadamente mayor. Este artículo argumenta que una de las razones que explica la enorme diferencia en los rendimientos en el sector de la caña está probablemente relacionada por un bajo uso del conocimiento como insumo. Mientras que en los Estados Unidos y la UE hay ejemplos de estructuras eficaces de colaboración entre agricultores, fábricas y centros de investigación, para facilitar la transferencia de conocimiento, con la excepción de Australia y Sudáfrica, la industria de la caña es carente de esos modelos exitosos. En países donde los promedios de producción de caña están alrededor de 50–70 t/ha, hay verdaderas oportunidades para incrementar significativamente los rendimientos a través de emplear el concepto de ganancias marginales, donde cada aspecto de la cadena de valor en la producción de caña se trata al más alto nivel.
CONHECIMENTO, UM INSUMO POUCO EXPLORADO PARA AUMENTAR MAIS DO QUE A PRODUTIVIDADE DE CANA

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PALAVRAS-CHAVE: Conhecimento, Insumos, Produtividade, Ganhos Marginais, Organização Social.

Resumo

AUMENTAR A PRODUTIVIDADE de cana continua sendo um dos maiores desafios na indústria em relação à estagnação das produtividades. A expansão da produção de cana terá que se originar de uma maior produtividade, uma vez que as áreas atuais em expansão ou a identificação de novas áreas adequadas à produção estão se tornando opções cada vez mais raras. Diferentemente do setor de açúcar de beterraba, especialmente na EU e nos EUA, onde a produtividade da beterraba nas propriedades é cerca de 30% menor do que aquelas obtidas nos centros de pesquisa, a divisão provável entre as diferentes produtividades de cana na propriedade e no centro de pesquisa é cada vez maior. Este trabalho argumenta que uma das razões mais convincentes que explica a grande diferença em produtividades no setor canavieiro é provavelmente a pouca exploração do conhecimento como insumo. Embora nos EUA e na UE existam exemplos de estruturas eficazes de colaboração entre os produtores, as indústrias e os centros de pesquisa para facilitar a transferência de conhecimento, com exceção da Austrália e da África do Sul, a indústria canavieira carece desses modelos bem sucedidos. Nos países em que a produtividade de cana gira em torno de 50–70 t/ha, existem oportunidades reais para aumentar as produtividades de maneira significativa pelo emprego de ganhos marginais conceituais, pelos quais cada aspecto da cadeia de valor da produção de cana é tratado da forma mais adequada possível.
CHALLENGES OF SHIFTING REVENUE SOURCES:
A CASE STUDY OF U.S. LAND-GRAIN UNIVERSITIES

By

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KEYWORDS: University, Agricultural Research,
Funding, Competitive Grants.

Abstract

THE US LAND GRANT University System was founded by the Morrill Act in 1862, and
established state universities devoted to improving agricultural research productivity in
each state. In the 150 years following the Morrill Act, US agricultural productivity gains
have been extremely strong. Numerous economic studies indicate a $10 social rate of
return for every dollar spent on agricultural research. However, despite these successes,
there have been recent funding shifts for US universities that have resulted in declining
state and federal formula fund support and increased reliance on private gifts and
competitive grants. For example, while state funds still provide the majority of support
for Land Grant universities, they were lower in real terms in 2005 than they were in
1980. Reasons for these funding shifts have included an increased emphasis on private-
good research, diversion of federal resources to military goals following 9-11, and the
world economic recession of 2008. University scientists have responded by greatly
increasing their competitive grant funding, and universities have increased expenditures
on research much faster than instruction. This has led to concern that an increased focus
on competitive grants may result in a shift towards basic research on national
agricultural goals, which may compromise the land grant mission to assist local
agricultural communities in each state. In turn, this may lead to further decline in state
funding if legislatures perceive their constituents’ needs are not being met. However,
universities are likely to continue to need to seek alternative revenue streams such as
intellectual properties and royalties. The challenge for universities in these difficult
economic times is to keep increasing their gift and grant funding while continuing to
address key problems of their core constituencies. Establishing linkages between local
and national agricultural priorities would be a helpful strategy for obtaining competitive
grant funding that addresses local problems.

History of US Land Grant University System and gains in agricultural productivity

2012 marked the 150th anniversary of the ‘Land Grant’ university system in the US. The
founding fathers of the US were cognizant of the net social benefits of education (Epplin, 2012). For example, John Adams stated in 1785 that ‘the whole people must take upon themselves the education of the whole people and be willing to bear the expenses of it’. However, through the 1850s, university education in the US was restricted primarily to the privileged classes studying liberal arts or theology in Ivy League institutions.

After decades of debate on how to improve the ‘grinding poverty and toil’ of the masses, in 1862 the Morrill Act was passed establishing ‘Land Grants’ of federal lands to each state to establish publicly funded agricultural universities. The date is noteworthy as the legislation was signed by President Abraham Lincoln during the US Civil War. There were multiple goals of this historic legislation. The Morrill Act opened up university education to a much broader spectrum of
economic classes. In addition, by granting land for agricultural experiment stations in each state, the act provided the basis for improved agricultural productivity throughout the US.

The Morrill Act was followed by the 1887 Hatch Act and the 1914 Smith-Lever Act which helped provide sustainable funding for the land-grant system, and set up a ‘State Agricultural Experiment Station’ (SAES) system with research stations located in each state to address local grower needs. Thus, in the US, university involvement in agricultural research has had a strong history of performing local, applied research specific to state needs.

The land grant system has contributed to very strong growth in US agricultural productivity. Productivity gains resulting from investments in US agricultural research have been summarised by Fuglie and Heisey (2007).

Total public (Federal and State Governments) and private funding for US agricultural research and development increased from 5 to 11 billion dollars from 1971 to 2006 (Figure 1), with the private sector accounting for most of the growth, although its investment has been more volatile.

![Trends in public vs. private funding for US agricultural research from 1970 to 2007 (Source: Fuglie and Heisey, 2007).](image)

Fuglie and Heisey (2007) examined US agricultural inputs, outputs and total factor productivity from 1948 to 2004, and found that output was 2.66 times higher in 2004 than it was in 1948, while actual aggregate input use declined. While inputs such as machinery and fertiliser increased, this was offset with declines in land and labour use. Social rates of return to investments in agriculture were found to be 45% (median of 35 studies), indicating that, for every $1 spent on agriculture, $10 was returned to the economy.

There are many factors that have contributed to Land Grant university success in raising US agricultural system productivity (Huffman and Just, 1994), including:

1) Area-specific needs can be met efficiently with local state scientists,
2) SAES researchers are close enough to local problems that their research can address them,
3) SAES research is occurring in a larger scientific community where advances in scientific knowledge are occurring regularly and
4) SAES university training of new scientists and graduate students as complementary activities also facilitates scientific exchange and trains new agricultural leaders.
There is additional global evidence of the excellent returns to agricultural R&D spending. Global public spending on agricultural R&D totalled $31.7 billion dollars in 2008 (Beintema et al., 2012). China, India and Brazil were the top-ranked countries for public agriculture R&D spending in the developing world, accounting for one quarter of global spending.

China and India were also noteworthy for accounting for half of the global increase of $5.6 billion during 2000–2008. Agricultural R&D investments in China and Brazil have led to 136 and 176% productivity growth from 1970–2009, respectively.

Beintema et al. (2012) also note that, in contrast to developing countries, agricultural R&D spending in high-income countries has decelerated from 2% annual growth in the 1980s, to 1.1% in 2000, to near 0 from 2005 to 2008. This funding deceleration has led to significant consequences for university systems.

Shifting revenue sources and resultant challenges for the US Land Grant University System

While the returns on investment to university agricultural research have been high, universities are facing challenges due to state and federal funding constraints, and are under increasing pressure to seek innovative funding sources.

The US State Agricultural Experiment Station (SAES) system was established to perform research in response to local needs. Federal and State funding for the SAES system is apportioned via Hatch Act ‘formula funding’ which includes proportions for agricultural marketing (20%), regional research (25%), and State shares of US rural population and farm population (52%) (Huffman and Evenson, 2006).

Figure 2 shows the trend in SAES funding from 1980 to 2003. While state funding still provides the majority of revenue, there have been declining trends in state and federal formula funds, and increasing trends in contracts and grants.

![Figure 2—Trends in US state university agricultural experiment station revenue from 1980 to 2003 (Source: Huffman and Evenson, 2006).](image-url)
Schimmelpfennig and Heisey (2009) reported that US state legislature support to SAES agricultural research declined by 16% from 2000 to 2005 and was lower in real terms in 2005 than it was in 1980. The SAES have offset declines in state legislative funding by increases in industry agreements, sales and non-federal sources (70%) and non-USDA federal funds (more than tripled).

Just and Huffman (2009) summarised the reasons for these funding shifts for universities. These include events such as increased incentives for private goods research (e.g. the Bayh-Dole Act of 1980 discussed below), increased out-of-state research partnerships, reduction of incentives for instruction, diverted federal funding priorities to the war on terrorism following 9-11, and the financial crisis of 2008, which have all contributed to declining state and federal support and to universities increasingly seeking contracts and gift funding sources.

In addition, tuition at public universities has been raised substantially in recent years. Just and Huffman (2009) concluded that a trend of privatisation of public universities may lead to higher tuition fees, and reduction in instruction and public-goods research.

There has long been a debate on the emphasis on geographic-specific applied research versus basic biological research, and on formula versus competitive grant funding in the US Land Grant system.

As state and formula funds have fallen (Figure 2), universities have emphasised competitive grant funding and university scientists have been increasingly successful in obtaining grants and other entrepreneurial income streams such as royalties.

Huffman and Evenson (2006) summarised some of the concerns regarding this shift in funding emphasis.

1) Formula funds can provide steady funding for long-term research such as plant breeding, whereas extramural funding has higher uncertainties and shorter time-frames.

2) Formula funds carry minimal overhead or indirect costs (IDC), allowing the funding to go directly for scientific research. In contrast, grant funding can carry IDC rates greater than 50% on some federal grants. This IDC is now ‘the cost of doing business’ with universities.

3) Competitive grant funding tends to favour universities that have the research infrastructure and geographic locations to perform research that is national in scope. Proposals of concern to a single state or lower-acreage crops are underfunded, even if they are critical for that region.

4) Competitive grant programs shift SAES scientist priorities to national agricultural priorities. Since preliminary data for grants is funded by the states (not the grants), this results in a leveraging of state funds for national agricultural priorities, funding that could be used on critical state needs.

A counterargument against formula funding has been that there may be limited accountability for the funds, and that the scientific projects performed with formula funds are not peer-reviewed and thus the research methods may not be of sufficient rigour.

However, university scientists are subjected to annual evaluations and must publish in peer-reviewed journals for promotion and tenure, which does serve as a de facto peer review of their research program.

As universities have looked for new income streams, they have aggressively pursued the patenting of discoveries. The Bayh-Dole Act of 1980 allowed universities to claim intellectual property from work performed on federal grants.

US university patents jumped from <400 per year in the late 1970s to >3000 per year in the 1990s (Just and Huffman, 2009). While land-grant university scientists have partnered with local businesses for over a century, there are new partnerships increasingly working with out-of-state private firms to provide R&D leading to a competitive advantage for those firms.
Huffman and Evenson (2006) found that Hatch formula funding had a greater impact on state agricultural productivity than competitive grant funding. They concluded that a danger in increasing focus on national competitive grants by SAES is further weakening of state funding if state legislators perceive universities are not responding to local needs.

This effect would likely vary by region, as SAES universities differ in the proportion of funds they receive from formula funds, grants and contracts (Table 1).

<table>
<thead>
<tr>
<th>State</th>
<th>Percentage of funds</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Competitive grants</td>
<td>Formula funds</td>
</tr>
<tr>
<td>Florida</td>
<td>19.1</td>
<td>39.6</td>
</tr>
<tr>
<td>Louisiana</td>
<td>7.2</td>
<td>69.4</td>
</tr>
<tr>
<td>Texas</td>
<td>15.4</td>
<td>45.7</td>
</tr>
<tr>
<td>Hawaii</td>
<td>10.5</td>
<td>28.7</td>
</tr>
<tr>
<td>Range all 50 states</td>
<td>0–38.9</td>
<td>23.1–91.2</td>
</tr>
</tbody>
</table>

For example, in 2000 the sugarcane-producing states of Florida, Louisiana, Hawaii and Texas had competitive grant and formula fund revenues ranging from 7–19, and 28–69%, respectively (Rubenstein et al., 2000).

Huffman et al. (2006) postulated that, in general, states with a large research infrastructure such as New York, Florida, Michigan, Wisconsin and California would benefit, and states such as New Hampshire, New Jersey, West Virginia, South Dakota, Alaska and Hawaii would suffer from an increase in competitive grant funding.

An additional challenge is the importance of agricultural maintenance research to prevent agricultural productivity declines.

Examples of maintenance research (as opposed to productivity-enhancing research) include evolving pest and disease complexes, climate change and other environmental factors, weeds and invasive species, and changes in nutrient requirements.

Sparger et al. (2013) found that 40% of US agricultural research is devoted to maintenance, and postulated that increased reliance on non-state funding sources may skew resources away from maintenance research.

While this paper has focused on US land grant universities, revenue and expenditure trends have been similar across other university types. Just and Huffman (2009) examined the shift in both revenue sources and expenditures in three categories of universities: private (e.g. Harvard, Yale), Public Land-Grant (e.g. Michigan State University, University of Florida) and Other Public (e.g. University of Michigan, Florida State University).

In all three institution types, expenditures on research increased at a much greater rate than those for instruction (Figure 3). Similarly, all university types experienced a relative decline in state support, and a large increase in private gifts, grants and contracts (Figure 4).

**Conclusions**

Revenue sources are shifting for universities, and university scientists are likely to continue to need to be entrepreneurial to generate funding for their programs. A key challenge for land grant universities will be to continue to generate increased contract and gift funding while still addressing key problems of their core constituencies.
It would be helpful to establish linkages between local and national agricultural priorities to obtain competitive grant funding that addresses local problems. For example, linking local environmental shifts to climate change, or new pest and disease pressures to invasive species issues, puts local problems in a broader context.

For sugarcane researchers, there have been expanded grant opportunities for biofuels research, but these opportunities will lead to greater impact if the research can be linked back to improving their core sugarcane programs.

Land Grant and other universities will continue to have to negotiate a delicate balancing act between funding needs and constituent concerns to negotiate a changing resource landscape.
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LES ENJEUX DU CHANGEMENT DE FINANCEMENT: UNE ÉTUDE DE CAS DES CONCESSIONS DE TERRES AUX UNIVERSITÉS AMÉRICAINES

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MOTS-CLÉS: Université, Recherche Agricole, Financement, Subventions par Mise en Concurrence.

Résumé
Le système de concessions de terre aux universités américaines a été créé par la Loi Morrill en 1862, et établit les universités publiques consacrées à l'amélioration de la productivité de la recherche agricole dans chaque État. Au cours des 150 années qui ont suivi la Loi Morrill, les gains de productivité agricole des États-Unis ont été extrêmement élevés. De nombreuses études économiques indiquent un taux social de rendement de 10 $ pour chaque dollar dépensé pour la recherche agricole. Cependant, malgré ces réussites, il ya eu récemment des changements de financement pour les universités américaines qui ont abouti à une réduction de l’appui financier tant au niveau de l’État que du gouvernement fédéral, et le recours accru aux dons privés et aux subventions par mise en concurrence. Par exemple, bien que les fonds de l'Etat servent à subvenir à la majeure partie du financement des universités bénéficiant de concessions de terre, ils sont plus faibles en termes réels en 2005 qu'ils ne l'étaient en 1980. Les raisons de ces changements de
financement incluent l’emphase accrue sur la recherche des biens privés, le détournement des ressources fédérales à des fins militaires suite aux évènements du 11 septembre, et la récession économique mondiale de 2008. Des chercheurs universitaires ont réagi en augmentant considérablement leur financement à travers les subventions par mise en concurrence, et les universités ont augmenté les dépenses pour la recherche beaucoup plus rapidement que pour l’enseignement. Ceci a amené à craindre qu’une emphase accrue sur les subventions par mise en concurrence ne se traduise par un changement vers la recherche fondamentale sur les objectifs agricoles nationaux, ce qui pourrait compromettre l’objectif des dons de terrains pour aider les communautés agricoles locales dans chaque État. En retour, cela peut conduire à un nouveau déclin du financement de l'État si les législateurs perçoivent que les besoins de leurs électeurs ne sont pas satisfaits. Cependant, les universités auront probablement à persévérer dans la recherche des sources alternatives de revenus, telles la propriété intellectuelle et les redevances. Le défi pour les universités en ces temps économiques difficiles est de poursuivre l’augmentation de leur financement à travers les dons et les subventions tout en continuant à traiter les problèmes clés de leurs circonscriptions de base. L’établissement des liens entre les priorités agricoles locales et nationales serait une stratégie utile pour obtenir un financement de subvention par voie de concours afin de traiter des problèmes locaux.

DESAFÍOS DEL CAMBIO DE FUENTES DE INGRESOS: UN ESTUDIO DE CASO DE LAS UNIVERSIDADES ESTATALES/FEDERALES DE LOS ESTADOS UNIDOS

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PALABRAS CLAVE: Universidad, Investigación Agrícola, Financiamiento, Proyectos Competitivos.

Resumen

EL SISTEMA UNIVERSITARIO estatal de los Estados Unidos fue fundado por la Ley Morrill en 1862 para establecer universidades dedicadas a mejorar la productividad a través de la investigación agrícola en cada estado. En los 150 años siguientes a la Ley Morrill, los incrementos de la productividad agrícola de Estados Unidos han sido extremadamente altos. Numerosos estudios económicos indican una tasa social de $10 de retorno por cada dólar gastado en investigación agrícola. Sin embargo, a pesar de estos éxitos, ha habido cambios recientes que han resultado en una reducción de los fondos estatales y federales para las universidades, que han resultado en una creciente dependencia por donaciones privados o búsqueda de fondos competitivos. Por ejemplo, mientras que los fondos estatales todavía proporcionan la mayor parte de apoyo a las universidades estatales, en términos reales son más bajas en 2005 comparados a los de 1980. Las razones para estos cambios de financiación han sido el mayor énfasis de la investigación en bienes privados, desvío de recursos federales a objetivos militares luego del 9-11 y la recesión económica mundial de 2008. Los científicos de las universidades han respondido incrementando considerablemente la búsqueda de fondos competitivos, llevando a que las universidades incrementen gastos en investigación más que educación. Esto causa una preocupación en el sentido de una mayor atención a los fondos concursables, que puede resultar en un cambio hacia la investigación básica y no a
objetivos para mejorar la producción agrícola nacional; que a su vez, puedan comprometer la misión de las universidades estatales que es ayudar a las comunidades agrícolas locales en los estados. A su vez, esto puede llevar a una mayor reducción de fondos estatales si los legisladores perciben que no se satisfacen las necesidades de sus electores. Sin embargo, las universidades seguramente seguirán buscando ingresos alternativos tales como pagos por propiedad intelectual y derechos de autor. El desafío para las universidades en estos tiempos difíciles de la economía es seguir buscando donaciones y el financiamiento estatal sin dejar de enfrentar los problemas fundamentales de su núcleo constituyente. Estableciendo vínculos entre las prioridades agrícolas locales y nacionales sería una estrategia útil para la obtención de fondos competitivos que enfrenten los problemas locales.

DESAFIOS DA MUDANÇA DE FONTES DE RECEITA: UM ESTUDO DE CASO DAS UNIVERSIDADES LAND-GRANT NORTE-AMERICANAS

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PALAVRAS-CHAVE: Universidade, Pesquisa Agrícola, Financiamento, Subsídios Concorrenciais.

Resumo
O SISTEMA NORTE-AMERICANO conhecido como Land-Grant Universities foi fundado pela lei Morrill em 1862, e estabeleceu universidades estaduais dedicadas a aprimorar a produtividade de pesquisas agronômicas em cada estado. Nos 150 anos subsequentes à Lei Morrill, os ganhos de produtividade têm sido muito significativos. Vários estudos econômicos indicam que cada dólar gasto em pesquisas agronômicas, dez dólares são ganhos. Entretanto, apesar do sucesso, algumas mudanças recentes no financiamento desses programas nas universidades norte-americanas têm provocado um declínio do financiamento estadual e federal e uma maior dependência de doações e concessões privadas. Por exemplo, embora o financiamento estadual ainda seja responsável pela maior parte das verbas para as universidades que participam do programa, elas sofreram uma diminuição real em 2005 em relação a 1980. As razões dessas mudanças incluem maior ênfase em pesquisas de bens privados, transferência de recursos para fins militares após os ataques terroristas de 11 de setembro e a recessão mundial econômica de 2008. Cientistas universitários responderam a essa situação aumentando as concessões de subsídios concorrenciais e aumentando os gastos em pesquisas muito mais rapidamente do que os gastos em ensino. Tal fato suscita a preocupação de que um maior enfoque em subsídios concorrenciais pode resultar em uma mudança em direção à pesquisa básica sobre as metas agrícolas nacionais, que podem comprometer a missão dos subsídios de auxiliar comunidades agrícolas locais em cada estado. Por outro lado, essa situação pode levar a um maior declínio no financiamento estadual se o poder legislativo perceber que as necessidades de seus constituintes não estão sendo atendidas. Contudo, as universidades provavelmente continuarão a buscar fontes de renda alternativas, como propriedades intelectuais e royalties. O desafio para as universidades nesses tempos econômicos difíceis é manter os financiamentos e continuar a tratar de problemas essenciais de seus estados. Uma estratégia útil seria estabelecer ligações entre as prioridades agrícolas locais e nacionais a fim de obter subsídios concorrenciais que tratem de problemas locais.
SUGARCANE RESEARCH AND DEVELOPMENT: A VIEW FROM THE PRIVATE SECTOR

By

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KEYWORDS: R&D Management, Private Sector, Plant Variety Rights.

Abstract

THE SUGARCANE MARKET in Brazil has developed to a reasonable size, permitting the appearance of competitive R&D companies. Recently, several multinational plant-breeding companies have established sugarcane-breeding programs in Brazil and are presently competing with the three well-established R&D companies and institutions. Strong Plant Variety Protection Laws in the country will permit these companies to secure their intellectual property rights and develop adequate value-capture models for their businesses. It seems clear that traditional public institutions or industry-funded not-for-profit research organisations will not have adequate value-capture mechanisms to raise sufficient revenue to re-invest in their research programs and remain competitive in the market. Yield gains observed for sugarcane during the past 50 years have been significantly less than those observed for crops such as maize, soybean, sugar beet and rapeseed/canola, where a more competitive variety R&D environment exists. It is expected that a more competitive environment with sugarcane will lead to greater yield gains.

Sugarcane R&D history

Sugarcane, a semi-perennial grass species, is cultivated on 25.4 million hectares in 100 countries for a total production of 1.8 billion tonnes of cane harvested in 2011 (data: FAOSTAT). This harvested area places sugarcane in 12th place among 161 crops harvested in 2011 included in the FAOSTAT database that recognises 1.3 billion hectares harvested with these 161 crops in 2011 (Figure 1).

![Fig. 1—World area (million hectares) occupied by selected crops in 2011 (faostat.fao.org).](image)
Sugarcane has widely been used for the production of sugar and, more recently, for the production of biofuels; either in first-generation processes by fermentation of the sugars contained in the juice, or second-generation processes by means of hydrolysing cellulose and hemi-cellulose contained in the sugarcane fibres (bagasse) or the leaf matter.

Sugarcane, as most other major crops, has a long history of research and development aimed at increasing yields and establishing efficient, profitable and sustainable agricultural practices.

Modern sugarcane research and development was initiated in the late 1800s, when it was discovered that sugarcane produced viable seeds, thus permitting genetic improvement through crossing of elite germplasm and selection of seedlings for local adaptation and disease resistance.

Breeding efforts were initiated to deal with diseases such as sereh and mosaic diseases, and research and development efforts evolved to include other fields of agronomy such as soils, fertilisers, weed science, irrigation among others.

Prominent research centres were established in Australia, Barbados, Indonesia (then Java), and USA (Hawaii) at the end of the 19th century.

Other research centres were established as the sugarcane industry became increasingly important to the economies of tropical countries throughout South America and the Caribbean, Africa and Asia. In general, these research centres were established as government institutions or not-for-profit sugarcane industry associations.

Governments in some cases established a levy on the cane harvested or exported product (sugar) and used these resources to, among other, support research in their research institutions.

Most sugarcane R&D institutions have relied on international collaboration to initiate or enhance their programs, especially with regard to the establishment of germplasm collections, essential for establishing successful breeding programs.

Co varieties from Coimbatore, India, POJ varieties from Java, CP varieties from Canal Point, USA, H varieties from Hawaii, USA and B varieties from Barbados can be found in the pedigrees of commercial varieties used in most sugarcane industries throughout the world.

Collaboration has been fostered by the International Society of Sugar Cane Technologists that has organised 27 international congresses and numerous workshops since its inception in 1924. Additionally, ISSCT maintains, with the support of the United States Department of Agriculture (USDA), an International Sugarcane Germplasm collection with free access to all interested parties.

Despite international collaboration, sugarcane R&D, especially with regard to variety development, remains a local effort.

Commercial sugarcane varieties used by the industry in one country are, in most cases, developed locally. This was not the case in the earlier stages of the industry’s history when varieties such as the Java ‘super cane’ POJ2878 or the Indian varieties Co213 and Co419 were widely used in practically all sugarcane industries of the world.

With the establishment of local sugarcane R&D efforts, and using a common germplasm base, locally bred varieties quickly replaced imported varieties. Due to its local nature, sugarcane variety development is not seen as a competitive activity.

Within a single country, sugarcane R&D is rarely viewed as a competitive activity, since it is uncommon to have more than one variety development institution within a single country.

**Sugarcane R&D challenges**

It is generally recognised that resources for sugarcane R&D are scarce and that the investors expect a return for their investment in the form of productivity and profitability gains that arise from the adoption of new technologies.

In the case of public institutions or industry-maintained not-for-profit research centres, resources applied in research tend to be seen as a cost and not an investment.
Figure 2 shows the increase of average world yields for five major crops relative to a base of 100% in 1961. In the 51-year period (1961–2011), average world yield of sugarcane increased to 140%. This represents an annual increase of 0.6%.

Soybeans with a 2142% (1.6% per annum) relative yield increase, sugar beet with a 232% (1.7% per annum) relative yield increase, maize with a 267% (1.9% per annum) increase and rapeseed/canola with a 324% (2.3% per annum) relative yield increase show substantially greater gains than those achieved with sugarcane.

It is difficult to justify investment in R&D when the returns, in terms of yield increase, average only 0.6% per year.

Comparisons of yield increases in sugarcane yields in different countries (Figure 3) show that two countries (Colombia and Thailand) stand out with 262% and 240% relative increases, respectively. Brazil, India and Australia exhibit relative increases of 176%, 152% and 131%, respectively.

Two other countries, South Africa and USA, show stagnant yields, with a decreasing trend over the past 50 years. It can be argued that the higher relative gains for Colombia and Thailand are due to the low initial values as the modern sugarcane industry only developed in these two countries in the past 30 years. In these, it would seem that investment in sugarcane R&D has delivered significant returns.

Australia, India and Brazil, however, are countries where the sugarcane industry and R&D institutions have been established for quite some time. The annual increase in these three countries, which varies from 0.5% per annum to 1.1% per annum, is not very satisfying, especially when compared to the gains observed in other crops during the same period.

The innovation models adopted by these countries should be reviewed with the objective to increase gains from R&D expenditure.

What are the challenges in developing a new R&D management model for sugarcane? Present systems of sugarcane R&D present a challenge for innovation.

Available models provide little or no incentive for innovation. Innovation is expected to generate benefits, in the case of sugarcane, to add value to the crop.
Fig. 3—Relative mean yield increase observed for sugarcane in selected countries (average yields for 1961= 100%) (faostat.fao.org).

A fraction of this benefit should be re-directed to the innovators as a stimulus to generate additional innovations, thus adding more value to the crop. When public institutions or industry-supported not-for-profit institutions lead innovation, the benefits generated by the innovation are captured almost entirely by the growers or the industry.

While it is necessary for the final customers (growers) to capture a significant portion of the added value generated by the innovation, it is also essential for the innovators to be compensated in order to pay for the investments needed to generate innovation and to provide incentive for future innovation.

In order to develop a more dynamic R&D model, one must create a competitive market. Seed companies for row crops, especially for maize and soybean, have competed in the market and, as a result, have delivered better varieties to the farmers on a continual basis.

The seed industry needs a market of sufficient size to justify large investment in R&D. Worldwide, maize occupies 170 million hectares and soybean more than 100 million hectares. This large world market permits the seed industry to capture value of their innovation over a large base. This is not the case with sugarcane.

Sugarcane occupies 25 million hectares worldwide, 60% of which is concentrated in two countries: Brazil and India (Figure 4). With the worldwide interest in sugarcane as an energy crop, there is expectation that the area of sugarcane will increase. This may make for a larger and more attractive market for private, for-profit R&D companies.

In addition to a relatively large market, R&D companies look for environments that respect intellectual property rights. Usually, successful value-capture mechanisms rely on royalties on intellectual property and that is the case with the successfully competing seed companies.

Plant Variety Protection Laws, commonly referred to as PVP, are laws that recognise plant breeding as an inventive process and, therefore, grant the inventors (plant breeders) the right to a limited monopoly to commercialise their invention (a new variety).

The UPOV system of variety protection is an internationally accepted system of PVP recognised by 71 countries. The system provides an incentive for plant breeders to develop new improved varieties of benefit for farmers.
Where there is an effective PVP system, the development of new varieties will be encouraged where there is commercial viability. A PVP system, however, should not be expected to encourage the development of new varieties where a favourable commercial market potential does not exist. If plant breeding is a necessity where there is no commercial market, this effort will have to be supported by the public sector.

In Brazil, we believe that favourable market conditions exist for the development of private commercial R&D programs for sugarcane. Presently, the area of sugarcane approaches 10 million hectares and is expected to double during the next decade, due to the increasing importance of ethanol in the Brazilian biofuels market.

With regard to plant variety protection, of the top 10 sugarcane growing countries, four countries have ratified the UPOV treaty: Brazil, China, Mexico and the USA. Additionally, the Brazilian PVP law has specific clauses that deal with sugarcane, which are favourable for the plant breeders.

With the increasing world interest in biomass and biofuels and the favourable market environment in Brazil, multinational breeding companies have shown interest in the crop in the country.

In 2008, Monsanto acquired Canavialis, a private Brazilian sugarcane-breeding program. In 2009, Syngenta announced the establishment of a sugarcane-breeding program in Brazil as well as a novel sugarcane-planting system dubbed PLENE.

Additionally in 2009, DuPont and the Australian BSES Limited announced a research and development alliance to improve productivity and the use of sugarcane varieties. The announcement of the BSES-DuPont alliance made clear the international trend in sugarcane research and development and the importance of the Brazilian sugarcane market.

Other multinational seed companies, such as BASF Plant Science and Bayer Crop Science, have announced projects to collaboratively develop sugarcane varieties in Brazil incorporating their proprietary GM traits in Brazilian sugarcane germplasm.

Additional to the multinational plant-breeding companies mentioned above, Brazil has three other traditional sugarcane R&D institutions developing sugarcane varieties. The CTC Centro de Tecnologia Canavieira was established as the Copersucar Technology Center in 1970. It has recently been restructured as a private for-profit company. It is responsible for developing the SP and CTC varieties that presently represent almost 50% of the market share of the sugarcane area.
The RIDESA program, a publicly funded sugarcane breeding program managed by a network of public universities, is responsible for developing the RB varieties that presently occupy 50% of the sugarcane area.

A third institution is the IAC. This is the most traditional of the three and is responsible for the development of the IAC varieties that occupied significant market share in the 1960s and 1970s, lost market share to the SP and RB varieties in the following decades, and has recently released some promising varieties that have yet to occupy significant market share.

It seems clear that the three traditional breeding programs will be challenged by the multinational entrants in the market and must change their business models if they intend to survive in the more competitive environment.

At present, they may have a competitive advantage with better-adapted germplasm, but this difference will most certainly be bridged once more efficient breeding strategies using molecular marker assisted selection or transgenic sugarcane varieties are fully deployed by the more technologically capable competitors.

In order to excel in the increasingly competitive environment, companies and institutions must adapt their business plans to capture more value from the benefits that they deliver to the growers in order to re-invest in technology and stand out among the competitors.

The ultimate beneficiaries will be the cane growers, who can expect the development of better varieties from various competitors catering to their needs.

RECHERCHE ET DÉVELOPPEMENT DE LA CANNE À SUCRE:
POINT DE VUE DU SECTEUR PRIVÉ

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Résumé
Le marché de la canne à sucre au Brésil ayant atteint à une taille raisonnable, a permis l'apparition d'entreprises concurrentielles en matière de Recherche et de Développement. Récemment, plusieurs entreprises multinationales engagées dans l'amélioration génétique ont établi des programmes d’amélioration de la canne à sucre au Brésil et sont actuellement en compétition avec les trois sociétés et institutions bien établies de R & D. Des lois strictes sur la protection des obtentions variétales dans le pays permettront à ces entreprises de protéger leurs droits de propriété intellectuelle et de développer des modèles adéquats à valeur captive pour leurs entreprises. Il semble clair que les institutions publiques traditionnelles ou des organismes de recherche à but non lucratif financés par l'industrie n'auront pas de mécanismes à valeur captive adéquats pour générer des recettes suffisantes pour réinvestir dans leurs programmes de recherche et rester compétitifs sur le marché. L'augmentation des gains pour la canne à sucre au cours des 50 dernières années a été nettement inférieure à celles observées pour les cultures telles le maïs, le soja, la betterave et le colza / canola, où un environnement plus compétitif de R & D existe. Il est anticipé qu'un environnement plus compétitif pour la canne à sucre conduira à de plus grands gains en rendement.
INVESTIGACIÓN Y DESARROLLO DE LA CAÑA DE AZÚCAR:
UNA VISIÓN DESDE EL SECTOR PRIVADO

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PALABRAS CLAVE: Manejo de la I&D, Sector Privado, Derechos del Obtentor de Variedades.

Resumen
EL MERCADO DE LA CAÑA DE AZÚCAR EN Brasil se ha desarrollado hasta un tamaño razonable, permitiendo el establecimiento de empresas de I &D competitivas. Recientemente, varias compañías multinacionales han establecido programas de mejoramiento genético de caña de azúcar en Brasil, las que actualmente están compitiendo con las tres empresas e instituciones bien establecidas de I&D locales. Por lo tanto, el establecimiento de Leyes adecuadas de Protección de Variedades en Brasil, permitirá a estas empresas asegurar sus derechos de propiedad intelectual y desarrollar modelos para una adecuada captura del valor de sus negocios. Está claro que las instituciones tradicionales públicas, así como las organizaciones de investigación sin fines de lucro que son financiadas por la industria no tendrán mecanismos de captura de un valor adecuado para aumentar los ingresos suficientes y reinvertir en sus programas de investigación para seguir siendo competitivos en el mercado. Las ganancias en producción por hectárea observados en caña de azúcar durante los últimos 50 años, han sido significativamente menores que los observados para cultivos como maíz, soja, remolacha azucarera y colza/canola, donde existen ambientes más competitivos de I&D. Se espera que un ambiente más competitivo de I&D en caña de azúcar llevará a mejores rendimientos de la producción.

PESQUISA E DESENVOLVIMENTO DE CANA-DE-AÇÚCAR:
UMA VISÃO DO SETOR PRIVADO

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Resumo
O MERCADO DA CANA-DE-AÇÚCAR no Brasil alcançou um tamanho considerável, permitindo o aparecimento de empresas competitivas de pesquisas e desenvolvimento. Recentemente, várias empresas multinacionais atuando em melhoramento de plantas estabeleceram programas de melhoramento de cana no Brasil e estão no presente concorrendo com três empresas e instituições conceituadas de pesquisa e desenvolvimento. Leis de Proteção a Variedades Fortes de Plantas no país permitirão que essas empresas garantam seus direitos de propriedade intelectual e desenvolvam modelos de captura de valor para seus negócios. Parece claro que instituições públicas tradicionais ou órgãos de pesquisa sem fins lucrativos não contarão com mecanismos suficientes de captura de valor para gerar receitas para reinvestir em programas de pesquisa e permanecer competitivos no mercado. Ganhos em produtividade observados para a cana durante os últimos 50 anos têm diminuido consideravelmente em relação àqueles destinados a culturas como milho, soja, beterraba e canola, que oferecem uma variedade mais competitiva de ambientes de pesquisa. Espera-se que um ambiente mais competitivo no setor da cana conduzirá a maiores ganhos de produtividade.
IPT BAGASSE GASIFICATION CONCEPTUAL ENGINEERING

By
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KEYWORDS: Bagasse, Gasification, Energy Efficiency.

Abstract
GIVEN THE GROWTH of sugarcane production in Brazil, gasification presents itself as an interesting destination for bagasse and straw. It allows for the production of syngas (H_2+CO_2) which can be turned into bio-diesel, monomers or other products for the chemical industry. IPT has been working on the conceptual design of a pilot plant that will test technological alternatives for pre-treatment and gasifier operation to allow the development of sufficient know-how to design an industrial plant. The total energy efficiency in the industrial plant was estimated at 55%, and the economic feasibility represented by the return on investment (ROI) should be around 25% if oil prices are close to US$81/barrel between 2020 and 2030. Key technical aspects include maintaining the slagging condition inside the gasifier, maximising pre-processing efficiency and achieving a low enough impurity content before entering the shift reactor. The present study describes the conceptual design of each step in the process for the pilot plant, energy efficiency and economic feasibility calculations.

Introduction
In 2010, the sugarcane industry in Brazil obtained 120 Mt of bagasse and straw as by-products from sugar and ethanol production. Given the growth of the automobile industry, a growth of ethanol from cane production is to be expected. The different estimates for total national production in the coming years can be seen in Figure 1.

![Fig. 1—Brazilian sugarcane production estimate [using data from EPE, 2012].](image-url)
An average-sized (4 million tonnes sugar cane/a) sugar/ethanol producer generates 800,000 tonnes of dry biomass per year. There are some well-established uses for it, but new more profitable and environmentally friendly alternatives deserve to be explored. Assuming only half of the bagasse is available for gasification, 400,000 tonnes per year still means a 200 kW plant, making industrial scale gasification possible.

Gasification produces syngas which can then be converted into energy, Fischer Tropsch biodiesel or monomers. It has higher energy efficiency when compared to other uses of bagasse and can produce important base chemicals.

Gasification is very sensible to raw materials, allowing for local development. The greatest challenge is to overcome the initial investment barrier, initially evaluated at US$3/W being required to reach US$1.2/W to make it commercially competitive.

Given this great potential, but a lack of immediate economic feasibility, IPT (São Paulo State Research Institute) is coordinating a project to build a 2.5 MW_th (megawatts of thermal energy) biomass gasification pilot plant in Piracicaba (SP).

The project’s goal is the development of know-how that may encourage investment in high-scale industrial plants for syngas generation through bagasse gasification. The expected use of such gas is the production of olefins, wax paraffin and others via processes like Fischer-Tropsch.

Our industrial partners are interested in developing the technologies for biofuels, biochemicals and electrical energy.

Two different types of gasifier technologies are usually considered for biomass (Basu, 2010): Entrained flow and fluidised bed.

Entrained flow consist of a vertically placed cylindrical reactor at the top of which fuel (bio-oil or bio-coal) and a gasifying agent (air or O_2) is inserted through a nozzle, usually in a swirling flow, forming a flame that carries either particles or droplets through the reactor as they undergo incomplete combustion, i.e. gasification. Residence times are small, temperature and pressure high (1500°C, 40 bar) ensuring low tar (gases released from the fuel have high viscosity when condensed) production. Operational difficulties may include flame blow-out and incomplete burn-out of particles.

Fluidised bed consists of a reactor filled with a fluidising agent (usually sand) that is fluidised (mixed and made apparently less dense by the passing of bubbles through it) with the insertion of a gas (H_2O or air). The fuel is fed at the bottom of the reactor and slowly makes its way to the top undergoing gasification as it comes in contact with the heated fluidising agent. Residence time is very long and temperatures are lower (600°C) ensuring complete particle burn-out and good efficiency (high CO/CO_2 ratio because complete combustion does not occur). Operational difficulties include high tar production, developing into plugging of the system.

It can be verified (Zhang, 2010) that entrained flow gasifiers have great scalability, making them an excellent option for lowering investment cost by using bagasse from several suppliers in a high-scale plant, as opposed to fluidised bed technology. For that reason, IPT has decided to focus on entrained flow gasification.

**Gasifier thermal power**

The gasifier was designed to operate at 2.5 MW_th. This capacity is considered suitable for a pilot plant. It allows for biomass to be supplied to the plant at a reasonable rate and allows for equipment to be large enough to allow for the analysis of effects that will be present in the industrial scale all the while being small enough to facilitate maintenance and installation. It also gives gasifier design a general direction to go, as its main dimensions are defined by this value.

**Operating pressure**

Considering that these processes require high-pressure (around 40 bar) syngas input, two possible solutions present themselves; either the gas is produced at low pressure (below 10 bar) and
compressed afterwards, or it is produced at high pressure. Should the latter be chosen, all reactants involved in the gasification reaction as well as the interior of the reactor must be at high pressure to ensure high-pressure syngas production.

In Table 1, an energy requirement comparison between the two possibilities can be seen, which shows that producing the gas at lower pressure for further compression is fourfold more energy demanding.

<table>
<thead>
<tr>
<th>Table 1—Comparison of energy requirement for compression, adapted from Higman, 2008.</th>
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<tbody>
<tr>
<td>Gasification pressure</td>
</tr>
<tr>
<td>Feed gas pumping</td>
</tr>
<tr>
<td>Oxygen compression</td>
</tr>
<tr>
<td>Syngas compression</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

It is considered that this difference in energy requirement outweighs the operational disadvantages of working at high pressure like feeding bio-coal into the gasifier at 40 bar; therefore, to become familiar with these difficulties and overcome them, we have decided to design the process with the gasifier and all following stages working at 40 bar pressure.

**Operating temperature**

Because the products of the gasification reaction are CO and H₂, the most interesting temperature for the gasifier would be 1300 °C for it is the one at which CO output is maximised with respect to CO₂ output, and the formation of tar is minimised when compared to lower temperatures like 1000 °C. However, to ensure ash slagging the temperature must be above the ash melting point inside the gasifier.

Early measurements show that most bagasse is delivered with reasonable (up to 3% weight) sand contamination. The sand may be acquired during storage, blown by the wind, or during harvesting, from the soil, in which case it likely stays attached to the fibres in spite of the fact that bagasse is washed during the milling stage. As such, we have chosen to raise the planned temperature inside the gasifier to 1500 °C to ensure ash slagging, and accept a small loss in efficiency.

However, the exact characteristics of the available bagasse with regards to calorific value and ash content cannot yet be determined, so the operating temperature is not set in stone like the operating pressure. Studies are being conducted with better sampling sizes as well as a great variety of suppliers to assess these values (CEC, 2009).

The possibility of avoiding sand contamination due to storage by having suppliers deliver bagasse extracted at the milling stage will be analysed. If it is effective, the temperature will be lowered to 1300 °C. On the other hand, should there still be a problem with ash melting even at 1500 °C, the addition of lime (CaO) to work as a flux is predicted as an alternative, as well as the eventual raising of the temperature to 1700 °C.

**Process description**

In the following, the four stages of syngas production from biomass, namely pre-treatment, gasification, shifting and gas cleaning are described. Process output and operating regime are described.

**Pre-treatment**

Pre-treatment consists of all stages prior to the gasifier itself, which are necessary to obtain the appropriate biomass fuel. In order to test the efficiency of different routes, the gasifier will be
alternately fed with fuel obtained from sugarcane bagasse in two forms: fast pyrolysis bio-oil or torrefaction bio-coal.

Bagasse is to be received with a high moisture content of around 50% in weight. Its feeding rate to the plant is determined to ensure that, after mass losses in pre-treatment, the fuel feeding rate into the gasifier will produce an operating power of 2.5 MW given each fuel’s higher heating value. This calculation is described in Equation 1.

$$M_{\text{dry bagasse}} = \frac{2.5 \text{ MW}}{\text{HHV}_\text{bio-fuel}} \cdot \frac{1}{\text{Efficiency}_{\text{pre-treatment}}}$$

(1)

Taking into account the information gathered with pre-treatment plant suppliers, a mass conversion efficiency of 70 and 80% was adopted for pyrolysis and torrefaction, respectively. This yields the following feeding rates:

- Moist bagasse for pyrolysis = 1130 kg/h
- Moist bagasse for torrefaction = 1110 kg/h

These values correspond to the gasification of bio-oil and bio-coal with high heating values of 23 and 20 kJ/kg, respectively. Due to variations in fuel characteristics, these values may go up or down by more than 30%.

The first stage of pre-treatment is drying to reduce the moisture to 10%. Afterward, for fast pyrolysis, bagasse must be sliced to particles under 6 mm to improve conversion to bio-oil in the pyrolysis reactor.

For torrefaction there is no such need. However, to ensure maximum carbon conversion in the gasifier, bio-coal obtained by torrefaction is ground to particles of, on average, 100 μm equivalent diameter.

Pyrolysis and torrefaction modules work independently of each other as well as of the gasifier. Both fuels will be stored in their final form until used when the gasifier is operating.

**Gasification**

Gasification is achieved by feeding the reactor with biofuel at a pressure of 40 bar as well as pure oxygen in sub-stoichiometric quantities to provoke incomplete combustion with formation of a product containing high molar fractions of CO and H₂ at a temperature of 1500°C, with possible variations to 1300°C and 1700°C.

The fuel mass flow into the gasifier depends on its high heating value, with the requirement of maintaining the operating power inside the gasifier at 2.5 MWth. The following mass flow rates were calculated:

- Bio-oil = 400 kg/h
- Bio-coal = 450 kg/h

Pure oxygen will be supplied to the gasifier to provoke incomplete combustion of the fuel. Also, its mass flow allows for temperature control, as a higher amount of oxygen will cause the temperature inside the gasifier to rise, albeit with a loss of efficiency. The following mass flow values were estimated:

- O₂ for bio-oil gasification = 230 kg/h
- O₂ for bio-coal gasification = 180 kg/h

These values were obtained considering the thermodynamic equilibrium of the incomplete combustion reactions inside the gasifier, with no consideration to the energy losses to gasifier wall due to cooling.

Several factors can influence these values such as fuel high heating value, moisture and chemically bound oxygen content, as well as (to a lesser extent and mostly for bio-coal) the devolatilisation and combustion kinetics.
Additional factors may also influence oxygen mass flow, such as vapour and carbon dioxide input into the gasifier.

Other inputs comprise vapour as an atomising fluid for bio-oil with mass-flow equivalent to 16% of that of the bio-oil and carbon dioxide as a transportation fluid for bio-coal in a (respectively) 3:1 mass flow ratio.

Vapour will also be used as a means to heat bio-oil to around 60°C to drop its viscosity to acceptable levels for feeding into the gasifier.

After gasification, the product gas is quenched in a secondary chamber right below the gasifier through direct contact with water at 30°C and 40 bar, dropping to temperatures between 220°C and 250°C.

The main role of quenching is ash and non-burnt char removal. When it comes into contact with the gases, water is heated up and mostly vaporised, becoming part of the gas mixture as it is transported to the following stages. The small portion of the water that did not vaporise is removed at the bottom with an estimated solids content of 10% in weight.

This water plus drag suspension is depressurised and cooled down for treatment and solid particle removal and afterwards is inserted in the water cooling system. The water that was vaporised and carried with the gas mixture will later be recovered via condensation, so there is no need for water make-up at this stage.

After gasification and quenching, the gas mixture requires some treatment to meet the requirements for synthesis, namely absence of particles and sulfuric compounds, CO₂ weight fraction less than 2%, H₂:CO molar ratio of 2:1 and negligible impurity content.

Therefore, a filter for solid particles, a sacrificial ZnO bed for sulfur removal, a shifting reactor for H₂:CO molar ratio, a condenser for water removal and a cleaning system based on organic solvent (methanol) absorption have been predicted.

**Shifting**

After leaving the gasifier and quenching, the water saturated gas mixture passes through a cyclone as an initial solid-gas separation step with the intent of removing coarse particles that might not have been eliminated during quenching.

The gas mixture is then pre-heated in a heat exchanger (without contact) by the current (containing the gas mixture) that leaves the shift reactor up to an approximate temperature of 350 °C to avoid condensation in the filter and ensure proper conversion in the shift reactor.

After heating, the gas mixture goes through a metallic fibre filter to remove fine particles. The now particle-free gas mixture is sent to a sacrificial ZnO (zinc oxide) bed for sulfur removal. This is done to prevent catalyst poisoning in the shift reactor.

The gas mixture is then sent to the shift reactor to adjust the H₂:CO molar ratio to 2 with creation of CO₂ and loss of H₂O according to the shifting reaction:

\[
CO + H₂O \leftrightarrow CO₂ + H₂
\]

Unwanted parallel reactions like the formation of methane are to be avoided by keeping the water-gas:dry-gas mass ratio above 0.9. This implies an addition of water vapour to the bio-oil stream (given that it carries a higher concentration of water due to the addition of vapour as an atomising fluid in the gasifier nozzle) and a larger addition of water vapour to the bio-coal current.

The gas mixture leaves the reactor at about 500 °C, it is then fully cooled to around 40°C in a condenser resulting in the removal of its excessive water content. The separated water is then reused in the quenching chamber.

**Gas cleaning**

The gas mixture leaves the condenser and goes through a second drying step by absorption through direct contact with a methanol stream. Additional methanol absorption steps will follow,
but this initial drying step is useful in that it prevents water from accumulating in the methanol, facilitating its subsequent regeneration.

After drying, CO₂ is removed from the gas mixture by consecutive methanol absorption in two columns.

This process differs from Rectisol® because of the higher temperatures used for methanol absorption, namely 15°C and –10°C. This strategy was selected since there is no need for such low temperatures (~–60°C) in the cleaning step, and also a cooling system of such proportion would not be feasible in a pilot plant.

Methanol is regenerated by flash evaporation and part of the CO₂ thus obtained is reused in the plant, whereas the rest of it, together with additional impurities, is burned in the flare.

The relatively clean gas mixture (approximately 1.5% CO₂ in volume) is composed of mainly H₂ and CO in the correct molar proportion is transferred for storage.

A small percentage of this gas may be burned to supply energy required for heating in any part of the process, should there be such a necessity. When it is not used for synthesis, nor stored any longer, the gas can be burned in the flare as well.

**Production/output**

The syngas (H₂:CO in 2:1 molar proportion) production under standard operating conditions averages around 265 kg/h with less than 2% impurities.

**Operation regime**

Due to the very high temperature and pressure inside the gasifier, the unit should operate 24 hours a day seven days a week, to avoid start-up and shut-down to preserve the gasifier refractory as well as other equipment parts.

Plant start-up time is estimated at two days. This period should be enough for controlled heating of all equipment. The gasifier in particular must be heated at a rate of, at most, 50°C/h avoiding refractory faults. Plant shut-down is also estimated at two days.

**Process flow diagram**

The mass flow values of all streams presented in the process flow diagram (Figure 2) are calculated considering the gasifier operating at a power of 2.5 MWth.

The conversion effectiveness of pyrolysis and torrefaction processes are assumed to be 70% and 80% respectively.

**Energy efficiency/Grassmann diagrams**

**Pilot plant**

From energy consumption estimates and energy balance calculations for pyrolysis and torrefaction processes, it is possible to analyse the energy content loss for each step in the pilot plant.

This analysis is made using a Grassmann diagram (Figures 3 and 5) showing the energy loss in each step of the process as well as the total efficiency.

The energy content entering the process is the fuel heating value, the natural gas heating value used for vapour generation, heating of drying air, torrefaction and flare operation and the electrical energy consumption.

The main energy contributions to the system are indicated in the pizza pie graphs (Figures 4 and 6). From these values the energy consumption in each step was subtracted.

The diagrams show that the efficiency is greater for bio-oil than for bio-coal. This is mainly due to the higher energy consumption in the torrefaction reactor.

The process also requires more energy in gas cleaning for bio-coal due to the greater formation of CO₂ during shifting and to gas recompression for bio-coal particle transportation.
Fig. 2—Simplified Process flow diagram for bio-coal route [adapted from IPT internal report, 2012].
Fig. 3—Grassmann diagram for energy flow for bio-coal.

Fig. 4—Supplied energy contribution for bio-coal.

Fig. 5—Grassmann diagram for energy flow for bio-oil.
The ultimate goal of the gasification pilot plant is the acquisition of sufficient know-how to allow for the construction of an economically viable industrial plant. Given this fact, different tests and research programs should be carried out in the pilot plant, where technical viability and optional solutions will be the main concern.

On the other hand, in the industrial plant, maximum energy efficiency is paramount to allow positive financial results. Also, given the magnitude of the mass flow rate, different solutions may be adopted to minimize energy loss. The following assumptions were made with regards to energy recovery in the industrial plant:

- Energy integration optimisation;
- Energy recovery from the gasifier is enough to generate 70% of the necessary vapour for the entire plant;
- The heat from the shift reactor plus flue gas from pyrolysis and torrefaction is enough to dry the bagasse;
- The syngas fraction used to clean the filter, rather than go to the flare is burned to reduce the gas consumption in torrefaction.

Considering the processing of 800 000 tonnes/year of moist bagasse and using the aforementioned assumptions, the data in Table 2 were calculated:

<table>
<thead>
<tr>
<th>800 000 Tonnes/year</th>
<th>Bio-coal</th>
<th>Bio-oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagasse input (50% moisture) [kg/h]</td>
<td>91 300</td>
<td>91 300</td>
</tr>
<tr>
<td>Plant power [MWth]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Syngas output [kg/h]</td>
<td>22 000</td>
<td>22 000</td>
</tr>
<tr>
<td>Electrical energy requirement [kW]</td>
<td>16 600</td>
<td>21 800</td>
</tr>
<tr>
<td>NG mass flow [kg/h]</td>
<td>1430</td>
<td>640</td>
</tr>
</tbody>
</table>

Energy efficiency estimates for the two alternatives torrefaction and pyrolysis are shown in the Grassmann diagrams given in Figures 7, 8, 9 and 10.

The main reduction in energy consumption is placed in the drying and shift stages, bringing the total efficiency to 55 and 56% for bio-coal and bio-oil respectively.

Energy consumption could be further reduced by increasing the efficiency of pyrolysis and torrefaction as well as reworking the cleaning system. It must be taken into account that this
estimate stems from the pilot plant design, and different tests performed in one such plant may allow for better technology selection.

**Fig. 7**—Grassmann diagram for energy flow for bio-coal in the industrial plant.

**Fig. 8**—Supplied energy contribution for bio-coal in the industrial plant.

**Fig. 9**—Grassmann diagram for energy flow for bio-oil in the industrial plant.
A technical and economic feasibility study was conducted by IPT researcher Abraham Yu for the implementation of a 648 MWth gasification plant producing green diesel using the Fischer-Tropsch process. This study was based on the projections of the cost of bagasse and the price of diesel oil in Brazil between 2020 and 2030. The diesel price estimate was based on a study by the California Energy Commission (CEC, 2009).

As a pessimistic scenario, we considered a high price of bagasse (70 US$/tonne) and a lower price of diesel (1.5 US$/litre), reducing the competitiveness of the gasification plant. For the optimistic scenario, we considered a lower price of bagasse (30 US$/tonne) and a higher diesel price (2.1 US$/litre), consequently increasing the competitiveness of the gasification plant.

The diesel produced by the Fischer-Tropsch process is treated as green diesel to distinguish it from well-known biodiesel. The green diesel produced is considered a drop-in fuel by having exactly the same characteristics as petroleum-based diesel.

Other scenario parameters in this feasibility study are the energy efficiency (bagasse to green diesel) of the gasification plant (55% optimistic, 45% and 35% pessimistic) and the number of operational months in a year. This parameter determines the size the gasification plant, since the total amount of bagasse is assumed to be fixed.

For a gasification plant with a capacity of 648 MWth, processing 1.6 million tonnes of bagasse per year and operating at an energy efficiency of 55%, it was found that the return on investment (ROI) is 114% in the expected scenario, and in an optimistic scenario the ROI is 286% (Table 4).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total capital investment (M US$, 2010)</th>
<th>Net present value (NPV) (M US$)</th>
<th>Return on investment (ROI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimistic</td>
<td>549</td>
<td>786</td>
<td>286%</td>
</tr>
<tr>
<td>Expected</td>
<td>689</td>
<td>334</td>
<td>114%</td>
</tr>
<tr>
<td>Pessimistic</td>
<td>917</td>
<td>−2</td>
<td>−1%</td>
</tr>
</tbody>
</table>

A series of sensitivity analyses has been carried out to estimate the minimum price of petroleum that would make the gasification plant unfeasible. These analyses started with the Expected Scenario. For oil prices above US$66/barrel, the Net Present Value (NPV) is positive, i.e., the plant would have a positive profit margin. For an ROI requirement of 25% (industrial standard

Fig. 10—Supplied energy contribution for bio-oil in the industrial plant.
ROI for investments in petrochemical plant), the price of oil will have to be US$81/barrel. The values of Pessimistic Scenario were then introduced gradually. Reducing the energy efficiency of the gasification plant from 45% to 35% and keeping the rest of the parameters of the expected scenario, the price of oil has to be US$97/barrel to have ROI=0. If in addition we demand an ROI of 25%, the price of oil will have to be at least US$117/barrel.

Conclusions

IPT has completed the conceptual design of the pilot plant and has estimated the economic feasibility and energetic efficiency of the industrial plant. The total energy efficiency in the industrial plant is estimated at 55%, and the ROI should be around 25% if oil prices are close to US$81/barrel between 2020 and 2030. Sugarcane production projections for that period show that there will be enough bagasse for gasification.

Key technical aspects include maintaining the slagging condition inside the gasifier, maximising pre-processing efficiency and achieving a low enough impurity content before entering the shift reactor.

There is no clear indication of the best route for pre-treatment, so the gasification pilot plant to be built in Piracicaba is unique in the sense that it will allow for the testing of both possibilities: pyrolysis and torrefaction.

The project predicts the construction of a full scale 648 MW industrial plant if, after testing in the pilot plant, technical-economic viability is verified.

REFERENCES


CONCEPTION IPT POUR LA GAZÉIFICATION DE LA BAGASSE

Par

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MOTS-CLÉS: Bagasse, Gazéification,
L'Efficacité Énergétique.

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Résumé
COMPTE TENU DE LA CROISSANCE de la production de canne à sucre au Brésil, la gazéification se présente comme une destination intéressante pour la bagasse et la paille. Elle permet la production de gaz de synthèse (H2 + CO2) qui peut être transformé en biodiesel, monomères ou autres produits pour l'industrie chimique. IPT a travaillé sur la conception d'une usine pilote qui permettra de tester des alternatives technologiques pour l'opération de prétraitement et du gazogène afin de permettre le développement d'un savoir-faire suffisant pour concevoir une installation industrielle. L'efficacité énergétique totale dans l'usine a été estimée à 55 %, et la faisabilité économique représentée par le retour sur investissement devrait être d'environ 25 % si le prix du pétrole est autour de 81$ US/baril entre 2020 et 2030. Les principaux aspects techniques incluent le control de la scorification dans le gazogène, maximiser l’efficacité des prétraitements et atteindre une teneur en impuretés assez basse avant d'entrer dans le réacteur de déplacement. L'étude décrit la conception de chaque étape du processus d'installation pilote, l'efficacité énergétique et des calculs de faisabilité économique.

GASIFICACIÓN DEL BAGAZO INGENIERÍA CONCEPTUAL

Por

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PALABRAS CLAVE: Bagazo, Gasificación,
Eficiencia Energética.

Resumen
DADO EL CRECIMIENTO de la producción de caña de azúcar en Brasil, la gasificación se muestra como un destino interesante para el bagazo y la paja. Esto permite la producción de Gas de Síntesis (syngas) el cual puede convertirse en biodiesel, monómeros u otros productos para la industria química. El IPT ha estado trabajando en el diseño conceptual de una planta piloto que comprobará alternativas tecnológicas para las operaciones de pre tratamiento y gasificación para posibilitar el desarrollo de suficiente conocimiento para diseñar un planta industrial. La eficiencia energética total en la planta industrial se estimó en 55% y la factibilidad económica, representada por el ROI debe ser alrededor del 25% si los precios del petróleo crudo es cercano a US$81/barril entre el 2020 y
el 2030. Aspectos técnicos clave incluye mantener las condiciones de escorificación dentro del gasificador, maximizando la eficiencia del pre tratamiento y alcanzando un contenido de impurezas suficientemente bajo antes de entrar al reactor de cambio. El presente estudio presenta el diseño conceptual de cada etapa en el proceso para los cálculos de la eficiencia energética y la factibilidad económica en la planta piloto.

**ENGENHARIA CONCEITUAL DE GASIFICAÇÃO DE BAGAÇO DO IPT**

Por

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**PALAVRAS-CHAVE:** Bagaço de Cana, Gaseificação, Eficiência De Energia.

**Resumo**

Devido ao crescimento da produção de cana-de-açúcar no Brasil, la gasificación presenta-se como un destino interesante para el bagaço e a palha. Ella permite la producción de singás (H₂+CO₂), que pode ser transformado en biodiesel, monômeros e outros productos para a indústria química. O IPT tem trabalhado no projeto conceitual de uma planta piloto que testará as alternativas tecnológicas para o pré-tratamento e a operação de um gaseificador, promovendo o desenvolvimento de know-how suficiente para o projeto de uma planta industrial. A eficiência total energética da planta foi estimada em 55% e a viabilidade económica representada pelo ROI deve ser de aproximadamente 25% se os preços do petróleo estiverem próximos a US$81/barril entre 2020 e 2030. Aspectos técnicos essenciais incluem a manutenção da escória no interior do gaseificador, maximizando a eficiência pré-processamento e alcançando baixo teor de impureza suficiente antes da entrada no reator. Este estudo descreve o projeto conceitual de cada etapa no processo para uma planta piloto, eficiência energética e cálculos de viabilidade económica.
PROSPECTS FOR THE DEVELOPMENT OF SUGARCANE BIOREFINERIES

By

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KEYWORDS: Bagasse, Biorefinery, Biofuels,
Green Chemicals, Pilot Plant.

Abstract
SUGARCANE BIOREFINERIES CO-PRODUCING fuels, green chemicals and bio-products offer great potential for improving the profitability and sustainability of sugarcane industries around the world. Sugarcane bagasse is widely regarded as one of the best biomass feedstocks for early adoption and commercialisation of biorefining technologies because of the large scale of the resource and its availability at sugar factories. Biomass biorefineries aim to convert bagasse through biochemical and thermochemical processes to produce low cost fermentable sugars which are a platform for value-adding. Through subsequent fermentation technologies or chemical synthesis, the sugars can be converted to fuels including ethanol and butanol, oils, organic acids such as succinic and levulinic and polymer precursors. Other biorefinery products can include food and animal feeds, plastics, fibre products and resins. Recent advances in biorefinery production technologies are being demonstrated in a unique research facility at the Queensland University of Technology’s Mackay Renewable Biocommodities Pilot Plant in Mackay, Australia. This pilot scale production facility located at Mackay Sugar Ltd’s Racecourse Mill is demonstrating the production of a range of fuels and other products from sugarcane bagasse. This paper will address the opportunities available for sugarcane biorefineries to contribute to future profitability and sustainability of the sugarcane industry.

Introduction
Historically, agricultural crops have been grown for the production of a principal product whether starch-based grains, oil seeds or sugars. All agricultural industries are now, however, considering ways to maximise the value from the entire crop. In particular, with increasing scarcity of crude oil, increasing petrol prices and the rapid progress in industrial biotechnology, there is a significant focus on creating additional value from the crop biomass residues to produce biofuels, green chemicals and other valuable bio-products.

Conventional sugarcane factories process the stalk from sugarcane to produce crystal sugar, molasses and energy co-products from bagasse (steam and electricity). Integrated sugar and ethanol production (from juice or molasses) has added value to sugarcane production and is an integral part of many sugar processing operations globally. The processing of juice or molasses into ethanol is the first step toward a sugarcane biorefinery.

A complete biorefinery, however, includes the sustainable processing of biomass into a range of valuable products (including food, feed, materials and chemicals), and energy (fuels, power, heat) (IEA Bioenergy, 2009). While sugarcane bagasse is currently widely used for cogeneration, the utilisation of this bagasse to produce higher value products is a profound opportunity to improve the sustainability and economic profitability of processing operations.
This paper assesses the prospects for the development of sugarcane biorefineries, the potential products from sugarcane biorefineries and reports on the research progress of an Australian biorefinery pilot plant that has been operating since 2010.

**The sugarcane biorefinery**

Over the past decade, there have been considerable developments in the concept of the sugarcane biorefinery and several reports have demonstrated the need to improve the economics of biofuels production through the integrated production of multiple co-products in a biomass biorefinery (Godshall, 2005; Pye, 2005; Edye *et al*., 2006; Peterson, 2006; Erickson, 2007; Day *et al*., 2008).

IEA Bioenergy Taskforce 42 classifies biorefineries according to four major elements, these being feedstocks, conversion processes, platforms and products (IEA Bioenergy, 2009). In a sugarcane biorefinery, the feedstocks can generally be considered as the products resulting from the sugarcane factory—bagasse, juice, sugar and molasses. In addition, by-products of the process such as filter mud may also be considered as potential feedstocks for biorefining processes.

For each of these potential biorefinery feedstocks from sugarcane, there are many potential products that can be produced as shown in Figure 1. These products range from lower value products such as animal feeds and fertilisers, to products of intermediate value such as fuels and bulk chemicals, to very high value proteins, pharmaceuticals and specialty chemicals.

![Fig. 1—Potential products for sugarcane biorefineries.](image)

The selection of appropriate conversion processes for the biorefinery is a function of the most efficient and cost effective way to get from the feedstock to the product.

The sucrose from sugarcane is readily fermented or chemically converted into biofuel and chemical products. The key challenge with the use of sucrose for the production of these products is its high cost. The use of molasses is also possible; however, the large scale adoption of these technologies may be limited by molasses price and availability.

As a result, sugarcane bagasse (and trash) has been the focus for the development of new biorefinery technologies for sugarcane. This is the result of bagasse being potentially available in very large quantities and having a much lower value than sugar or molasses.

Sugarcane bagasse is a complex mixture of cellulose, hemicellulose and lignin with minor amounts of ash, proteins, lipids and extractives. The structure of bagasse, like other lignocellulosics, makes the fibre very resistant to biological degradation or enzymatic bioprocessing and hence bagasse processing generally requires severe chemical, thermal and/or physical pretreatments prior to chemical or biological conversion to final products (O’Hara *et al*., 2011).
A comprehensive study of over 500 samples of Australian sugarcane biomass including bagasse showed a large variation in the composition of biomass (Oxley et al., 2012). The compositions of bagasse on a dry basis reported in the literature are typically as follows: cellulose 34–47%; hemicellulose 20–29%; and lignin 18–28% (Rao, 1997; Pena et al., 2000; Aguilar et al., 2002; Goncalves et al., 2005; Gray, 2007; Zhang et al., 2013).

Bagasse conversion technologies can generally be classified as either biochemical or thermochemical processes to produce intermediate chemical platforms. These platforms include fermentable sugars, lignin, syngas and bio-oils and provide a uniform basis from which to develop downstream processing technologies.

**Sugarcane factories as renewable energy and biotechnology hubs**

As an agricultural industry, the sugarcane industry is regionally based and central to the economic viability of rural and regional communities. The industry provides employment, economic growth, development and in many cases essential services to the local communities in which they exist. As sugarcane is a rapidly perishable product, sugarcane processing infrastructure must be located within the midst of the sugarcane growing region which ensures the on-going regional nature of the industry.

In centralised infrastructure, sugarcane factories process the sugarcane feedstock into products. For this purpose, they require services infrastructure including boilers, electrical generation and distribution equipment, cooling water, effluent treatment, maintenance and other services.

Future sugarcane factories will not only integrate sugarcane processing, sugar production and renewable energy production as they do now, but in addition produce biotechnology products. Further to the emergence of biorefinery processes, however, is the opportunity for these facilities to develop into regional renewable energy and biotechnology hubs attracting related industries and innovation enterprises able to make use of the central infrastructure, energy availability and co-product streams as inputs to their processes (Figure 2.)

![Fig. 2—Sugarcane factories—renewable energy and biotechnology hubs.](image-url)
In this way, the development of sugarcane biorefineries leads to higher regional employment, creates opportunities for the emergence of small to medium enterprises (SMEs) in higher technology industries and builds demand for employment in more highly skilled jobs.

In addition, the creation of a strong manufacturing base around low carbon technologies provides resilience in a manufacturing sector which has the potential to be adversely impacted by the implementation of future greenhouse gas abatement policies.

These benefits result in very significant social and development outcomes for regional communities, providing longer term sustainability of these communities which are essential to the economic well-being of a country.

**Bagasse as a biorefinery feedstock**

Biomass from sugarcane is widely considered to be one of the best feedstocks for early commercialisation of biorefining technologies. Biomass from sugarcane has many key advantages as a feedstock with the most significant of these being:

- Sugarcane is a highly efficient C4 photosynthetic crop producing high yields of biomass on an annual basis;
- The sugarcane resource is massive and globally distributed;
- Sugarcane is an established industrial crop with well understood farming practices, pest and disease profiles and well established and sophisticated varietal development programs;
- In terms of potential economic value, the biomass component of the crop (bagasse and trash) is vastly underutilised; and
- The major biomass residue from the crop (bagasse) is already at a centralised processing facility (the sugarcane factory).

These advantages result in sugarcane bagasse having a much lower feedstock risk profile and often a lower feedstock price than many other potential biorefinery feedstocks.

With the commercialisation of new biorefining technologies being subject to significant technical and commercial risk, the ability to reduce feedstock risk is a key requirement for early adopters of biorefinery technologies.

**Potential chemical products for sugarcane biorefineries**

**Leading potential chemical products from biomass**

Most organic chemicals produced from fossil based resources can also be produced from biomass (Bridgwater *et al.*, 2010). Several studies have assessed the range of potential chemical products from biomass and, in fact, over 300 chemicals have been identified (Werpy *et al.*, 2004; Bridgwater *et al.*, 2010).

Table 1 shows a summary of the most promising chemical candidates from several of these assessments including the potential chemicals able to be produced from biomass, sugars, lignin and syngas.

The following sections assess in more detail some of the more promising potential chemical options from both the sugars and lignin platforms.

**The sugars platform**

Carbohydrates make up approximately 54–76% of bagasse on a dry basis. These carbohydrates mostly consist of structural cell-wall polymers principally cellulose and hemicellulose.

These carbohydrates can be hydrolysed to monomer sugars mainly consisting of glucose, xylose and arabinose. In the thermal and chemical processes for the treatment of bagasse, however, a range of oligomers and carbohydrate degradation products are formed depending upon the severity of the conditions employed.
Table 1—Leading candidates for the production of value-added chemicals from biomass.

<table>
<thead>
<tr>
<th>Products from biomass (Bridgwater et al., 2010)</th>
<th>Chemicals from sugars (Werpy et al., 2004)</th>
<th>Chemicals from lignin (Holladay et al., 2007)</th>
<th>Chemicals from syngas (Spath et al., 2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2-Propanediol Epichlorohydin Lactic acid Diesel Gasoline Kerosine Ethanol Methanol DME Char Wood pellets Animal feed 1,3-Propanediol Carbon dioxide</td>
<td>1,4-Succinic, fumaric and malic acids 2,5-Furan dicarboxylic acid 3-Hydroxy propionic acid Aspartic acid Glucaric acid Glutamic acid Citric acid Leucin acid 3-Hydroxybutyrolactone Alcohols (e.g., glycerol, sorbitol, xylitol/arabinitol)</td>
<td>Macromolecules Carbon fibre Polymer modifiers Thermoset resins Aromatic chemicals BTX (benzene, toluene, xylene) derivatives Phenol Lignin monomers Propyophenol Eugenol Syringol, Oxidised lignin monomers Syringaldheyde Vaniliain Vanillic acid</td>
<td>Hydrogen Ammonia Methanol and derivatives ( d, l )-methyl ether (DME) Acetic acid Formaldehyde Methyl tert-butyl ether (MTBE) Methanol to olefins Methanol to gasoline Ethanol Mixed higher alcohols Oxosynthesis products ( C_3 \sim C_{15} ) aldehydes Isosynthesis products (isobutene, isobutane)</td>
</tr>
</tbody>
</table>

Biochemical processes require pretreatment of bagasse in a reactor at moderate temperatures (~160–180°C) and pressures (~6–20 bar) and generally in the presence of alkalis, mild acids or solvents. Following pretreatment, the solid residue can be much more readily hydrolysed using enzymes (cellulases, glucosidases, xylanases) into the monomer sugars. Depending upon the quantity of carbohydrate degradation formed in the pretreatment process, these ‘fermentable sugars’ formed can be biologically converted (fermented) into target chemical products. Product purification requirements depend upon the product produced but can include distillation, crystallisation, solvent extraction, membrane separation, ion exchange or chromatographic techniques.

Research work currently underway at QUT is developing technology for the in-planta expression of cellulase enzymes in sugarcane, novel pretreatment processes and enzyme delivery technologies.

Thermochemical processes are typically undertaken at more elevated reaction temperatures (>200°C) in a low oxygen environment. Because these higher temperatures are effective at converting biomass into products, thermochemical processes can be highly efficient. Thermochemical processes generally require shorter reaction times than biochemical processes and have quite different product separation and purification requirements.

Based upon the reaction conditions used and the types of intermediate products formed, thermochemical processes can be classified as gasification, pyrolysis, or liquefaction. Typical operating conditions for these processes are shown in Table 2.

Table 2—Typical reaction conditions for thermochemical biorefinery processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature (°C)</th>
<th>Pressure (bar)</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction</td>
<td>250–330</td>
<td>1–240</td>
<td>Liquid</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>280–630</td>
<td>1–5</td>
<td>Liquid and gas</td>
</tr>
<tr>
<td>Gasification</td>
<td>800–1000</td>
<td>1–20</td>
<td>Solids and gas</td>
</tr>
</tbody>
</table>

Research work currently underway at QUT in thermochemical processing is investigating liquefaction of bagasse to create a renewable bio-crude. In this reaction, the macromolecules in bagasse undergo degradation in water to produce oil-like compounds which separate from the aqueous phase. Other products including acetic acid and acetone remain dissolved in the water phase. During liquefaction, a reduction in oxygen is achieved through the generation of \( \text{H}_2\text{O} \) and \( \text{CO}_2 \).
One of the major attractions of the liquefaction process is that the biomass feedstock does not require drying prior to processing. This is a major energy saving when compared to other thermochemical processes.

A study conducted by PNNL/NREL in 2004 (Werpy et al., 2004) identified a number of key sugar-derived platform chemicals that can be produced from biomass. The product identification was proposed as a guide for research and reflects economics, industrial viability, size of markets, and the ability of a compound to serve as a platform for the production of derivatives. The list of target platform chemicals was refined in 2010 based on advances in technology developments (Bozell and Petersen, 2010) and is shown in Figure 3.

The majority of the compounds identified are predominantly produced via fermentation pathways whereas others can be produced by thermochemical pathways (shaded area in Figure 3). The polyols (sorbitol and xylitol) are mostly produced through catalytic hydrogenation of sugars but can also be produced via biochemical pathways. Lactic acid is also a byproduct from the thermochemical conversion of biomass synthesis.

Levulinic acid is an ideal platform chemical that can be utilised to produce a number of biochemicals including succinic acid, resins, polymers, herbicides, pharmaceuticals and flavouring agents, solvents, plasticisers, anti-freeze agents and biofuels/oxygenated fuel additives as shown in Figure 4.

<table>
<thead>
<tr>
<th>Levulinic acid</th>
<th>Sorbitol</th>
<th>Xylitol</th>
<th>Furans (Furfural)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Levulinic acid" /></td>
<td><img src="image2" alt="Sorbitol" /></td>
<td><img src="image3" alt="Xylitol" /></td>
<td><img src="image4" alt="Furans" /></td>
</tr>
<tr>
<td>Succinic acid</td>
<td>Lactic acid</td>
<td>Biohydrocarbons (Isoprene)</td>
<td>(Hydroxymethyl furfural)</td>
</tr>
<tr>
<td><img src="image5" alt="Succinic acid" /></td>
<td><img src="image6" alt="Lactic acid" /></td>
<td><img src="image7" alt="Biohydrocarbons" /></td>
<td>(Furan dicarboxylic acid)</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Glycerol</td>
<td>Hydroxypropionic acid</td>
<td></td>
</tr>
<tr>
<td><img src="image8" alt="Ethanol" /></td>
<td><img src="image9" alt="Glycerol" /></td>
<td><img src="image10" alt="Hydroxypropionic acid" /></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3—Top 10 chemicals produced from sugars.

Esterified derivatives of levulinic acid can be used as food, flavouring and fragrance agents. Ethyl levulinate is also used as an oxygenated additive. Levulinic acid can be condensed with aromatic alcohols to produce diphenolic acid which is used in the production of polymers,
lubricants, fire-retardant materials, paints and as a replacement for bisphenol A. Levulinic acid can be readily halogenated to yield organic halides such as 5-bromolevulinic acid that can be further converted to δ-aminolevulinic acid which are useful pharmaceutical agents and herbicides.

Some biofuel derivatives of levulinic acid such as γ-valerolactone (GVL) and 2-methyltetrahydrofuran (MTHF) can be readily blended with petroleum products to create cleaner-burning fuels with the advantage that they do not suffer from phase separation to become contaminated with water (c.f. ethanol). Alternatively GVL can be converted to valeric biofuels by esterification to pentenooates esters or hydrogenated to pentanoic acid which can be catalytically upgraded to 5-nanonone by ketonisation and hydrogenated to alkanes or alcohols (depending on catalyst employed). The alcohols can be subsequently dehydrated to alkenes and oligomerised enabling production of C₆-C₂₇ hydrocarbon fuels.

![Fig. 4—Levulinic acid as a platform chemical (Rackemann et al., 2010).](image)

Succinic acid is another platform chemical that is receiving much attention. It is typically produced by bacterial fermentation of glucose but can also be catalytically oxidised from levulinic acid with a yield of ~80%. Succinic acid is a versatile intermediate that can produce derivatives such as γ-butyrolactone (agrochemicals and pharmaceuticals), 1,4-butanediol (plastics, fibres, films and adhesives) and tetrahydrofuran (THF: solvent for polyvinylchloride and intermediate for fibres and polyurethanes).

Furanics (furfural and HMF) are also versatile chemicals and can be readily transformed into solvents, acrylate and polyester monomers, pharmaceuticals, agrichemicals, and biofuels. HMF can be catalytically converted to energy dense biofuels such as 2-methylfuran (MF) and 2,5-dimethylfuran (DMF) or oxidised to highly functional monomers such as 2,5-furandicarbaldehyde and 2,5-furandicarboxylic acid (FDCA).

FDCA is a monomer for production of many polymers and has been touted as a green replacement for terephthalic acid and isophthalic acid, principally used as precursors of polyester for clothing and plastic bottles, as well as fine chemicals. HMF and furfural can be converted to kerosene and diesel range biofuels through condensation reactions.
Furfural is also considered a versatile industrial solvent and chemical precursor for foundry products. Furfural derivatives include agricultural chemicals (herbicides, insecticides and preservatives), perfumes and flavouring agents (furan, furanol, nitrofuran, furamone), plastics, resins and synthetic fibres (nylon), dyes, rubbers and paints. Table 3 provides estimates of the potential value of products from the biomass carbohydrates and derivative products.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Value (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose pulp</td>
<td>~$500/t</td>
</tr>
<tr>
<td>Glucose</td>
<td>$600–700/t</td>
</tr>
<tr>
<td>Carbohydrate hydrolysis products</td>
<td></td>
</tr>
<tr>
<td>HMF / HMF esters</td>
<td>$2000–4000/t</td>
</tr>
<tr>
<td>Levulinic acid / esters</td>
<td>$2000–3000/t</td>
</tr>
<tr>
<td>Polyols (sorbitol/xylitol)</td>
<td>$2000–3000/t</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>$1800/t</td>
</tr>
<tr>
<td>Furfural</td>
<td>$1500/t</td>
</tr>
<tr>
<td>Formic acid / Acetic acid</td>
<td>$900/t</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$600–800/t</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>$400/t</td>
</tr>
<tr>
<td>Upgraded products</td>
<td></td>
</tr>
<tr>
<td>Fuel additives</td>
<td>$900/t</td>
</tr>
<tr>
<td>Terephthalic acid / FDCA</td>
<td>$900/t</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>$1800/t</td>
</tr>
<tr>
<td>Furfuryl alcohol</td>
<td>$2000/t</td>
</tr>
<tr>
<td>Bisphenol – A</td>
<td>$2300/t</td>
</tr>
<tr>
<td>Polymers and resins</td>
<td>~$2500/t</td>
</tr>
<tr>
<td>Solvents (MF, DMF, THF, MTHF, BDO, GVL)</td>
<td>$2000–5000/t</td>
</tr>
<tr>
<td>Herbicides</td>
<td>&gt;$2500/t</td>
</tr>
<tr>
<td>Flavouring agents</td>
<td>&gt;$5000/t</td>
</tr>
</tbody>
</table>

The lignin platform

Lignin has found commercial applications in a variety of low value industrial products such as concrete additives, phenol-formaldehyde resins and animal feed pelleting aids as well as in some small market high value adding products such as vanillin, dispersants and pesticides.

The depolymerisation of lignin via thermochemical processes (pyrolysis or liquefaction) generates a multitude of products.

Base catalysed depolymerisation (BCD) is the most common thermochemical treatment applied for lignin conversion. BCD hydrolysis of lignin can produce a range of oxygenated aromatics with high potential as platform chemicals (high market volume) including phenol, substituted phenols, catechols, cresols, syringols, guaiacols.

Phenol is considered the most suitable oxygenated aromatic product because of its very large market volume and value as a platform chemical. Further conversion of these oxygenated aromatics can produce:

(i) BTX chemicals (benzene, toluene and xylene), cyclohexane and cyclohexanol through reduction reactions; and

(ii) aromatic diacids, quinones, terephthalic acid, vanillin, etc by oxidation reactions.

Table 4 provides estimates of the potential value of products from the BCD hydrolysis of lignin and derivative products from phenol.
### Table 4—Value added compounds derived from lignin.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Value (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignin</td>
<td>$136/t (based on heating value)</td>
</tr>
<tr>
<td>BCD hydrolysis products</td>
<td></td>
</tr>
<tr>
<td>Phenol</td>
<td>$1500/t</td>
</tr>
<tr>
<td>Catechol/guaiacol</td>
<td>$2000–3000/t</td>
</tr>
<tr>
<td>Cresol</td>
<td>$1100/t (based on xylene price)</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>$1800/t</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>$1375/t</td>
</tr>
<tr>
<td>Formic acid/acetic acid</td>
<td>$900/t</td>
</tr>
<tr>
<td>Methanol</td>
<td>$400/t</td>
</tr>
<tr>
<td>Phenol upgraded products</td>
<td></td>
</tr>
<tr>
<td>Terephthalic acid</td>
<td>$900/t</td>
</tr>
<tr>
<td>Bisphenol – A</td>
<td>$2300/t</td>
</tr>
<tr>
<td>Cyclohexanol</td>
<td>$2300/t</td>
</tr>
<tr>
<td>Adipic acid</td>
<td>$2650/t</td>
</tr>
<tr>
<td>Vanillin/syringol/syringaldehyde</td>
<td>$&gt;10 000/t (niche market)</td>
</tr>
<tr>
<td>Xylene</td>
<td>$800/t</td>
</tr>
<tr>
<td>Toluene</td>
<td>$950/t</td>
</tr>
<tr>
<td>Benzene</td>
<td>$1100/t</td>
</tr>
</tbody>
</table>

**Pilot plant demonstration of biorefinery technologies in Australia**

While considerable laboratory scale research is being conducted to develop cost-effective biorefinery processes, the complexity of the integrated processes cannot be adequately developed and demonstrated solely on results obtained from laboratory research. Effective pilot scale trials are an essential component in the development of new technologies to prove the effectiveness of new technologies obtained in the laboratory. From these pilot trials, it is possible to optimise key process parameters prior to the large scale engineering and further scale up to demonstration or commercialisation scale.

The Mackay Renewable Biocommodities Pilot Plant (MRBPP) is publicly available research infrastructure that was jointly funded by the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS) and the Education Investment Fund (EIF), Queensland Government and the Queensland University of Technology (QUT) in Brisbane, Australia. The facility is hosted by Mackay Sugar Ltd on the Racecourse Mill site in Mackay, Queensland. The MRBPP was developed to:

- Bridge the gap between laboratory research and commercial investment;
- Rapidly advance the commercialisation of new technologies; and
- Connect global innovators to Australian feedstock suppliers, investors and end-users.

The MRBPP is owned and operated by QUT and has been demonstrating biorefinery processes at the pilot scale since 2010. A description of the facilities, infrastructure and equipment at the MRBPP has been previously reported (Wong *et al.*, 2011). Since 2010, a range of biomass feedstocks have been processed including sugarcane, bagasse, corn stover, *Eucalyptus*, sweet sorghum and energy grasses. Several biochemical pretreatment processes have been demonstrated including alkaline, single- and two-stage mild acid, solvent-based and autohydrolysis pretreatments.

Figure 5 shows the process for two-stage mild acid pretreatment of bagasse in the pilot plant to produce a pentose rich hydrolysate and a steam exploded solid residue. The solid residue is subsequently hydrolysed to produce the glucose rich fermentable sugar product. Images of typical reaction products are shown in Figure 6.

The MRBPP has been used to extract and purify lignin from sugarcane bagasse and this lignin is being used for the ongoing development of some of the products detailed previously. Significant work is continuing on the development of novel and effective bagasse pretreatment processes and the MRBPP is providing significant experience in understanding the opportunities...
created by these processes and some of the benefits and challenges associated with the physical and chemical processing of sugarcane bagasse at scale.

Trials at the MRBPP are continuing with a range of Australian and international partners, but with a common interest in the future opportunities for the production of high value fuels and chemicals from sugarcane bagasse.

![Diagram of the process](image)

**Fig. 5**—Production of fermentable sugars via the two-stage mild acid pretreatment process at the MRBPP.

![Images of bagasse and pretreated fibre](image)

**Bagasse**  **Pretreated fibre**

**Fig. 6**—Conversion of bagasse to fermentable sugars. Figures show the bagasse feedstock, steam exploded acid treated fibre, and the progress of enzymatic hydrolysis of the solid residue 0–40 h.

**Conclusion**

There are many potential conversion technologies, platforms and products for sugarcane biorefineries. Conversion technologies include biochemical and thermochemical processes and
result in the production of valuable chemicals including levulinic acid, succinic acid, furanics and their derivatives.

The sugar industry is in a prime position to be a major feedstock supplier and investor in the emerging industrial biotechnology industry.

Bagasse is widely seen as one the best feedstocks for the early stage adoption and commercialisation of biorefinery technologies.

The adoption of biorefinery technologies into integrated sugarcane processing facilities creating renewable energy and biotechnology hubs offers improved economic viability and profitability for the sugar industry in the future. In addition, there are significant social, commercial and environmental benefits that accrue to the regional communities and this reinforces the need for strong public policy to assist in the development of these new industries.

Acknowledgements

The authors wish to thank the Australian Government Department of Innovation, Industry, Science and Research (NCRIS program), Queensland Government, QUT and Mackay Sugar Ltd for funding and support for the establishment of the MRBPP.

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PERSPECTIVES POUR LE DÉVELOPPEMENT DE 
BIO RAFFINERIES DE CANNE À SUCRE

Par 
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MOTS-CLÉS : Bagasse, Bio Raffinerie, 
Biocarburants, Produits Chimiques, Usine Pilote.

Résumé
Les bio raffineries de canne à sucre produisant des combustibles, des produits chimiques 
écologiques et des bio-produits offrent un grand potentiel pour l’amélioration de la rentabilité et de 
la viabilité des industries de la canne à sucre dans le monde entier. La bagasse est considérée 
comme l'une des meilleures matières premières de biomasse pour une adoption rapide et pour 
la commercialisation des technologies de bio raffinage ; cela est en raison de la grande échelle de 
la ressource et de sa disponibilité à la sucrerie. Les bio raffineries visent à convertir la bagasse à
travers des processus biochimiques et thermochimiques pour produire des sucres fermentescibles, à faible coûts, et qui sont une plateforme pour le développement. Grace aux technologies de fermentation ou de synthèse chimique, les sucres peuvent être convertis en combustibles, y compris l'éthanol et le butanol, en huiles, acides organiques tels que succinique et levulinique et polymères. D’autres produits de bio raffinerie peuvent inclure les aliments pour les humains et pour les animaux, des matières plastiques et des produits en fibre et en résines. Des progrès récents dans les techniques de production de bio raffinerie sont démontrés dans le centre de recherche Queensland University of Technology, Mackay Renewable Biocommodities Pilot Plant, en Australie. Cette unité de production pilote située à la sucrerie Racecourse, de Mackay Sugar Ltd, explore la production d'une gamme de carburants et d’autres produits de la bagasse. Ce document présente des opportunités pour les bio raffineries afin de contribuer à la rentabilité et la viabilité de l’industrie de la canne à sucre.

PERSPECTIVAS PARA EL DESARROLLO DE BIOREFINERÍAS DE CAÑA DE AZÚCAR

Por

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Resumen

LAS BIOREFINERÍAS DE CAÑA de azúcar coproduciendo energía, productos químicos verdes y bioproductos, ofrecen un elevado potencial para mejorar las ganancias y la sostenibilidad de las industrias de la caña de azúcar alrededor del mundo. El bagazo de la caña de azúcar es considerado ampliamente como una de las mejores fuentes de biomasa para la adopción temprana y la comercialización de las tecnologías de biorefinerías, por su apreciable volumen y disponibilidad en las ingenios azucareros. Las biorefinerías de biomasa tienen el objetivo de convertir el bagazo, mediante procesos termoquímicos y bioquímicos, en azúcares fermentables baratos que es una base para alcanzar valor añadido. Mediante posteriores tecnologías de fermentación ó la síntesis química el azúcar puede convertirse en combustibles, incluyendo el etanol y el butanol, aceites, ácidos orgánicos tales como el succínico y el levulinico y precursores poliméricos. Entre otros productos de la biorefinería se incluyen alimentos para humanos y animales, plásticos, productos fibrosos y resinas. Recientes avances en las tecnologías de producción de las biorefinerías se demuestran en facilidades de investigación únicas en la Mackay Renewable Biocommodities Pilot Plant de la Queensland University of Technology, ubicada en Mackay, Australia. Estas facilidades de producción piloto ubicadas en el Racecourse Mill de Mackay Sugar Ltd., demuestran la producción unespectro de combustibles y otros productos a partir del bagazo de la caña de azúcar. Este artículo muestra las oportunidades disponibles para las biorefinerías de caña de azúcar de contribuir a la futura ganancias y la sostenibilidad de la industria azucarera de caña.
PERSPECTIVAS PARA DESENVOLVIMENTO DE BIORREFINARIAS DE CANA-DE-AÇÚCAR

Por

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PALAVRAS-CHAVE: Bagaço, Biorrefinaria, Biocombustíveis, Químicos Verdes, Planta Piloto.

Resumo

As biorrefinarias de cana que coproduzem combustíveis, químicos verdes e bioproductos oferecem grande potencial para aumentar a rentabilidade e a sustentabilidade das indústrias de cana no mundo. O bagaço da cana é considerado uma das melhores matérias primas de biomassa para adoção precoce e comercialização de tecnologias de biorrefinaria devido à grande quantidade desse recurso e à sua disponibilidade nas fábricas de açúcar. As biorrefinarias de biomassa têm por objetivo converter o bagaço por processos bioquímicos e termoquímicos para produzir açúcares fermentáveis de baixo custo que são uma plataforma para agregação de valor. Por meio de tecnologias de fermentação ou síntese química subsequentes, os açúcares podem ser convertidos em combustíveis, inclusive etanol e butanol, óleos, ácidos orgânicos, tais como os ácidos succínico e levulínico e os precursores do polímero. Outros produtos de biorrefinaria são alimentos e rações animais, plásticos, produtos de fibra e resinas. Avanços recentes nas tecnologias de produção de biorrefinarias estão sendo demonstrados em uma instalação de pesquisa única Planta Piloto de Biocommodities Renováveis de Mackay da Universidade de Tecnologia de Queensland, Austrália. Essa instalação de produção em escala piloto, localizada em na Mackay Sugar Ltd. Racecourse Mill, está demonstrando a produção de uma variedade de combustíveis e outros produtos a partir do bagaço da cana. Este trabalho tratará das oportunidades disponíveis para biorrefinarias de cana a fim de contribuir para a rentabilidade futura e a sustentabilidade na indústria.
INTRODUCTION AND OVERVIEW OF THE CURRENT SITUATION REGARDING THE EMPLOYMENT OF BIOMASS

By

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Keywords: Biomass, Bioenergy, Biofuels, Biochemical, Sugarcane.

Abstract

The sugarcane industry for a long time has focused only on the cane juice, its extraction and conversion to sugar. Bagasse was considered a residue and burnt inefficiently to generate steam and power. In the last decades, bagasse gradually started to be converted into energy in a more efficient way, supplying all the sugar industry energy needs (power, steam and electricity) and, in some cases, significant excess electricity has been exported to the grid, becoming another important source of revenue. This motivated several studies of more advanced energy generation systems to boost energy exports. In more recent years, technologies called 2nd and 3rd generation have taken over the scene with many options, promising to convert biomass into more valuable products such as biofuels, chemicals, fertilisers, pellets, etc. Unfilled expectations and opportunities are rising. On the other hand, these technologies are competing for the same biomass, and this has to be considered. The industry has started to question ‘which way to go’, strategy and investment wise. The present study provides a broad scenario for the biomass availability, and its employment, with a close view to the main processes and products that might have an important role in the future of the biomass in the sugarcane industry.

Introduction

The sugarcane industry experienced a considerable growth in the past decades, pushed by the increase in sugar demand and in a few countries by an ethanol program. More than 80 countries grow sugarcane and there is still potential for expansion in the cultivated area. The importance of this industry has been recognised by its capacity to achieve significant reductions in greenhouse gas emissions relative to fossil fuel use, considering ethanol and the biomass-based electricity production. In the course of increasing the competitiveness of this industry, optimisation of raw materials use, production processes and energy efficiency have been a trend. Biomass has emerged as an unexplored avenue in terms of the amount available and the new products that could be obtained from it. The main raw material of the sugarcane is the juice containing the sucrose. Sugarcane fibre or biomass, considered a by-product until some time ago, has taken the scene in the last years.

Due to the importance attributed to biomass, energy savings became important to use the bagasse efficiently at the factory, added to additional biomass that could be obtained with the trash (sugarcane leaves and tops). Research of the biomass potential, characteristics, logistics and recovery equipment became important. Energy crops have been studied as another source of biomass, among them the Energy Cane. This could be a sugarcane variety with average sugar content and with considerably higher fibre content, or a sugarcane variety with much higher fibre and almost no sugar.
Gasification, cellulose hydrolysis, C5 fermentation, anaerobic digestion and pyrolysis are some of the biomass processes presently being discussed, studied and developed as a means of obtaining new products. Diverse products have been thought such as a range of biofuels (bioethanol, isobutanol, biodiesel, jet fuel, dimethyl ether, methanol), chemicals (n-biobutanol), bioplastics, fertilisers, biogas (methane, hydrogen, etc.) and solid biofuels (briquettes, pellets, torrified or not) and the already produced electricity and heat, produced more efficiently.

The actual scenario presents an array of technologies and products under development. This effervescence contrasts with an ancient industry that has survived for centuries based on a single product – sugar, and using no more technology than is sufficient to be as cost competitive as possible, and that now is faced with decisions to be taken for a business and equipment that should last decades. It is a time of questioning: what use should be made of the biomass, product and technology wise.

Materials and methods

The material presented in this paper is the outcome of published data, information exchange with researchers, CTC internal development projects, consultancies and the author’s view about biomass utilisation by the sugarcane industry.

Discussion

The biomass in the sugarcane industry

The biomass in the sugarcane industry has always been the bagasse, the fibre in the cane stalk that after juice extraction has a moisture content around 50%. Fibre in the sugarcane stalk varies in the range of 11 to 17% (dry matter). Another source of biomass is trash, left in the field after unburned cane harvesting.

During harvesting, part of the trash is carried with the cane to the factory, and is referred to as vegetal impurity or extraneous matter. Therefore, bagasse is composed of sugarcane stalk fibre and a percentage of trash in the form of vegetal impurity in the cane. Vegetal impurities in the range of 6 to 8% (wet basis) in the total cane load are a good reference for unburned cane.

An average trash amount of 14% (dry matter) to the total stalk weight has been determined (Hassuani et al., 2005). Considered a problem in the past, especially regarding harvesting operations, trash has recently been viewed as an important biomass source. What amount of trash should be left in the field, the cost of trash recovery and transport and its characteristics have been the subject of many studies.

Present status of biomass use in the sugarcane industry

Bagasse has been the sole biomass employed in the factory and its use has been to generate energy. The mainstream technology used to convert bagasse into energy is the Rankine cycle, where the energy carrier is water, and bagasse is burned to increase the energy content of the water, which is converted into steam, producing ‘work’ in a steam turbine. Thermal power (steam heat), mechanical power (steam driving turbines to run pumps, milling tandems, etc.) and electricity (steam driving steam turbine generators) provide the necessary energy demand of the factory.

Adoption of higher boiler pressure and temperature technology has improved energy efficiency levels, increasing electricity generation and making possible the production of excess electricity to be sold to the grid. The technical and economic feasibility of the high pressure Rankine cycle has led to the establishment of several sugarcane facilities with more efficient energy systems, generating excess ‘green electricity’ for sale to the grid. Most new facilities were built with boilers operating at steam conditions of 67 bar/490°C, 100 bar/520°C and up, and some old installations (22 bar/300°C) have changed over to higher pressure boilers in a process called ‘retrofit’.

The employment of steam condensing turbogenerators, and the reduction of process steam consumption has also made possible the increase in electricity export to the grid. Steam
The consumption of 500 to 600 kg of steam per tonne of cane has been reduced to 400 kg/t and even 380 kg/t, but due to the investment needed in process equipment, the reduction in steam consumption has not advanced as much as it could be technically achieved (around 280 kg/t). Bagasse has been the main biomass fuel used by this industry. Exceptionally, additional fossil fuel has been employed to extend the generation period, such as coal in Mauritius. Some studies have been made to use natural gas as supplementary fuel, with no project implemented so far (the high cost of the fuel needs bigger plants to gain scale and efficiency).

Integration of the sugarcane factory with other processes or industry, consuming heat, power and electricity is an important way of increasing global energy efficiency and improving economics. Mills incorporating vinasse concentration or integrated to a sugar refinery or even mill process integrated to soybean biodiesel production are examples of this optimisation.

Though not common, sporadic niche application for sugarcane biomass has been carried on. One example is the use of bagasse for the pulp and paper industry in the nominated Ritter Process and implemented at Ledesma Mill in Argentina. Bagasse fibrous material is separated and treated with a lactic acid solution before storage and processing for paper production.

The use of trash for energy generation

The increase in energy generation and export of electricity by the mill can be made in three ways: i) increasing energy generation efficiency, ii) reducing energy consumption and iii) increasing the amount of fuel. Recently trash has emerged as an important biomass alternative to increase the fuel amount. Two important trash collecting routes have been considered: baling and partial cleaning. For the first one, trash in the field is left to dry and then is baled, bales loaded onto trucks (Figure 1) and transported to the mill where some of the mineral impurities are removed and trash is shredded and fed to boilers.

![Fig. 1—Rectangular trash bales loaded onto truck.](image)

In the second route, harvester cleaning fan speed is reduced, letting more vegetal impurities go with the cane to the factory. Cane reaching the factory has the trash and mineral impurities separated by a dry cleaning system (Figure 2), with trash shredded before being sent to boilers.

Both routes have been implemented in a few mills in Brazil, with advantages and disadvantages for each one. Typical amounts of recovered trash are in the range of 30 to 50% of the available trash in the field. The definition of the amount of trash to be recovered depends on agronomic and economic factors. Electricity export increases of 70% can be achieved if recovering 50% of the field available trash in unburned areas, using 67 bar/490°C boilers.
The optimisation and the commercial deployment of the trash technologies are still in its initial phase, depending in many cases on specific country policies, energy transmission structure and market prices.

Table 1 highlights the substantially larger amount of electricity export that can be generated using higher pressure steam and power cogeneration technologies, already well-established commercially, assuming the use of the bagasse and the additional 50% of the available trash.

Table 1—Sugarcane potential for electricity export at a typical Brazilian mill today.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Export electricity potential – bagasse (kWh/t cane)</th>
<th>Export electricity potential – bagasse and 50% of the trash (kWh/t cane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 bar, 300 °C</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>67 bar, 490 °C</td>
<td>63</td>
<td>108</td>
</tr>
<tr>
<td>100 bar, 520 °C</td>
<td>74</td>
<td>126</td>
</tr>
</tbody>
</table>

The biomass considered is the bagasse from sugarcane with an average of 11% fibre content in the stalk and 7% (in weight) of vegetal impurities in the cane load and process steam consumption around 480 kg of steam/t cane.

Boosting biomass conversion to electric power

Other technologies for biomass electric power generation have been considered, especially gasification-based power generation, including gasifier-engine, gasifier-gas turbine, and gasifier-fuel cell systems. In the 1980s and 1990s there was significant research and development on power generation from biomass gasifier gas turbine/steam turbine combined cycles and biomass gasifier internal-combustion engine systems, leading to the construction and successful technical operation of some pilot and demonstration plants around the world. Different technological alternatives have been developed and tested, such as atmospheric and pressurised gasification, air and oxygen blown gasification, fluidised and circulating bed, entrained flow, and so on.

The integrated gasification combined cycle (IGCC) also called biomass integrated gasification with gas turbine (BIG-GT) has been considered the indicated technology for energy generation at the mill site (Figure 3).
During gasification, biomass (dried to a moisture content of 10 to 20% by weight) is heated to 800–1100°C (typically by combusting a portion of the biomass in oxygen) to cause it to be converted into a mixture of combustible and non-combustible gases. Contaminants in the gas are removed and the gas burnt in a gas turbine to generate electricity. The hot gases coming out of the gas turbine produce steam in a heat recovery steam generator (HRSG).

Nevertheless, there has been no commercial-scale demo plant that could prove its economic competitiveness in the production of electricity. Analysis of several commercial and pilot-scale projects, some of them built and even commissioned such as the ARBRE project in the UK and the VARNAMO project (Sydkraft, 2001) in Sweden (Figure 4), indicated that the failure to achieve commercial success was mainly due to economic factors. Other factors, such as technology risk, institutional arrangements and secure biomass supply played their role as additional barriers.
Nevertheless, specific electricity export above 200 kWh/t of cane (with 50% of trash) and electric efficiencies above 40% to the fuel energy, almost twice that of the Rankine cycle, still attracts developers and environment specialists to the gasification technology, keeping the theme in everyone’s agenda as a promise for the future. On the other hand, investments above US$ 2000/kW installed and price of US$ 70/MW exported electricity (Larson and Carpentieri, 2008), with the use of 50% of the bagasse and 50% of the trash for gasification, are still a barrier hindering the implementation of the new technology. In fact, biomass can be co-gasified with coal, which can offer some valuable synergies, especially in the reduction of GHG (Green House Gases) emissions, what is already being commercially made at some electricity-generating facilities such as the Buggenum facility in the Netherlands (Pastoors, 2006), and several co-gasification projects are under development in Europe and in the U.S.

**New alternatives – Conversion of biomass to liquid fuels and chemicals**

For the production of liquid fuels and chemicals, there are a variety of possible conversion routes (Figure 5). Second-generation ethanol or butanol could be made via biochemical processing, while other second-generation fuels including methanol, Fischer-Tropsch liquids (FTL), dimethyl ether (DME) and green diesel could be made via thermochemical processing. Unrefined fuels such as pyrolysis oils are also produced thermochemically.

**Thermochemical biomass conversion to liquid fuels and chemicals**

Thermochemical production of biofuels begins with gasification or pyrolysis. Gasification is more capital-intensive and requires a larger scale for the best economics, but the intermediate fuel, the gas (also called synthesis gas, or syngas) is better converted to the final products when compared to the bio-oil from pyrolysis.

Raw pyrolysis oils are denser than water, highly acidic, odoriferous, carcinogenic, and require considerable refining before they can be used in engines. Pyrolysis bio-oil production has been considered as a possible pre-treatment step to facilitate feeding into a gasifier, especially a pressurised one.

Gasification-based processes can produce a variety of different biofuels, including Fisher-Tropsch diesel (FTD) and FT gasoline (FTG), dimethyl ether (DME), gasoline (via methanol,
MTG) or gasoline and diesel (via the MOGD process – methanol to olefins to gasoline and distillate), ethanol, and mixed alcohols (MOH). After gasification, contaminants in the gas are removed, followed by adjustments to the composition of the gas, using ‘gas reforming’ (CH4 + H2O → CO + 3H2), ‘water-gas shift’ (CO + H2O → CO2 + H2) reactions and carbon dioxide (CO2) removal, preparing the gas for further downstream processing of the final products (Figure 6). Major components of the clean and concentrated syngas are carbon monoxide (CO) and hydrogen (H2) that react when passed over a catalyst to produce liquid fuel. The design of the catalyst determines what biofuel is produced.

A second option for converting syngas to liquid fuel and one that has received less attention is represented by the dashed lines in Figure 6, where specially-designed micro-organisms ferment the syngas to ethanol or butanol. Despite considerable research, development, and pilot-scale demonstration work conducted by a few companies, commercial-scale projects are still needed to demonstrate viability.

Many second-generation thermochemical fuels are fuels that are already being made commercially from fossil fuels using processing steps that in some cases are identical to those that would be used for biofuel production (Figure 5). These fuels include methanol, refined Fischer-Tropsch liquids (FTL), dimethyl ether (DME) and diesel. Figure 7 indicates some of the possible bioproducts that can be obtained from biomass through gasification to substitute the fossil ones.

![Diagram of process steps for thermochemical biofuels production](image)

**Fig. 6**—Illustration of process steps for thermochemical biofuels production (Larson, 2008).

**Fig. 7**—Gasification bio-products as substitutes for conventional fossil ones (adapted from Larson, 2008).
Candidate diesel fuel substitutes are FT diesel or DME. While the future markets for these are far larger than the production potential of the sugarcane industry (as with electricity), there are challenges with both fuels that presently make them less attractive than electricity. FT diesel cannot be made without a significant co-product of naphtha (or naphtha upgraded to gasoline), and the economics of the diesel production depend on reasonable prices received for the co-product.

Chemical markets for naphtha are relatively small compared to fuel markets, so gasoline would need to be the end co-product. DME is an excellent diesel engine fuel, but vehicle fuel storage and delivery systems must be modified to enable DME use. This discourages the consideration of DME production for vehicles.

The use of DME as a Liquefied Petroleum Gas (LPG) replacement requires no infrastructure or end use equipment modifications for blends of up to about 25% DME in LPG. However, the potential of the sugarcane industry for producing DME should be compared to the expected demand for LPG to verify the economic feasibility, since in most cases the conversion of a small amount of sugarcane biomass will be able to meet DME blending limitations. Similar consideration applies to nitrogen fertiliser production from sugarcane biomass.

Most of the equipment components needed in a system for producing syngas for biofuel production is commercially available today. However, two areas needing further engineering development and demonstration are the feeding of biomass into large-scale pressurised gasifiers and the clean-up of the raw gas produced by the gasifier. The relatively low bulk density of biomass makes it challenging to feed into a pressurised gasifier efficiently and cost-effectively (Wilen and Rautalin, 1993).

Development is also needed in the area of syngas clean-up (especially tar removal or destruction) because tolerance to contaminants of downstream processes is low. Tars have been the most problematic of syngas contaminants and have been the focus of much attention. Methods for removal (or conversion to light permanent gases) are known, but still inefficient and/or relatively costly. The technologies involved in the conversion of syngas by catalytic synthesis are fully commercial today in some cases – FT, DME, MTG – while others are not yet commercially demonstrated, but are under active development (e.g., mixed alcohols, syngas fermentation technologies).

**Biological biomass conversion to liquid biofuels and chemicals**

Second-generation biochemically-produced alcohol fuels are often referred to as ‘cellulosic ethanol’ and ‘cellulosic biobutanol’. The basic steps for producing these include pre-treatment, saccharification, fermentation, and distillation.

Pre-treatment is done to separate the main biomass constituents: cellulose, hemicellulose and lignin, so that the complex carbohydrate molecules constituting the cellulose and hemicellulose can be broken down into simple sugars by enzyme-catalysed or acid-catalysed hydrolysis (water addition). Acid hydrolysis for ethanol production was already practised commercially in the 1930s, but due to high capital and operating costs was uncompetitive. Some companies are now once again promoting acid hydrolysis processes.

Cellulose is composed of long chains of glucose (6-carbon) sugar molecules which structure is difficult to separate into simple sugars, but once separated, the sugar molecules are easily fermented to ethanol using well-known micro-organisms, and some micro-organisms for fermentation to butanol are known. Hemicellulose consists of polymers of 5-carbon sugars and is relatively easily broken down into its constituent sugars such as xylose and pentose. However, fermentation of 5-carbon sugars is more challenging than that of 6-carbon sugars. Some recently developed micro-organisms are able to ferment 5-carbon sugars to ethanol and others to butanol (Jeffries, 2006; Aden et al., 2002). Lignin consists of phenols, which for practical purposes are not fermentable. However, lignin can be recovered and utilised as a fuel to provide process heat and electricity at an alcohol production facility or used as a raw material to other products.
A variety of different process designs have been proposed for production of second generation ethanol. One relatively well-defined approach for ethanol production is the use of separate hydrolysis (or saccharification) and fermentation steps. Other concepts include one that combines the hydrolysis and fermentation steps in a single reactor (simultaneous saccharification and fermentation) (Aden et al., 2002), and one that additionally integrates the enzyme production (from biomass) with the saccharification and fermentation steps (consolidated bioprocessing or CBP) (Zhang and Lynd, 2005). Less work has been done on butanol. There are only a few operating commercial demonstration plants for cellulosic ethanol production in the world today, such the one owned by Iogen (www.iogen.ca) in Canada, and the one of Inbicon (Langhans, 2012) in Denmark.

Presently, expected yield potential for the enzymatic-hydrolysis processes is about 270 litres of ethanol per tonne of dry biomass, but some researchers believe that the potential can reach 400 litres, with adequate financial support for research, pilot and commercial scale projects. The biological technology has been supported by some governments and research institutions. Development and demonstration efforts presently include (Houghton et al., 2006):

- Development of biomass with lower lignin content and structure that facilitates access to carbohydrate molecules.
- Improvement of enzymes: increased efficiency and reduced cost.
- Development of microorganisms that are able to ferment 5-carbon sugars efficiently.
- Development of robust processes and microorganisms to operate under commercial conditions.

It can be said that at the present stage of research developments, cellulosic ethanol can be produced, but producing it competitively still requires significant research.

Solid biofuels

The use of solid biofuels has gained attention, especially with co-firing of biomass pellets in coal electricity generation plants, as a means of reducing GHG emissions. Commercial plants pelletising agricultural biomass wastes are a reality today, such as the one in the UK, providing biomass pellets for the Drax Coal Energy Plant. The same technology could be used with sugarcane bagasse or trash. Though not common, bagasse pelletising has been employed in a few places such as in a plant in Iran. Demand for biomass pellets in Europe has increased rapidly in the past decade from a consumption of less than 2 million tonnes to more than 12 million tonnes, pushed basically by co-firing with coal. The dissemination of the use of this biofuel in many countries depends on a combination of: adequate regulatory structure of prices for the green energy, logistics of the biomass and pellets, technical support for the fossil fuel end user substitution, and guarantees of fuel supply. Thermal upgrading of solid biofuels is also under research. Torrefaction, carbonisation, charcoal production, are technologies being pursued, as a means to improve biomass properties.

Final comments

Given the significant amount of biomass resources potentially available from sugarcane operations today and in the future, the conversion of this biomass to any product requires that the potential market is large enough relative to the potential sugarcane industry production. Electricity and transportation fuel markets will generally satisfy this criterion.

Concern about climate change, energy security and high oil prices are factors contributing to accelerate the development in advanced biomass conversion technologies for power generation and for transportation fuels production. Among the technologies competing for this market, biological and thermochemical are the leading ones.

Biological processing of biomass is focused today mainly on ethanol production. The adoption of ethanol as a transportation fuel by some countries, created a big market for the product. Ethanol production could significantly increase by its production from lignocellulosic materials, a technology strongly pursued nowadays.
Advantages of the biomass derived ethanol include avoiding impact on food-price and indirect land use change due to biofuels production. There is a strong worldwide push for the substitution of transportation fossil fuels by biofuels, but presently the international market for bioethanol is still uncertain. Tariffs on imported ethanol in several countries, the need of a distribution network and modifications in the car engines are barriers to overcome. In the technical and economic aspects of the biological conversion, aside from fermentation of C6 sugars to ethanol, commercially-viable conversion rates (including fermentation of C5 sugars) are yet to be demonstrated, although many significant efforts are underway to overcome this drawback.

Anaerobic digestion, a biological processing technology to produce gas used in gas engines and turbines, that has been used in some countries, has historically not been of interest due to the size of fermentation reactors, considering the amount and characteristics of the feedstock (vinasse, bagasse and sugarcane trash) and the process characteristics (long retention time). The production of chemicals, such as butanol, acetic acid, succinic acid, xylitol, and others are more valuable products recently under consideration to be produced from biomass, which normally face the limitation of a small market potential.

Gasification is considered by several researchers as an important thermochemical conversion technology that should be introduced in the sugarcane sector because of the tremendous flexibility it offers for new revenue streams (electricity, liquid fuels, chemicals, etc.). Gasification-based technologies offer some intrinsic advantages over biochemical systems for power generation and for production of liquid fuels, synthetic natural gas, nitrogen fertilisers and other synthesised products.

For liquid fuels production, while biological processes have historically been favoured because of the familiarity of traditional ethanol processes, thermochemical processing offers

(i) more flexibility in the variety of feedstock (and variations within a given feedstock,
(ii) lower performance sensitivity to variations in process conditions such as temperature or feedstock contamination levels, and
(iii) a diversity of fuel and chemical end-products. No new fundamental research breakthroughs are needed.

Some engineering development work is still needed (such as feeding of sugarcane bagasse and trash into pressurised gasifiers), but the primary requirement preceding deployment of gasification-based conversion is system demonstration at the commercial scale. The challenge of getting to technically workable systems that are also economically viable should not be underestimated.

Most and not to say all mentioned technologies are not yet commercial, and no certain bet can be made on which ones will prevail. The economic competitiveness of the green products vis a vis the petrochemical ones is still a great challenge. Despite technical success, the deployment of any technology will strongly rely on a ‘learning curve’, which maturation depends on adequate regulatory and economic conditions favouring research, demonstration of the technology and the installation of a set of first plants.

Presently this scenario is favouring the biological process, especially in the United States, where huge resources have been provided for research and demonstration of the cellulosic ethanol (called advanced ethanol) technology, added to a regulatory mandate setting advantages for its commercialisation. Nevertheless, delays in the technical success of the process can change this scenario.

The electric engine is another technological route competing with liquid fuel engine for the huge car market. Strong research and investments have been made, especially focusing on reducing battery weight and increasing mileage, with significant involvement of the auto industry. Hybrid and electric cars are already a technical success, and the deployment of this technology has already started, and its impact on the fuel market should not be underestimated.
Gasification-based power could, in the future, supply significant increase in the amount of sugarcane electricity and cellulosic ethanol can greatly increase the ethanol production. Other products and technologies will come up, but the process has not been as fast as one would expect, due to the already mentioned challenges. In this dynamic scenario of new technologies and products, delay in technology reaching commercial competitiveness increases the risk of market changes, and increases uncertainty in technology deployment success. In most countries, electricity continues to be the safe choice in the near and medium future, with a market large enough to readily absorb all electricity generated from sugarcane biomass. Electricity generation is a familiar process to the sugarcane industry, and marketing channels are already well established in most countries. High pressure boilers, use of trash as additional fuel, reduction of process steam consumption are commercial technologies not fully utilised yet, that if implemented can increase the competitiveness of electricity even more.

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INTRODUCTION ET APERÇU DE LA SITUATION ACTUELLE DE L'EMPLOI DE LA BIOMASSE

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Résumé
PENDANT LONGTEMPS, L'INDUSTRIE de la canne à sucre a mis l'accent uniquement sur le jus de canne, son extraction et sa conversion en sucre. La bagasse était alors considérée comme un résidu et brûlée de façon inefficace pour générer de la vapeur et de l'énergie. Au cours des dernières décennies, la bagasse a progressivement commencé à être convertie en énergie de manière plus efficace, fournissant toute l'énergie nécessaire à l’industrie sucrière (travail mécanique, vapeur et électricité) et, dans certains cas, un excédent significatif d'électricité a été exporté sur le réseau publique, devenant ainsi une autre source importante de revenus. Cela a motivé plusieurs études sur des systèmes plus avancés de génération d'énergie pour augmenter cette export. Plus récemment, les technologies dites de 2ème et 3ème génération sont mises en avant avec de nombreuses options, promettant de convertir la biomasse en produits à plus haute valeur ajoutée tels que des biocarburants, des produits chimiques, de l’engrais, des granulés, etc.. Malheureusement, les attentes et opportunités non satisfaites sont en train de monter. De plus, ces technologies sont en concurrence pour la même biomasse, et cela doit être considéré. L'industrie a commencé à se demander « sur quelle voie aller », la stratégie et les investissements judicieux. La présente étude fournit un large scénario sur les disponibilités de la biomasse et son emploi, avec une vue précise sur les principaux procédés et produits qui pourraient avoir un rôle important sur l'avenir de la biomasse dans l'industrie de la canne à sucre.

REVISION DE LA SITUACIÓN ACTUAL DEL EMPLEO DE LA BIOMASA

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Resumen
LA INDUSTRIA DE LA CANA de azúcar se enfocó por largo tiempo solamente en el jugo de caña, su extracción y su conversión en azúcar. El bagazo era considerado un residuo y se le quemaba ineficientemente para generar vapor y potencia. En las últimas décadas se comenzó a convertir el bagazo en una forma más eficiente, suministrando todas las necesidades energéticas de la industria (potencia, vapor, electricidad) y, en algunos casos, cantidades significativas de electricidad han sido
Exportadas a la red, convirtiéndose en otra fuente importante de ingresos. Lo anterior motivó varios estudios de sistemas mas avanzados de generación de energía para incrementar la exportación a la red. En años mas recientes, han aparecido en escena tecnologías denominadas de 2ª y 3ª generación con muchas opciones, prometiendo convertir biomasa en productos mas valorados tales como biocombustibles, químicos, fertilizantes, pellets, etc. Las expectativas insatisfechas y las oportunidades están creciendo. Por otro lado, estas tecnologías compiten por la misma biomasa y esto tiene que ser considerado. La industria ha planteado la pregunta “que dirección tomar”, en estrategia y enfoque de inversión. El presente trabajo plantea un escenario amplio para la disponibilidad de biomasa y su empleo, concentrándose en los principales procesos y productos que podrían tener un papel importante en el futuro de la biomasa en la industria de la caña de azúcar.

INTRODUÇÃO E PANORAMA A SITUAÇÃO ATUAL DO EMPREGO DA BIOMASSA

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Resumo
Durante muito tempo, indústria de cana focou-se somente no caldo de cana, em sua extração e conversão em açúcar. O bagaço era considerado um resíduo e queimado de sem eficiência para gerar vapor e energia. Nas últimas décadas, o bagaço começou aos poucos a ser convertido em energia de maneira mais eficiente, atendendo a todas as necessidades energéticas da indústria de açúcar e, em alguns casos, excedentes de eletricidade tem sido exportados e se tornado importante fonte de receitas. Esse fato motivou vários estudos de sistemas mais avançados de geração de energia para aumentar as exportações de eletricidade. Nos últimos anos, tecnologias denominadas segunda e terceira geração dominaram a cena com muitas opções, prometendo converter biomassa em produtos mais valiosos, como biocombustíveis, químicos, fertilizantes, pellets, etc. Ainda há muitas expectativas e oportunidades não exploradas. Por outro lado, essas tecnologias estão competindo com a mesma biomassa, e isso deve ser considerado. A indústria começou a questionar qual o caminho tomar em termos de estratéjias e investimentos. Este estudo apresenta um cenário amplo da disponibilidade de biomassa e seu emprego, com uma visão íntima dos principais processos e produtos que poderiam ter um papel importante no futuro da biomassa na indústria da cana-de-açúcar.
THE SUGAR AND ALCOHOL INDUSTRY IN THE BIOFUELS AND COGENERATION ERA: A PARADIGM CHANGE

By

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KEYWORDS: Biofuels, Biorefinery, Cogeneration, Thermal Integration, Co-Products, Sustainable Development.

Abstract

The aim of this paper is to discuss the major technological changes related to the implementation of large-scale cogeneration and biofuel production in the sugar and alcohol industry. The reduction of the process steam consumption, implementation of new alternatives in driving mills, the widespread practice of high steam parameter use in cogeneration facilities, the insertion of new technologies for biofuels production (hydrolysis and gasification), the energy conversion of sugarcane trash and vinasse, production of animal feed, process integration and implementation of the biorefinery concept are considered. Another new paradigm consists in the widespread spreading of sustainability studies of products and processes using the Life Cycle Assessment (LCA) and the implementation of sustainability indexes. Every approach to this issue has an objective to increase the economic efficiency and the possibilities of sugarcane as a main source of two basic raw materials: fibres and sugar. The paper presents the concepts, indicators, state-of-the-art and perspectives of each of the referred issues.

Introduction

Undoubtedly, the balance of the first decade of the XXI century indicates the need for a change in the approach to solving the problem of insufficient fuel sources with the guarantee of food supply and a reduction in environmental impacts. The sugar and alcohol industry could contribute to a solution for the energy and environmental problems by expressing the full potential of the sugarcane culture, capable of providing a high potential for diversification, in the form of energy, materials, and the provision of new sources of food. Current paradigms have been overtaken by technology, history and necessity. Therefore, it is mandatory for change which is the proposal of this paper. Several new approaches in the future sugar and alcohol industry have been proposed (Escobar et al., 2009; Ojeda, et al., 2011; Murphy et al., 2011; Soccol et al., 2011; Lora and Venturini, 2012):

- New sugarcane varieties and new agro-techniques.
- Reduction of energy consumption in the production process.
- New alternatives of juice extraction (milling) systems.
- Steam parameter increases in cogeneration facilities.
- New biofuels technologies: gasification, hydrolysis and genetic engineering manipulation of microorganisms for biofuels production.
• Vinasse and sugarcane trash residual energy conversion.
• Materials and chemicals as by-products.
• Process integration.
• Biorefinery to transform materials into fuels, power, and chemicals using biological and chemical conversion processes.
• Industrial ecology: integration to terrestrial geochemical cycles.
• Sustainability assessment: Life Cycle Assessment (LCA).

Sugarcane agricultural production is the base and the indispensable support of the implementation of large-scale cogeneration systems and biofuels production. The cogeneration and biofuels goals will be based on the lignocellulosic residues, forcing parametric and technological changes which, in a few years, can lead to a completely different sugarcane, sugar, fuel and bioproducts industry: the biorefineries. The goal of this paper is to discuss the major technological changes related to the implementation of large scale cogeneration and biofuel production. The greater part of the results presented in this paper were obtained from the Brazilian Excellence Group in Thermal Power and Distributed Generation (NEST) and research projects of the Cuban Research Institute of Sugarcane Co-products (ICIDCA).

**The sugar and alcohol industry: Yesterday, Today and Tomorrow**

In the near future, by-products and energy in sugar and alcohol mills will move from a marginal or secondary production to a mainstream production that will broaden the spectrum of the sugarcane industry and make its economy more sustainable (Figure 1). The agro-industrial diversification should be considered an essential complement to sugar production that will increase the efficiency of the sugarcane operation and will provide true sustainability to the sugar and alcohol economy.

![Fig. 1—Evolution of the diversification concept in sugar and alcohol mills.](image)

Lora *et al.* (2008) and Lora *et al.* (2006) analysed the thermodynamic limits of ethanol and electricity production from sugarcane using current average or foreseen productivity indicators. The analysed scenarios were:
• Scenario A: ethanol production by the traditional way plus bioethanol production through Dedini Rapid Hydrolysis (DRH) of bagasse to obtain the maximum ethanol production.
• Scenario B: ethanol production by the traditional way (100% ethanol) plus cogeneration.
• Scenario C: current Brazilian ethanol facility (50% ethanol and 50% sugar) plus cogeneration.
• Scenario D: current Brazilian ethanol production (50% ethanol and 50% sugar) plus cogeneration using biomass integrated gasification with combined cycle gas turbine (BIG/GT).
• Scenario E: a kind of ‘cane-electric plant’. This installation will generate electricity by using ethanol in gas turbines and, in addition, bagasse is burnt in the recovery boiler at the bottoming cycle of the combined cycle to obtain the maximum electricity production.
• Scenario H: production of hydrogen (H₂) from the ethanol reforming to be used in a Solid Oxide Fuel Cell (SOFC) coupled to a gas turbine.

The option with the highest efficiency in the use of sugarcane energy was scenario A, corresponding to the maximisation of ethanol production by combining conventional first and second generation ethanol production as shown in Figure 2.

![Figure 2](image)

Fig. 2—The thermodynamic limits of the ethanol and electricity production from sugarcane. (a) Surplus electricity index; (b) Ethanol yield; (c) Energy in products (from the whole sugarcane energy content).
New varieties of sugarcane and agro-techniques: high sugar recovery in the mills

Sugarcane produces biomass and simple carbohydrates in the field and the mill recovers them. Therefore, the plant constitutes the crucial and determining element to productivity and economic feasibility. This represents 55–65% of the production cost of any current production alternatives, even reaching 70% for ethanol production (Lima and Bonomi, 2011). The sugarcane plant is composed of 83–92% of juice and 8–17% fibres. In Brazil, the lowest fibre contents are 7-8%, while the highest are 16–18%. The average found in the Southeast region is 11%, ranging from 9–15%, and the recommended fibre content in the sugarcane is 12.5% (Bassetto, 2006).

The objective for new varieties and new agro-techniques is the guarantee of higher agricultural yields. The sugar yield must be achieved from the lowest weight possible of sugarcane. Currently, the maximum attainable yields in the world are about 15.0 tonnes sugar/ha/year. Colombia has a sugar productivity of 10.23 tonnes sugar/ha/year (Moncada et al., 2013), Australia 12.07 tonnes sugar/ha/year (Renouf et al., 2008), Cuba 7.98 tonnes sugar/ha/year (Casas et al., 2011) and Brazil 10.80 (Fischer et al., 2008).

Thus, considering the harvesting, transportation, and milling to produce one tonne of raw sugar, Australia (crop yields of 85.0 tonnes sugarcane/ha/year) cuts, transports and mills 2.05 tonnes of sugarcane less than Colombia (crop yields of 93.0 tonnes sugarcane/ha/year), due to sugarcane varieties with higher sugar content. This means a significant difference that has an impact on the economy.

To make the new ethanol projects competitive, studies have pointed to the importance of investments in research, development and innovation (RD&I). In general, the investments can provide for the development of new sugarcane varieties, greater agricultural and industrial yields, and soil management techniques tailored to the locations considered in the projects. Investments in RD&I in the sugarcane environment significantly favours the search for greater agricultural efficiency, and agricultural genetic engineering manipulation promises significant increases in sugar content and biomass availability.

The sugar and alcohol industry has three different concepts in relation to sugar recovery:

- The percentage of sucrose content in sugarcane in the field, usually referred to in the sugar industry as the polarisation value (pol), could range between 14.5% and 16.0% at the peak of maturity of the best varieties.
- When the sugarcane is processed in the mill, we have ‘the yield’, that refers to the amount of sugar (tonnes) obtained from 100 tonnes of cane milled. It ranges between 12.5% and 14.0% in a good mill, and of course it will depend on the sucrose content of the cane that is being milled.
- The overall recovery performance is the expression of the amount of sugar that could be produced; around 90% in a good mill.

The three terms cannot be used alternatively, because each one has its specific use and meaning.

Overall performance in the sugar industry is defined by the industrial efficiency index. Sugar recovery is the key parameter indicating the amount of sugar recovered as a per cent of sugar entering the mill. The operating parameters vary within the mill region due to differences in sugarcane quality and varieties, mill equipment age and efficiency, and other specific operating conditions. Increasing mill capacities, extraction and fermentation performance were the main drivers behind increasing industrial efficiencies. Sugar extraction from sugarcane has increased in the period 1977–2003. The average annual improvement was 0.3%, and some mills have already reached extraction efficiencies of 98%. At present, the industrial efficiency is around 90% and it is difficult to expect a large evolution considering only today’s commercial technologies (Goldemberg, 2008).
Reduction of energy consumption in the production of sugar and alcohol

The whole industrial production chain should be driven by a specific objective to minimise (a) the consumption of electricity and steam, and (b) process losses, thereby improving the overall mill efficiency. Juice concentration by vacuum evaporation makes the operation have greater thermal energy requirements. The alternative would be to convert this net unitary energy demand into regenerative energy by employing the obtained vapour in each evaporation effect of the system as the energy source of the remaining stages of the installation.

Thus, it is possible to bleed vapour from the 1st, 2nd and 3rd evaporator vessels for the preheating of sugarcane juice, ethanol distillation, for vacuum pans, etc. This makes it possible to reduce the specific process steam consumption from 500 kg steam per tonne cane to 350 kg steam per tonne cane. This has been achieved and shown to be viable and operationally stable in a few sugar mills.

Sugarcane production is seasonal with an average of 150 operational days per year, another 160 days the sugarcane mill remains inactive, with 35–45 days for maintenance, repairs and capital investments. Hence, it is required to store biomass for the inter-crop period and this could be achieved by storing surplus bagasse and the available sugarcane residues (trash). Other evaluated options were eucalyptus wood and saccharine sorghum. For every 10 million tonnes cane processed, if the steam consumption is reduced from 500 kg/tc to 400 kg/tc, it is possible to recover an additional 450 000 tonnes of bagasse or 45 kg of surplus bagasse per tonne of cane.

It should be noted that, to define the specific steam consumption to be reached in a sugar and alcohol mill, a cost benefit analysis must be performed. Table 1 summarises the typical values of specific process steam consumption for different types of sugar and alcohol mills.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical values</td>
<td>~500</td>
<td>kg/tc</td>
</tr>
<tr>
<td>Improved values</td>
<td>430–450</td>
<td>kg/tc</td>
</tr>
<tr>
<td>Optimised distillery</td>
<td>370</td>
<td>kg/tc</td>
</tr>
<tr>
<td>Theoretical limit (Chang et al., 1999)</td>
<td>260–295</td>
<td>kg/tc</td>
</tr>
</tbody>
</table>

For the case of sugar mills and distilleries, the available technical alternatives to reduce the steam consumption are (Hassuani et al., 2005; Ensinas et al., 2007):

- Minimise the amount of water used in the vacuum pans and centrifugals.
- Fermented broth preheating before distillation.
- Thermal integration of distillation columns.
- Steam bleeding from the 1st, 2nd and 3rd effects for juice heating.
- Regenerative heat exchangers for juice/vinasse, juice/juice and juice/condensate.
- Mechanical stirrers for vacuum pans.
- Use of Flegstil technology and molecular sieves in the alcohol distillery.
- Syrup concentration up to 70 brix.
- Second stage steam bleeding for vacuum pans.

Milling system alternatives

For many years, the mills used in the sugarcane industry were driven by a set composed of steam turbine, speed reducers and open gears, with approximately 90% of market dominance. This was due to the low price of this technology at the time and reduced incentive to increase the energy efficiency of the facility (Lora and Venturini, 2012).

The demand for more efficient equipment opened space for electric motors, which indirectly contributed to improving the overall efficiency of the mill cogeneration system.
If the mill does not operate under high steam parameters that provide significant amounts of electricity with high efficiency cogeneration, the electrification of the mills has no economic feasibility (Pistore and Lora, 2006).

With regard to the extraction station systems, diffusers being the extraction economical alternative, have lower energy consumption and lower operation and maintenance costs. However, the required space is increased.

Another disadvantage related to this technology is that it carries more impurities with bagasse to the boilers, requiring more frequent cleaning of them. The average sucrose extraction in Brazilian mills for milling tandems is in the range of 96.5–97.5 and for diffusers is 97.5-98.5 (CGEE, 2009).

The use of hydraulic motors to drive the mills is a new and viable alternative of lower power demand that also gives the possibility of a more flexible operation, and that must be taken into account in the search for less energy demand in the sugar mills.

**Steam parameter increases in cogeneration plant and surplus electricity production**

Of the 18.84 MJ per kg of sugar that is consumed in a sugar factory, around 10.88–11.72 MJ are required as thermal energy in the production process and just 1.51–1.61 MJ are required as mechanical energy, a fact that enables the widespread use of the steam cycle in the cogeneration system.

A repetitive question in this case is what should be the most appropriate steam pressure in a sugar and alcohol mill? For decades, the pressure used in the boilers did not exceed 1.0 MPa. Afterwards, this value had increased to 2.0 MPa, and values of 4.0 and 6.0 MPa are commonly found in modern thermal power stations. However, pressures of 8.0 and 12.0 MPa are already being used in new facilities. The definition of the steam parameter values in specific cases requires a cost/benefit analysis.

Among the works dealing with the evaluation of cogeneration potential of the sugar and alcohol mills, it is possible to highlight those carried out by Avram et al. (2007), Lora et al. (2006), Lora et al. (2000) and Albert-Thenet (1991).

Avram et al. (2004) evaluated some technologies that increased the surplus electricity generation and energy integration of a sugarcane factory, indicating a potential for cogeneration of 123–153 kWh/tc when using high steam parameters (6.3 MPa), bagasse drying with steam and burning of concentrated vinasse.

The Equipav Sugar and Alcohol Mill has implemented a modern cogeneration system, deploying new boilers and extraction-condensing steam turbines, operating with steam parameters of 6.5 MPa and 480 °C.

This system was implemented simultaneously with the adoption of measures to reduce the steam consumption in the process (from 530 kg/tc to around 430–450 kg/tc). The exported electricity increased as a result of these measures from 14–18 kWh/tc to 78 kWh/tc. The specific investment in generating equipment was 315 USD/kW (Cruz, 2006).

The new technology in prospect to increase the electricity generation is the Biomass Integrated Gasification Combined Cycle (BIG/CC) power systems in which the rate of surplus generation could reach values of 220–380 kWh/tc.

Nowadays, the insufficient development of the gasification technology and gas cleaning remains a problem.

The International Sugarcane Biomass Utilization Consortium (ISBUC/ISSCT) and the Brazilian government are beginning to work on two separate projects for the development of the technology for bagasse and sugarcane trash gasification.

Figure 3 shows a scheme of a BIG-GT system, coupled to an installation in a sugar and alcohol mill.
It is necessary to consider that the increases in the index of surplus electricity generation must be accompanied by a reduction of the steam consumption in the process. This interaction is shown in Figure 4.

Table 2 shows data of the surplus electricity generation index with corresponding values of the specific process steam consumption.
Table 2—Comparative data of the electricity surplus generation index in sugar and alcohol mills showing specific values of steam consumption for each case.

<table>
<thead>
<tr>
<th>Steam pressure (MPa)</th>
<th>Steam consumption in the process (kg/tc)</th>
<th>Index of surplus electricity generation (kWh/tc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>&gt; 500.0</td>
<td>10.0–14.0</td>
</tr>
<tr>
<td>6.5</td>
<td>Reduction of steam consumption down to 430–450 kg/tc.</td>
<td>60.0</td>
</tr>
<tr>
<td>6.5</td>
<td>Sugarcane trash utilisation (50%)</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Recent research developed by CGEE (2009)  
BIG-GT power system  
* Center for Strategic Studies and Management, Brazilian Government, Brazil.

New technologies for biofuels production: hydrolysis and gasification

The bagasse and sugarcane trash can be used to produce biofuels through two alternative technological routes: the biochemical route (enzymatic hydrolysis plus fermentation) and the thermochemical route (gasification plus chemical catalytic synthesis). A second generation biofuel plant was modelled having a capacity of 400 MWth, or 1777 tonnes dry bagasse per day (Obando et al., 2010). The results are shown in Figures 5 and 6 and the grey columns represent the total investment cost and the black lines the variation in range of biofuel production cost.

![Figure 5](image1.png)

**Fig. 5**—Comparison of the total investment cost and specific biofuel production cost obtained by biochemical and thermochemical routes (current scenario).

![Figure 6](image2.png)

**Fig. 6**—Comparison of the total investment cost and specific biofuel production cost obtained by biochemical and thermochemical routes. Optimistic scenario with the cost of enzymes of 1.79 USD/GJHHV (0.05 USD/L of bioethanol).
For the ethanol production plant using Simultaneous Saccharification and Fermentation – SSF and Simultaneous Saccharification and Co-Fermentation SSCF enzymatic hydrolysis, the enzyme costs represent 66 and 70% of the total biofuel production costs, respectively. The behaviour of the production costs for the SSCF case is similar to SSF. A reduction of 55% in the cost of the enzymes results in a bioethanol production cost of 11.21 USD/GJ HHV, referred this indicator to energy units GJ of high heating value – HHV, (0.314 USD/L). Significant changes in the production costs are not observed for variations in the other economical parameters. The bioethanol production cost through SSF technology is larger than the production cost by the SSCF method at 17.14 USD/GJ_{HHV} (0.48 USD/L of bioethanol) and 16.07 USD/GJ_{HHV} (0.45 USD/L of bioethanol), respectively. These costs are still are very high when compared with the costs of ethanol starting from sugarcane juice and from corn.

Different from the case of the biochemical platform is the thermochemical one, in which the largest percentage of the biomethanol production cost corresponds to investment with 65%, followed by the fixed costs of maintenance and operation (22%), cost of sugarcane bagasse (18%) and electricity commercialisation revenues (−4%). It is observed that the total investment cost of the biomethanol plant is much higher than for the bioethanol plants. The production cost of the bioethanol starting from the enzymatic hydrolysis is higher than the production cost of biomethanol. This is due mainly to the high annual total costs involved in the biochemical platform (Figure 5).

Bioethanol production costs are greater than biomethanol ones, which are 13.68 USD/GJ_{HHV} (0.383 USD/L) and 11.73 USD/GJ_{HHV} (0.328 USD/L), respectively (Figure 6). Bioethanol production cost becomes competitive when compared with the production costs of the sugarcane juice ethanol. Considering the process energy efficiency (GJ_{production}/GJ_{required}), the biomethanol production starting from biomass presents a greater value, of 45.3%, than bioethanol production through enzymatic hydrolysis types, both SSCF and SSF, which have an efficiency of 34 and 25%, respectively.

The technologies of both routes are still in the pilot plant stage. They allow, in principle, to produce a wide range of biofuels: ethanol, methanol, butanol, dimethyl ether (DME), etc. The bottleneck in the thermochemical route is the insufficient development of the large scale biomass gasification technology. The recent price reduction of enzymes made the biochemical route more attractive and the first industrial scale facility will begin operation in 2013. It will be a true trial of its viability which is still to be shown.

According to Lima and Bonomi (2011), with the implementation of the conventional ethanol production together with the bioethanol production through a biochemical route (enzymatic hydrolysis), the ethanol production will increase from 82 L/tc up to 118 L/tc.

Dias et al. (2011) simulated a commercial first generation ethanol distillery (1G) with the implementation of a second generation (2G) ethanol production process using bagasse and trash. The main issues to be considered in 2G ethanol production are the type of implemented bagasse pre-treatment (H$_2$O$_2$, steam explosion and Organosolv), the hydrolysis time and the biodigestion of obtained pentoses. The 2G ethanol plant capacity was around 20–27 L/tc for the steam explosion pre-treatment and 24–48 h hydrolysis time. The 2G ethanol process was shown to have a 19–22% higher production cost. Surplus electricity index for the best cases reached 110 kWh/tc.

The Brazilian Company GraalBIO intends to build in 2013 the first lignocellulosic ethanol facility from sugarcane bagasse with a capacity of 82 million litres of ethanol per year. The company is also working to develop a specific variety of sugarcane to be used in second generation facilities.

**Waste energy utilisation: vinasses and sugarcane trash**

Among the wastes from ethanol production, the most aggressive, but also that which has the most potential and diversity of use is the vinasse. Typically, 8–15 litres of vinasse is generated for every litre of ethanol produced. Vinasse recirculation technology implemented in Colombian
ethanol distilleries by the Indian Praj Company, and using dedicated yeast strength, reduced the vinasse yield down to 4 L/L of ethanol.

The vinasse generated in a sugar and alcohol mill is in the temperature range of 70–80 ºC, deep brown in colour, acidic in nature (low pH), and high concentration of dissolved organic and inorganic matter. The biochemical oxygen demand (BOD) and chemical oxygen demand (COD), the index of its polluting character, typically range between 35 000–50 000 mg/L and 100 000–150 000 mg/L, respectively (Rocha et al., 2008; Pant and Adholeya, 2007).

There are several options for the use of the vinasse: return to agricultural fields, anaerobic digestion and methane production, aerobic fermentation to produce animal feed protein concentrate and incineration of concentrated vinasse. One of the most attractive treatment and energy conversion technologies is the anaerobic digestion. However, there has not been widespread adoption due mainly to the investment related with the anaerobic reactor. Real costs of biogas derived from actual costs of anaerobic digestion facilities, without considering the economic impact of inorganic fertiliser replaced are 0.038 USD/m³ of biogas. The economic internalisation of this factor reduces this value to 0.022 USD/m³, (Salomon et al., 2011; Salomon and Lora, 2009).

In Figures 7 and 8 the differential mass and energy balance for agro-industrial systems for the case of vinasse anaerobic digestion and concentration of the vinasse up to 65% to enable the combustion in boilers together with fuel oil are shown (Rocha et al., 2010). In both cases, a considerable amount of electricity is generated, and the potassium contained in the residual mud and ash is available as a fertiliser.

![Fig. 7—Differential mass and energy balance for anaerobic digestion of vinasse.](image-url)
Sugarcane trash is a valuable residue of the sugar and alcohol agricultural production stage. The amount of this waste is around 10–14 t/ha, or 140 kg/t sugarcane (dry basis). The collection of sugarcane trash and its transport to the facility is associated with an additional cost, mainly due to its low density, so this differentiates it from the sugarcane bagasse. Due to its high value as an additional energy source, new equipment is being developed to collect and compress the sugarcane trash to make simpler and less costly its collection and transport to the energy plants. In any case, it is advisable to associate the trash with high efficiency conversion technology in the cogeneration plants (Hassuani et al., 2005).

According to recent studies performed by Sugarcane Technology Center (CTC) and the Brazilian Sugarcane Industry Association (UNICA), the fraction of sugarcane trash that could be removed from the field would be 50%, but more rigorous research is needed, and conservative values could be in the range of 30–50%, depending on the type of soil and the climatic conditions of the cultivated areas.

![Fig. 8—Differential mass and energy balance for combustion of the concentrated vinasse.](image)

The single experience in industrial scale of extensive sugarcane trash utilisation for power generation over several years was the Equipav facility in Brazil. The main objective in this case was to ensure the fuel for off-season electricity generation. The installed capacity of this power plant is 135 MW. In the Equipav mill, 50% of the trash is mechanically collected and transported to the industrial facility. The annual generation of Equipav Mill is around $620 \times 10^3$ MWh, of which $470 \times 10^3$ MWh are delivered to the public grid.

**Production of materials and chemical products**

The diversification of the sugar and alcohol industry has been the subject of many years of research at the ICIDCA in Cuba. These results are described in the Handbook of Sugarcane By-products (ICIDCA, 2000). The book ‘By-Products of the Cane Sugar Industry’ published by Maurice Paturau in 1969 is another important reference (Paturau, 1969). In the 80s, there were in Cuba dozens of factories with co-product plants that produced boards, paper, animal feed, drugs, furfural and other derivatives (Almazán et al., 1998). Today these products are being produced in various countries. The main industrialised by-products of the sugar and alcohol industry are:

- Furfural: production plants are in operation in Australia, South Africa and the Dominican Republic. An important indicator is the need for 25 tonnes of bagasse to produce one tonne of furfural. Main furfural applications are refining of lubricating oils, discoloration agent, purification technologies for C4 and C5 hydrocarbons,
reactive sorbent, wetting agent and chemical feedstock for furan derivatives (IFC, 2012).

- Fibre and particle boards: plain and laminated boards for furniture and flooring. New fibre board plants in India, USA, China, Indonesia and Iran (Youngquist et al., 1994).

- Paper: bagasse is used as the raw material for paper production in Colombia, Argentina, Indonesia, India, Bangladesh, Iraq and Pakistan. The Quena paper factory in Egypt has a capacity of 144 000 tonnes of paper per year, uses 70–85% of bagasse (Häussler, 2001).

- Composite materials: bagasse filled polyethylene (PE) and polypropylene (PP). Characteristics of bagasse/glass fibre composites were studied by Tewari et al. (2012).

- Food containers and disposable tableware, already commercially available in several countries.

- Biopolymers: ethane, polyethylene and polypropylene. In Brazil, the Braskem Company produces the so-called ‘green plastics’. Polyethylene is produced from ethanol, where ethylene (C₂H₄) is an intermediate compound (Coutinho, 2011). Dow Chemical Company and Crystalsev created a joint venture in 2007 for the implementation of a plant for the production of 350x10⁶ t/year of Linear Low Density Polyethylene (LLDPE) (Dow, 2007). The project was taken up in 2011 by a new joint venture between Dow and Mitsui.

- New bio-products: sorbitol, levulinic acid, lactic acid, succinic acid, furan dicarboxylic acid (FDCA), hydroxymethylfurfural (HMF), 3-hydroxypropionic acid and bio-hydrocarbons. The International Consortium for Sugarcane Biotechnology (ICSB) is working on the concept ‘Sugarcane as a Biofactory’.

Animal feed production

Another way to use the vinasse from the distillation of ethanol is the production, by means of biotechnology, of a protein concentrate, which can be used as fodder.

Vinasse contains carbon compounds and nitrogen assumable by the microorganisms and widely available; therefore, it could be used for the production of microbial biomass. This biomass could be used as a protein supplement, called single cell protein (SCP) for animal feed. Vinasse offers the added advantage that it is relatively free of toxins and fermentation inhibitors. SCP is normally considered to be a valuable source of protein but it also contains nucleic acids, carbohydrates, cell wall material, lipids, minerals and vitamins (Silva et al., 2011).

The first laboratory studies about the utilisation of vinasse for the propagation of microbial biomass can be traced back to the late 60s. The reduction of organic load and, at the same time, the production of valuable protein is the best feature of this process. The vinasse being an environmental threat could become a precious advantage as a source of energy and carbon for the biosynthesis of microbial biomass by the aerobic propagation of yeast cells (Otero et al., 2007).

Optimal conditions for SCP production and COD reduction of vinasse have been specified for different species of microorganisms in continuous cultures. Under these conditions, the COD reduction levels range from 40 to 70% (Silva et al., 2011; Shojaosadati et al., 1999; Nudel et al., 1987). The stillage medium increases the biomass production and COD reduction levels, but its application depends on economical evaluation of the process. So, the most appropriate way will be to combine the alternative of protein biosynthesis with fertigation. Biogas from vinasse biodigestion could be used for yeast drying.

To give an idea of the numbers involved, an ethanol distillery with a capacity of 200 000 L/day will give enough vinasse for the operation of a protein synthesis installation of 50 t/day of a
protein concentrate of 92% dry matter, 45% crude protein. In an average distillery, 4.0–6.0 kg of yeast per each 100 litres of ethanol 100°GL can be recuperated (de Souza et al., 2012).

Vinasse yeast has a protein content of 45% while pasture grass has a protein content of 6-10%. The yeast SCP can partially substitute for grass in cattle grazing on pasture and thereby potentially release land (land substitution) for increased sugarcane production, with minimal land use change effects. It is possible to state that a positive land release is the resulting advantage of the use of the vinasse for SCP production. For the vinasse yeast plant size of 22.2 tonnes/day, the land released is 1000 ha. For increased production of the yeast plant, additional land can be released to a limit of about 1800 ha for a 40 tonnes/day plant, which means increasing up to 144 000 tonnes of sugarcane cultivation if desired. A conservative approach indicates that the land for cattle grazing in Brazil could be reduced by 50% (de Souza et al., 2012).

**Process integration**

The production of co-products should be combined, when possible, with sugar production by ‘integrated technological schemes’, linked together from the technological point of view, energy and services/utilities (Escobar et al., 2011).

Escobar (2010) conducted an integrated assessment of a cogeneration plant and a distillery in an autonomous distillery using Aspen Plus™ and Gate-Cycle™ software. The study involved the simultaneous evaluation of the influence of various steam parameters of the cogeneration plant, different types of mill drives and changes in the ethanol production technology. Figures 9(a) and 9(b) show the process integration in an alcohol distillery and Tables 3 and 4 summarise the evaluated scenarios. A few alternatives were evaluated for each scenario. For example C6: DF-MST-AD means 4.2 MPa and 300 °C steam parameters, diffuser milling system, multiple stage driving steam turbine and atmospheric distillation.

The income from the sale of surplus electricity for steam parameters of 4.2 MPa and 420°C and different technologies used in the ethanol production plant was determined. For a commercialisation price of the surplus electricity of 68.00 USD/MWh, the income generated from the sale of ethanol at a price of 0.30 USD/L is 30.95 USD/te on average (Figure 10).

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**Fig. 9(a)—Process integration in an alcohol distillery – cogeneration plant.**
Fig. 9(b)—Process integration in an alcohol distillery – distillery.

Table 3—Analysed scenarios C1–C5 (Escobar, 2010).

<table>
<thead>
<tr>
<th>Equipment and parameters</th>
<th>C1 (Base Case)</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler: 2.0 MPa, 300°C</td>
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<td></td>
<td></td>
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<tr>
<td>Boiler: 4.2 MPa, 420°C</td>
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<td>X</td>
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<td></td>
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<tr>
<td>Boiler: 6.0 MPa, 490°C</td>
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<td></td>
<td>X</td>
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<tr>
<td>Boiler: 8.0 MPa, 510°C</td>
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<td></td>
<td>X</td>
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<tr>
<td>Boiler: 12.0 MPa, 520°C</td>
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<td></td>
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<td>Electric Generators</td>
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<tr>
<td>Backpressure Turbines</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Condensing–Extraction Steam Turbines (CEST)</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>Mills</td>
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<tr>
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<td>Distillation station</td>
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<td>Atmospheric Distillation (AD)</td>
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<td></td>
<td>X</td>
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</tr>
</tbody>
</table>

Fig. 10—Specific income of technological alternatives considered in scenario C6.
Table 4—Analysed scenarios C6–C9 (Escobar, 2010).

<table>
<thead>
<tr>
<th>Equipment and parameters</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
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<tr>
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<td>Boiler: 6.5 MPa, 490°C – CEST</td>
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<td>Boiler: 8.0 MPa, 510°C – CEST</td>
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<td>X</td>
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<tr>
<td>Boiler: 12.0 MPa, 520°C – CEST</td>
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<td>X</td>
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<tr>
<td>Electric generators</td>
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<tr>
<td>Backpressure Turbines</td>
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<td></td>
</tr>
<tr>
<td>Condensing–Extraction Steam Turbines (CEST)</td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mills</td>
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<td></td>
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<tr>
<td>Multistage Turbines (MST)</td>
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<tr>
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<td>a</td>
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<td>X</td>
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<tr>
<td>Diffuser – Multistage Turbines (DF-MST)</td>
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<td>X</td>
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<tr>
<td>Diffuser – Electric Motors (DF-EM)</td>
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<td>Evaporation station</td>
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<td>Distillation station</td>
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</tbody>
</table>

* It is not economically feasible (Pistore and Lora, 2006).

The AD and MD distillation stations were not considered in the same scenario, and therefore cannot be considered to be mutually exclusive because they form two different scenarios to account for the steam reduction in the plant. Figure 11 shows the values of the distillery global efficiency for the different evaluated scenarios.

![Fig. 11—Comparison of exergetic efficiency of ethanol plants with different technologies.](image)

It is possible to note that the use of systems based on MST combined with a MD system (scenario C8) gives increments of 2% in the global efficiency of the plant in relation to the base case. Implementation of mills driven by commercially available EM equipped with AD and MD systems allow increases in the overall efficiency of 0.3 and 1.4%, respectively. When technological alternatives are composed of DF-MST-AD and DF-EM-AD systems, the increase in the efficiency is 1%. The overall efficiency could be increased by 3% through the use of the DF-MST-MD and DF-EM-MD systems of the scenario C8 in relation to the base case.

It is possible to note that the use of systems based on MST-MD (scenario C9) gives increments of 2% in the global efficiency of the plant in relation to the base case. When the technological alternative EM-AD is used, the increase in the global efficiency is 0.3%.
The overall efficiency could be increased by 2% through the use of the EM-MD system, 1.5% for the use of the technological alternative DF-MST-AD, 3% for DF-MST-MD technological alternative, 2% for DF-EM-AD and 3% for DF-EM-MD technological alternative system of the scenario C9 in relation to the base case.

In relation to the technological alternative MST-AD in scenario C6, incorporation of technological alternatives DF-MST-AD, MST-MD and DF-MST-MD increases the specific income through the sale of surplus electricity of the plant by 12%, 11% and 22%, respectively. For scenarios C7, C8 and C9, the best specific incomes are obtained when the technological alternative utilised is DF-EM-MD. In these scenarios the incomes are 26%, 23% and 22% higher in comparison to the scenario MST-AD.

Another factor that contributes to the reduction in process steam consumption and a reduction in the volume of vinasse produced is the alcohol content in the fermented wine. For an AD system, increases in alcohol content of wine from 7 to 9% enable a decrease of approximately 18% in the specific consumption of steam in the system (kg/L of hydrated ethanol).

For a MD system, it is possible to obtain a decrease of approximately 3% in the specific steam consumption of the system for every 0.5% increase in alcohol content of wine. It can be seen in Figure 12 that the vinasse production per litre of the hydrated ethylic alcohol (HEA) produced decreases by approximately 6% for every 0.5% increase in alcohol content of wine.

![Fig. 12—Specific vinasse production in the plant related to the alcohol content in the distillation of fermented wine.](image)

**Biorefineries: The materialisation of the process integration**

The biorefinery concept is analogous to the oil refinery which produces multiple fuels and products from petroleum. However, unlike the oil refinery, a biorefinery uses renewable resources and its wastes in an integrated and diversified way. Based on the thermochemical, biochemical platforms or a mixture of both, the biorefineries can produce a wide range of products (chemicals, fuels, fertilisers, plastics, etc.) and energy with a minimum waste generation and very low pollutant emission. Figure 13 shows the main possible routes to be implemented in a sugarcane based biorefinery.

Among the main advantages of implementing this type of system in the sugar and alcohol industry, are the energy efficiency, the production of alternative fuels (e.g. methanol), lower emission levels, all at reduced costs. In Brazil, the program PAISS (Technological Innovation for the Energy and Biochemical Production from Sugarcane) from BNDES (Brazilian Development Bank) and FINEP (Studies and Projects Funding) provided for the construction of 12 pilot plants and seven industrial plants.
Figures 14 and 15 present the results of the mass and energy balances of a sugarcane biorefinery model, based on the thermochemical platform (gasification), which produces biomethanol, bioethanol and electricity to the grid, consisting of an autonomous distillery, cogeneration plant and annexed methanol plant (Cases 2 and 4 respectively). Figure 15 includes a BIG/GT system. Figure 16 shows the results of the exergetic efficiency of processing sugarcane under biorefineries systems (Renó, 2011) for the four cases:

- Autonomous distillery, cogeneration plant and autonomous methanol plant (Case 1).
- Autonomous distillery, cogeneration plant and annexed methanol plant (Case 2).
- Sugar and alcohol mill, cogeneration plant and annexed methanol plant (Case 3).
- Sugar and alcohol mill, cogeneration plant, annexed methanol plant and BIG/GT (Case 4).
Figure 14 shows the total available exergy rate from the sum of the products exergy (methanol, ethanol and electricity) pointed out in the shaded area of the circle for each of the analysed cases and the overall exergy destruction rate (unavailable exergy that is the sum of the destroyed and the lost exergies) pointed out in the white area of the circles. All the analysed cases showed the feasibility of the integration of production derived on the structural framework of the sugar and alcohol mills. It is noteworthy that the exergy analysis showed that the sugarcane energy use is increased due to the complementation and diversification of production within the biorefineries.

Figure 16—Exergy efficiency of the sugarcane energy utilisation in different thermochemical platform biorefinery schemes.
Industrial ecology

The return of nutrients to the soil through fertigation (Figure 17), the anaerobic digestion sludge and/or the ash from vinasse incineration are ways of integrating the sugar and alcohol industry to the terrestrial geochemical cycles and a true contribution to the mitigation of soil degradation. The production of protein concentrates for animal feed is the shortest way to a more rational utilisation of the soil in cattle raising.

![Fig. 17—Integration of the sugarcane agro-industry to geochemical cycles through fertigation.](image)

Sustainability evaluation: Life Cycle Assessment

In the sugar and alcohol industry, as in any other human activities, the sustainability evaluation is presently mandatory. LCA is considered the standard tool for sustainability studies (Lora et al., 2011) despite its inconsistencies. The real possibility of the implementation of ‘environmentally based’ trade barriers and certification systems forced the funding of projects and research to solve the bottlenecks of sustainability evaluation methodologies.

Two main indicators are used: the Output/Input Index also known as Energy Ratio (Renewable Energy/Fossil Energy Relation) and the reduction in greenhouse gases (GHG) emissions of a biofuel when compared with the substituted fossil fuel (for example ethanol and gasoline). The best sugar and alcohol factories in Brazil and other countries show excellent values in both indexes; otherwise it is necessary to carry out these studies for different geographical and technological scenarios for process improvements or alternatives selection.

The international sustainability criteria for biofuels prioritise the energy ratio and the reduction in life cycle GHG emissions in comparison to fossil fuels (gasoline and diesel). The energy ratio and the reduction in life cycle GHG emissions of the ethanol production resulting from different studies are shown in Table 5.

Conclusions

The sugarcane agro-industry is the base and the indispensable support for the implementation of a large scale energy cogeneration system and biofuels production. Also, any strategy must keep in mind that sugar is more than a sweetener; it is the simplest, purest, safest and cheapest source of energy that human beings have.

For that reason, the cogeneration and biofuels goals – in an economic and ecological coherent development – will be based on the lignocellulosic residues, forcing parametric and technological changes which, in a few years, can lead to a completely different sugarcane, sugar and fuel industry. The changes will be so radical as to present a novel profile, forcing a new paradigm for the increase of the sugarcane energy, food and safe world contribution.
### Table 5—Energy ratio and GHG emissions of ethanol production.

<table>
<thead>
<tr>
<th>Reference</th>
<th>GHG emissions (kg CO₂/kg ethanol)</th>
<th>GHG reduction (%)</th>
<th>Energy ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brazilian studies</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavalett et al. (2013)</td>
<td>0.672</td>
<td>76.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Seabra et al. (2011)</td>
<td>0.597</td>
<td>78.7</td>
<td>–</td>
</tr>
<tr>
<td>Walter et al. (2011)</td>
<td>1.035</td>
<td>63.1</td>
<td>9.0</td>
</tr>
<tr>
<td>Luo et al. (2009)</td>
<td>0.378</td>
<td>86.5</td>
<td>9.3</td>
</tr>
<tr>
<td>Macedo et al. (2008)</td>
<td>0.553 (2005 scenario)</td>
<td>80.3</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>0.438 (2020 scenario)</td>
<td>84.4</td>
<td></td>
</tr>
<tr>
<td><strong>Other countries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argentina (Acreche and Valeiro, 2013)</td>
<td>1.420</td>
<td>49.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Mexico (García et al., 2011)</td>
<td>2.582</td>
<td>7.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Thailand (Silalertruksa and Gheewala, 2009)</td>
<td>0.869</td>
<td>68.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Petroleum gasoline (Wang et al., 2011)</td>
<td>2.80</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The European value of petroleum gasoline life cycle GHG emissions is 83.8 kg CO₂-eq./GJ and the USA value ranges between 90 and 110 kg CO₂-eq./GJ (Wang et al., 2011).

Technological development will allow the advancement from the current option, limited to bioethanol (1st generation biofuels), to cellulosic bioethanol, methanol, DME, biobutanol, biodiesel (jet fuel) and diesel/gasoline (Fischer-Tropsch synthesis) all obtained from biochemical and thermochemical conversion platforms of lignocellulosic residues (2nd and 3rd generation biofuels).

This will allow the use of huge amounts of raw material (sugarcane trash) and the reduction of the impact on food production. More investments in RD&I programs are necessary so that the technologies for the production of 2nd and 3rd generation biofuels can reach a commercial stage.

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L’INDUSTRIE SUCRE-ALCOOL DANS L’ERE DES BIOCARBURANTS 
ET DE LA COGENERATION: UN CHANGEMENT DE PARADIGME

Par

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MOTS-CLES: Biocarburant, Bioraffinerie, 
Cogénération, Integration Thermique, 
Coproduits, Développement Durable.

Résumé

Le but de cet article est de discuter des changements technologiques majeurs relatifs à 
l’implémentation de cogénération et de production de biocarburant à grande échelle dans l’industrie 
sucré-alcool. La réduction de la consommation de vapeur dans le process, l’implémentation de 
 nouvelles alternatives dans l’entraînement des moulins, l’utilisation courante de vapeur haute 
pression dans les centrales de cogénération et l’insertion de nouvelles technologies pour la 
production de biocarburants (hydrolyse et gazéification), la conversion énergétique du non canne et 
de la vinasse, la production d’aliments pour le bétail, l’intégration des procédés et le concept de 
bioraffinerie sont autant de sujets abordés. Un autre nouveau paradigme est l’étude courante de la 
durabilité des produits et des procédés via l’Analyse du Cycle de Vie (ACV) et l’attribution 
d’indexes de durabilité. Toutes ces approches ont pour objectif d’augmenter l’efficacité économique 
et les possibilités de la canne à sucre en tant que principale source de matières premières : les fibres 
et le sucre. Cet article présente les concepts, les indicateurs, l’état de l’art et les perspectives des 
différents éléments abordés.
LA INDUSTRIA DE AZÚCAR Y ALCOHOL EN LA ERA DE LOS BIOCOMBUSTIBLES Y LA COGENERACIÓN: UN CAMBIO DE PARADIGMAS

Por

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PALABRAS CLAVE: Biocombustibles, Biorefinería, Cogeneración, Integración Térmica, Co-Productos, Desarrollo Sostenible.

Resumen

El objetivo de este artículo es discutir los principales cambios tecnológicos relacionados con la implementación de producciones de biocombustibles y la cogeneración de energía a gran escala en la industria de azúcar y alcohol. Se consideran la reducción del consumo de vapor en el proceso, la implementación de nuevas alternativas de movimiento de los molinos, la práctica generalizada del empleo de altas presiones de vapor en las instalaciones de cogeneración, la inserción de nuevas tecnologías para la producción de biocombustibles (gasificación e hidrólisis), la conversión energética de la paja de la caña y las vinazas de destilerías, producción de alimento animal, integración de procesos y la implementación del concepto de biorefinerías. Otro nuevo paradigma consiste en la generalización de los estudios de sostenibilidad de productos y procesos empleando la Evaluación del Ciclo de Vida (Life Cycle Assesment , LCA) y el establecimiento de índices de sostenibilidad. Cada abordaje a este aspecto, tiene como objetivo incrementar la eficiencia económica y las posibilidades de la caña de azúcar como la principal fuente de dos materias primas básicas: fibras y azúcares. El artículo presenta los conceptos, indicadores, el estado del arte y las perspectivas, en cada uno de los aspectos referidos.
A INDÚSTRIA DE AÇÚCAR E ÁLCOOL NA ERA DE BIOCOMBUSTÍVEIS E COGERAÇÃO: UMA MUDANÇA DE PARADIGMA

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PALAVRAS-CHAVE: Biocombustíveis, Biorrefinaria, Cogeração, Integração Térmica, Coprodutos, Desenvolvimento Sustentável.

Resumo

O OBJETIVO DESTE TRABALHO é discutir as principais mudanças tecnológicas relacionadas à implementação de cogeração de larga escala e produção de biocombustíveis em uma indústria de açúcar e álcool. São avaliadas a redução do consumo de vapor do processo, a implementação de novas alternativas em moendas, a prática disseminada de uso de parâmetro de alto vapor nas instalações de cogeração, a inserção de novas tecnologias para produção de biocombustíveis (hidrólise e gasificação), a conversão de energia da palha da cana e da vinhaça, a produção de ração animal, a integração do processo e a implementação do conceito de biorrefinaria. Outro novo paradigma consiste em disseminar estudos de sustentabilidade de produtos e processos utilizando a Avaliação de Ciclo de Vida (LCA) e a implementação de índices de sustentabilidade. Todas as abordagens dessa questão têm por objetivo aumentar a eficiência econômica e as possibilidades da cana-de-açúcar como a principal fonte e duas matérias primas básicas: fibras e açúcar. Este trabalho apresenta brevemente os conceitos, os indicadores, o estado da arte e as perspectivas de cada uma das questões abordadas.
MOLECULAR BREEDING FOR COMPLEX ADAPTIVE TRAITS—CAN CROP ECOPHYSIOLOGY AND MODELLING EASE THE PAIN?

By

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KEYWORDS: Genotype-to-Phenotype, Trait Physiology, QTL, Functional Genomics, Crop Improvement.

Abstract

Progress in crop improvement is limited by the ability to identify favourable combinations of genotypes (G) and management practices (M) in relevant target environments (E) given the resources available to search among possible combinations. Phenotypic performance of the array of possible combinations forms what can be viewed as an adaptation landscape. Crop improvement then becomes a search strategy on that complex G*M*E landscape. However, currently we cannot reliably predict (and navigate to) the desired destination on the adaptation landscape. We require prediction of phenotype based on genotype to underpin yield advance. In plant breeding, traditional methods have involved measuring phenotypic performance of large segregating populations in multi-environment trials and applying rigorous statistical procedures based on quantitative genetic theory to identify superior individuals. This phenotypic selection approach has been successful but inefficient. Developments in molecular genetic technologies have allowed the focus of practical crop improvement to shift from the level of the individual (genotype) to the level of the genomic region. The ability to inexpensively and densely map/sequence genomes has facilitated development of molecular breeding strategies using genome wide prediction approaches. However, their applicability to complex traits is constrained by gene-gene and gene-environment interactions, which restrict the predictive power of associations of regions with phenotypic responses. Despite this limitation, it has been possible to design molecular breeding strategies for complex traits that, on average, outperform phenotypic selection. Here it is argued that crop ecophysiology and functional whole plant modelling can provide an effective link between molecular and organism scales to enhance molecular breeding. A physiological framework that facilitates dissection and modelling of complex traits can inform phenotyping methods for marker detection and underpin prediction of likely phenotypic consequences of molecular breeding in target environments. This approach holds considerable promise for effectively linking genotype to phenotype for complex adaptive traits. In this presentation, a specific example is presented for drought adaptation in sorghum.

Introduction

Progress in crop improvement is limited by the ability to identify favourable combinations of genotypes (G) and management practices (M) in the relevant target environments (E) given the resources available to search among possible combinations. Phenotypic performance of the array of possible combinations forms what can be viewed as an adaptation or fitness landscape (Cooper and Hammer, 1996).
Crop improvement then becomes a search strategy on that complex G*M*E landscape. However, currently we cannot reliably predict (and navigate to) the desired destination on the adaptation landscape. We require prediction of phenotype based on genotype to underpin yield advance. In plant breeding, traditional empirical methods have involved measuring phenotypic performance of large segregating populations in multi-environment trials and applying rigorous statistical procedures based on quantitative genetic theory to identify superior individuals. This phenotypic selection approach has been successful for a number of crops, but cost per unit yield gain has risen substantially, interactions with management are not integrated, and genotype-by-environment interactions confound selection.

With recent progress in molecular technologies for genome sequencing and functional genomics, it has been widely expected that a gene-by-gene engineering approach would enable enhanced efficiency in crop improvement. Indeed, there have been successes in developing plants that better resist pests or tolerate herbicides. Those cases involved single-gene transformations where plant phenotypic response scaled directly from the level of molecular action. This could be described as a short ‘phenotypic distance’. However, little of this promise has been realised for key complex traits where relationships among components and their genetic controls involve quantitative multi-gene interactions. Integrating gene effects across scales of biological organisation in such situations is not straightforward. Complexities associated with gene interactions, mediated via transcriptional and post-transcriptional regulation, or distributed control of fluxes in plant metabolic pathways are major impediments to scaling from gene network to phenotype, so that phenotypic prediction based on a gene-by-gene approach remains elusive (Hammer et al., 2006; Benfey and Mitchell-Olds, 2008).

Developments in molecular genetic technologies have nonetheless allowed the focus of practical crop improvement to shift from the level of the individual (genotype) to the level of genomic region (e.g. quantitative trait locus – QTL) (Hammer and Jordan, 2007). The ability to inexpensively and densely map genomes has facilitated development of molecular breeding strategies.

However, their applicability to complex traits is limited by context-dependent gene effects attributed to gene-gene and gene-environment interactions, which restrict predictive power of associations of genes/genomic regions with phenotypic responses. There is a long ‘phenotypic distance’ due to the extent of the biological integration required from the causal polymorphisms at genome scale to the phenotype of interest (e.g. Sinclair et al., 2004). Despite this limitation, Cooper et al. (2005) found that even though many of the context-dependent effects of genetic variation on phenotypic variation can reduce the rate of genetic progress from breeding, it is possible to design molecular breeding strategies for complex traits that on average will outperform phenotypic selection.

Continuing advances in genotyping and crop genomics (Heffner et al., 2009; Morrell et al., 2012; Morris et al., 2012) have now facilitated association mapping approaches that assess correlation of phenotype with genotype in populations or panels of unrelated individuals. Such genome wide association studies rely on advanced statistical procedures to develop associations between a phenotype and genomic marker profile. Genomic selection involves the use of phenotypic prediction equations based on profiles of marker data from a training set of genotypes.

The predictions are then applied across breeding materials that are genotyped extensively but not phenotyped. This offers considerable potential for more rapid genetic gain in breeding. However, for complex traits, the procedure still suffers from context-dependent effects and the ‘phenotypic distance’ problem.

In addition, association mapping and genomic selection rely on the stability of the relationship between a phenotype and the set of genomic markers found in the training set, which is strongly dependent on the relevance of the genotypes and environments sampled.
In this paper, I review approaches to G-to-P prediction and discuss how whole plant/crop ecophysiology and functional whole plant modelling can provide an effective link between molecular and organism scales to enhance molecular breeding and crop improvement. This involves dissecting complex traits to more robust targets by reducing ‘phenotypic distance’ and context dependencies. This requires robust dynamic crop growth and development models that can predict consequences of context-dependent genotype and environment effects in target production regions.

**G-to-P prediction and context dependencies**

There is a range of approaches for G-to-P prediction for complex traits that can be somewhat simplistically represented in relation to broad levels of biological organisation (Figure 1). Gene network models have potential to account for gene context dependencies but require advanced knowledge of network structure and dynamics. Model species (e.g. *Arabidopsis*) provide opportunities to capture such knowledge. However, the issue of scaling from network to whole plant phenotypic response remains, unless direct associations exist, as for example with transition to flowering (van Oosterom *et al*., 2006; Salazar *et al*., 2009). Functional whole plant models have potential to account for environment context dependencies as they attempt to encapsulate dynamic plant-environment interactions based on physiological understanding (Tardieu, 2003; Reymond *et al*., 2003; Chenu *et al*., 2008; Yin and Struik, 2008). It is plausible to link the vector of coefficients defining the plant model to genomic regions, but the issue of scaling from coefficient to gene level is problematic.

![Fig. 1—Approaches to G-to-P prediction and their association with level of biological organisation.](image)

### Functional whole plant modelling

Plant/crop models have been used extensively to facilitate decision making by crop managers, and to aid in education, but Hammer *et al.* (2002) suggested that greater explanatory power was required for their effective application in understanding and advancing the genetic regulation of plant performance and plant improvement. This is now even more prescient in the genomics era. Agronomic models contain a mix of descriptive and explanatory approaches that suffices for their application in decision/discussion support for crop management.

Adequate prediction of resource use, crop growth and yield can be obtained with algorithms that describe aspects of crop growth, such as plant leaf area as a function of thermal time or plant leaf size distribution. The coefficients of these algorithms can be mapped to genomic regions, but this is unlikely to diminish any context dependencies, i.e. the coefficients will retain the context dependencies of the phenotypic variable they describe.

A physiological framework that facilitates further dissection and modelling of traits provides an avenue to overcome this problem. By enhancing the explanatory power of the modelling approach while not introducing undue complexity, it is possible to have phenotypic attributes as emergent properties of the model dynamics. This approach holds considerable promise for effective linking of genotype to phenotype and, hence molecular biology/genetics with crop improvement.

Recent developments within the APSIM modelling platform (Hammer *et al*., 2010) have focussed on structuring a generic cereal template to better accommodate the hierarchy of
physiological determinants of crop growth and development needed for this more explanatory approach to plant modelling. They detail a case of the staygreen phenotype in sorghum (i.e. extended retention of green leaf area during grain filling), which was generated as an emergent consequence of canopy N dynamics associated with genetic differences in dwarfing. Taller genotypes required more N for structural stem tissue, leaving less available for leaves, which was more rapidly diminished by translocation to grain during grain-filling. Hence, staygreen was generated in the shorter genotypes, but was caused by genetic effects on height!

Whole plant physiology and modelling as the missing link

Robust explanatory plant models have the potential to underpin G-to-P prediction by linking their coefficients with the genomic regions known to be associated with complex traits. However, to be effective, the linkage to model coefficients must reduce (or remove) the environmental and genetic context dependencies related to the phenotypic trait(s) that they generate. For example, the seasonal pattern of leaf area development is critical to resource (e.g. light, water) capture, and hence to crop growth and timing of stress. Studies at organ level (Reymond et al., 2003; Tardieu et al., 2005) on leaf expansion rate (LER) in maize have found that stable QTLs could be identified for responses of LER to temperature, vapour pressure deficit and water status, whereas QTLs for leaf area were dependent on the growing environment. Hence, by moving to the level of LER, environment context dependencies were removed.

Some of the genomic regions associated with LER were also associated with silk extension and grain set in maize (Welcker et al., 2007). By enhancing the APSIM cereal template to operate at this level and incorporate genomic associations on LER and grain set, Chenu et al. (2009) were able to quantify impact at the crop yield level of the QTLs involved for a range of drought and climate scenarios.

Similarly, the dynamics of water capture by root systems through the crop life cycle is critical to drought adaptation in water-limited environments. Slight changes in availability of soil moisture reserves associated with root system architecture, and the timing of that availability can have major consequences on yield in terminal drought environments, as suggested in wheat by Manschadi et al. (2006). In studies on sorghum in large rhizotrons, nodal root angle in young sorghum plants was shown to influence vertical and horizontal root distribution of mature plants in the soil profile and, hence, their ability to extract soil water (Singh et al., 2012).

Types with narrower root angle tended to explore the soil profile more effectively at depth. These results suggest that the known genetic variation in nodal root angle of young sorghum plants could be a useful selection criterion for specific drought adaptation, given the relatively straightforward phenotyping system (Singh et al., 2011).

Simulation studies based on possible differences in root architecture (Figure 2) suggest significant yield advantage (up to 15%) in low-yielding situations in a key sorghum production environment in NE Australia.

Pursuing genetic variation in this trait, Mace et al., (2012) identified four QTL for nodal root angle in sorghum that explained 58.2% of the phenotypic variance and were validated across a range of diverse inbred lines.

Three of the four nodal root angle QTL showed homology to previously identified root angle QTL in rice and maize, whereas all four QTL co-located with previously identified QTL for the drought adaptation trait ‘stay-green’ in sorghum.

A putative association between nodal root angle QTL and grain yield, which was consistent with the simulation studies, was identified through single marker analysis on field testing data from a subset of the mapping population grown in hybrid combination with three different tester lines.

The identification of nodal root angle QTL presents new opportunities for improving drought adaptation mechanisms via molecular breeding to manipulate a trait for which selection has previously been very difficult.
These examples demonstrate that whole plant ecophysiology and modelling can aid molecular breeding via improved G-to-P prediction in two main ways:

1. Physiological dissection of complex traits in a dynamic framework - Experimental studies in controlled genetic backgrounds provide the means to determine and quantify the functional biology underpinning phenotypic differences, and thus inform high throughput phenotyping. Dynamic process concepts in crop models provide the analytical context to frame that understanding. Attributes can then be linked to genomic regions (QTLs) in a way that reduces context dependency and ‘phenotypic distance’ and generates coefficients for dynamic crop models that quantify ecophysiological implications of genetic regulation.

2. Predicting consequences of genetic variation – Crop models with trait genetics embedded in their coefficient structure can be implemented in a predictive context to estimate by simulation the likely relevance of genetic variation for specific environments and management systems (i.e. G*M*E). This simulated phenotypic value has the potential to provide a basis for weighting genomic regions in molecular breeding in a manner that is more robust than empirical genomic selection approaches.

In both of these example cases, incorporating explanatory sub-models based on physiological insight into the quantitative crop model provided a basis to link changes at genomic regions directly to their emergent phenotypic consequences at the crop level via intermediary traits in a way that reduced context dependencies and ‘phenotypic distance’. Such an approach provides a pathway to effective applications in molecular breeding (Cooper et al., 2005). Further, the functional whole plant models can be used to explore breeding strategies by generating the adaptation landscape of possible G*M*E combinations on which breeding system simulation tools can map the trajectories resulting from specific breeding approaches (Cooper et al., 2002; Chapman et al., 2003; Hammer et al., 2005; Messina et al., 2009). In this way, functional plant modelling can provide the missing link between molecular knowledge, genotyping capacity, and the practice of crop improvement.

Easing the pain in molecular breeding for complex traits simply requires an awakening of awareness of the potential of whole plant physiology and modelling among those advocating direct genomic approaches, equivalent to their expectations of others in relation to the genome-focussed technologies they propound.
Acknowledgements
This paper summarises the research of a team of people who have worked with me over a number of years. It would not have been possible without their enthusiasm and dedication nor without the financial support of a number of funding agencies.

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SÉLECTION MOLÉCULAIRE POUR LES CARACTÈRES ADAPTIFS COMPLEXES – EST-CE QUE L’ÉCOPHYSIOLOGIE ET LA MODÉLISATION DES CULTURES PERMETTENT-ELLES D’AISER LE PROBLÈME ?

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MOTS-CLÉS: Génotype-au-Phénotype,
Physiologie du Trait, QTL,
Génomique Fonctionnelle,
l’Amélioration des Cultures.

Résumé
Le progrès dans l’amélioration génétique des cultures est limité par l’aptitude à identifier les combinaisons favorables des génotypes (G) et les pratiques culturales (M) dans les environnements ciblés concernés (E) compte tenues ressources disponibles pour la recherche parmi les combinaisons génétiques possibles. La performance phénotypique de l’ensemble des combinaisons possibles peut être envisagée comme un paysage d’adaptation. L’amélioration des cultures devient alors une stratégie de recherche sur un paysage complexe G x M x E. Toutefois, actuellement, on ne peut prédire de façon fiable (et naviguer vers) la destination souhaitée sur le paysage d’adaptation. On a besoin de la prédiction du phénotype sur la base du génotype pour cibler le progrès pour le rendement. Dans le domaine de l’amélioration génétique, les méthodes traditionnelles ont consisté à mesurer la performance phénotypique de grandes populations en ségrégation dans les essais multilocaux et l’application des procédures statistiques rigoureuses fondées sur la théorie génétique quantitative pour identifier les individus supérieurs. Cette approche de la sélection phénotypique a été un succès mais inefficace. L’évolution des technologies génétiques moléculaires ont permis d’orienter la focalisation de la pratique l’amélioration des cultures du niveau de l’individu (génotype) à celui de la région génomique. La capacité de la cartographie dense des séquences génomiques a facilité le développement des stratégies de la sélection moléculaire en utilisant une approche plus large de la prédiction. Cependant, son application aux traits complexes est limitée par les contraintes de l’interaction gène-gène et gène-environnement, qui limitent le pouvoir prédictif des associations des régions aux réponses phénotypiques. Malgré cette limitation, il a été possible de concevoir des stratégies de sélections moléculaires des caractères complexes qui, en moyenne, surpassent la sélection phénotypique. Ici on fait valoir que l’écophysiologie des cultures et la modélisation fonctionnelle de la plante dans son ensemble peuvent offrir un lien efficace entre les échelles moléculaires afin de rehausser la sélection moléculaire. Un cadre physiologique qui facilite la dissection et la modélisation des caractères complexes peut informer les méthodes de phénotypage pour la détection des marqueurs et soutenir la prédiction probable des conséquences phénotypiques de la sélection moléculaire pour des environnements ciblés. Cette approche est très prometteuse pour relier d’une façon efficace le génotype au phénotype pour les caractères adaptifs complexes. Dans cette présentation, un exemple concret est présenté pour l’adaptation à la sécheresse chez le sorgho.
MEJORAMIENTO MOLECULAR DE COMPLEJAS CARACTERÍSTICAS ADAPTATIVAS – PUEDE LA ECOFISIOLOGÍA DEL CULTIVO Y MODELIZACIÓN SUAVIZAR EL DOLOR?

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PALABRAS CLAVE: Genotipo y Fenotipo,
Fisiología de Una Característica, QTL,
Genómica Funcional,
Mejoramiento de Cultivos.

Resumen

EL PROGRESO EN EL MEJORAMIENTO de cultivos está limitada por la capacidad para identificar combinaciones favorables de genotipos (G) y las prácticas de manejo (M) en ambientes relevantes específicos (E) usando los recursos disponibles para buscar individuos entre las mejores combinaciones posibles. El comportamiento fenotípico de una serie de formas de combinaciones posibles puede considerarse como un escenario de adaptación. El mejoramiento de cultivos entonces se convierte en una estrategia de búsqueda en ese complejo escenario G*M*E. Sin embargo, actualmente nosotros no podemos predecir confiablemente (o navegar hacia) el destino deseado en el escenario de adaptación. Requerimos una predicción del fenotipo basado en el genotipo para apuntalar la ganancia en producción. En mejoramiento vegetal, los métodos tradicionales han implicado medir el comportamiento fenotípico en ensayos con poblaciones segregantes grandes en múltiples ambientes, aplicando procedimientos estadísticos rigurosos basados en la teoría genética cuantitativa para identificar a individuos superiores. Este enfoque de selección fenotípica ha sido exitoso pero ineficiente. Los desarrollos tecnológicos de la genética molecular han permitido un enfoque práctico de mejoramiento de cultivos para cambiar desde el nivel individual (genotipo) al nivel de una región genómica. La disponibilidad a bajo costo para establecer densos mapas/secuencias de genomas ha facilitado el desarrollo de estrategias de mejoramiento molecular usando métodos de predicción basados en el genoma. Sin embargo, su aplicabilidad en caracteres complejos está limitada por las interacciones entre gen-gen y gene-ambiente, lo que limita poder predecir asociaciones de regiones genómicas con respuestas fenotípicas. A pesar de esta limitación, ha sido posible diseñar estrategias de mejoramiento molecular para características complejas que, en promedio, superan a la selección fenotípica. Se ha argumentado que la eco-fisiología del cultivo y la modelación del funcionamiento de toda la planta, pueden proporcionar un vínculo efectivo entre la escala molecular y organismo para favorecer el mejoramiento molecular. Un marco fisiológico que facilita la disección y modelación de características complejas puede informar a los métodos fenotípicos para la detección de marcadores y sustentar la predicción de posibles consecuencias fenotípicas usando el mejoramiento molecular en ambientes específicos. Este enfoque se presenta considerablemente prometedor para vincular eficazmente genotipo con el fenotipo de complejas características adaptativas. En esta presentación, se muestra un ejemplo concreto de adaptación para sequía en sorgo.

Resumo
O PROGRESSO NA MELHORIA de culturas limita-se à capacidade de identificar combinações favoráveis de genótipos (G) e a práticas de manejo (M) em ambientes alvo relevantes (E) dados os recursos disponíveis para busca entre combinações possíveis. O desempenho fenotípico de uma variedade de combinações possíveis formam o que pode ser considerado um cenário de adaptação. A melhoria de cultura torna-se então uma estratégia de busca no complexo cenário G*M*E. Entretanto, atualmente não somos capazes de estimar com confiança o destino desejado no cenário de adaptação (e nem de ir em direção a ele). É necessário estimar o fenótipo com base no genótipo para sustentar o avanço da produtividade. Em melhoramento de plantas, métodos tradicionais envolvem a mensuração do desempenho fenotípico de grandes populações segregativas em experimentos em diversos ambientes e aplicando-se rigorosos procedimentos estatísticos com base na teoria genético-quantitativa para identificar indivíduos superiores. Essa seleção fenotípica é bem-sucedida, porém ineficiente. Desenvolvimentos em tecnologias de genética molecular tem permitido mudar o foco da melhoria prática de culturas do nível do indivíduo (genótipo) para o nível da região genômica. A capacidade de mapear/sequenciar genomas de maneira econômica e densa tem facilitado o desenvolvimento de estratégias de melhoramento molecular com o uso de amplas abordagens de estimativa de genoma. Entretanto, sua aplicabilidade para traços complexos é restrita a interações gene-gene e gene-ambiente, o que limita o poder de estimativa de associações de regiões com respostas fenotípicas. Apesar dessa limitação, tem sido possível projetar estratégias de melhoramento molecular para traços complexos que, em média, apresentam melhor desempenho na seleção fenotípica. Nesse ponto, argumenta-se que a ecofisiologia da cultura e a modelagem funcional da planta inteira podem oferecer uma ligação entre escalas moleculares e de organismo para aprimorar o melhoramento molecular. Um quadro fisiológico que facilita a disseccão e a modelagem de traços complexos pode informar métodos de fenotipagem para detecção de marcadores e sustentar a estimativa de possíveis consequências fenotípicas do melhoramento molecular nos ambientes alvo. Essa abordagem é muito promissora como um ligação efetiva entre o genótipo e o fenótipo para traços adaptativos complexos. Nesta apresentação, será discutido um exemplo específico de adaptação a seca pelo sorgo.
IMPACT OF PATHOGEN GENETICS ON BREEDING FOR RESISTANCE TO SUGARCANE DISEASES

By

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Abstract

DISEASES ARE LIMITING factors of sugarcane production and breeding for resistance to diseases is a major goal in sugarcane variety improvement. Diseases result from complex interactions between plants, pathogens and environment, including humans and insect vectors of pathogens. History has shown that durability of resistance of sugarcane to diseases varies according to the host cultivar and to the pathogen in a given environment. Some sugarcane cultivars have been grown for decades without losing efficiency of resistance to the disease they were bred or screened for; others became susceptible and showed disease symptoms rapidly after being grown commercially. Disease outbreaks and breakdown or overcoming of plant resistance suggesting changes in the pathogen populations have been observed for several sugarcane diseases. Emergence of new pathogens or new strains of a pathogen generally results in a change of the varieties grown in a sugarcane growing area. Pathogen population genetics must therefore be taken into consideration for breeding and screening new sugarcane varieties for resistance to diseases. Knowing the genetic diversity of a pathogen in a given location is very important, especially when plants are artificially inoculated with pathogens for screening. Furthermore, sugarcane genetics is very complex and few disease specific resistance genes have been identified so far, and selection for these traits is also complex. Sequencing and analysis of genome variation of sugarcane pathogens varying in virulence should result, in the future, in the identification and comprehension of the molecular determinants involved in these genetic changes, and subsequently also facilitate breeding for resistance.

Introduction

Sugarcane is the host of numerous pathogens that can affect sugarcane production and cause yield losses. More than 100 pathogens, including bacteria, fungi and viruses, have been reported to cause diseases of sugarcane (Rott et al., 2000). Several of these diseases can cause considerable losses.

Importance of a disease is often thought to be related to the geographical distribution of a pathogen, but this is not always true. Smut caused by Sporisorium scitamineum (previously known as Ustilago scitaminea) causes one of the most, if not the most, important disease of sugarcane and is distributed worldwide.

This disease caused or still causes severe yield losses in numerous geographical locations where the disease occurs. However, other diseases can be as devastating and be limited to only a few or even only one geographical location. One of the most famous examples is Ramu stunt which
almost destroyed the fledgling commercial sugarcane industry in Papua New Guinea in the 1980s. Ramu stunt, whose causal agent is most likely a virus, has so far only been reported in this country (Braithwaite et al., 2007).

On a world basis, sugarcane is one of the crops for which very few pesticides are used to control diseases. Because of the cost of pesticides and their application on large areas, as well as the potential negative impact of these products on the environment, sugarcane producers try to control diseases with resistant varieties.

Breeding and screening sugarcane for resistance is, therefore, a very important and a key process for the cultivation and production of sugarcane. To be as efficient as possible, this process relies, among others, on the knowledge of the biology of pathogens, and especially their genetics that can greatly impact breeding and screening of sugarcane for resistance to diseases.

Emergence of a new disease or a new strain or race of a pathogen

What is emergence of a disease?
In plant pathology, emergence can be defined as an unexpected meeting between a plant and a pathogen but also as a disease whose incidence, geographical distribution or host range has significantly increased within a given period of time (Anderson et al., 2004). This definition includes time and space factors that are specific to biological invasions. Diseases result from complex interactions between plants, pathogens and environment, including humans and insect vectors of pathogens.

Smut emergence
Emergence of a new disease in a sugarcane growing location has been observed several times in sugarcane history. One of the most recent examples is the appearance of smut in Australia where the disease was absent until 1998 when it was recorded for the first time in Western Australia (Croft et al., 2008). It was only a few years later, in 2006, that the disease was found in Queensland, the major sugarcane growing area of the country.

Emergence of smut in Australia resulted in great losses but, because the local industry had anticipated a possible arrival of the disease and had tested varieties for smut resistance in Indonesia for several years, it was able to quickly propose the replacement of susceptible varieties by resistant ones. One of the key conditions for this successful replacement was the occurrence of the same genetic strain of the pathogen in Indonesia and Australia (Braithwaite et al., 2004).

Brown rust emergence
Brown rust, caused by *Puccinia melanocephala*, was considered a ‘minor’ disease until it spread to the Western hemisphere in 1978. Because sugarcane was not screened for resistance to brown rust until then and, because most grown cultivars were susceptible to the disease (especially cultivar B4362 that occupied a significant area of commercial production), the disease caused losses as high as 50% and caused the replacement of the susceptible cultivars by more resistant ones (Raid and Comstock, 2000).

Orange rust emergence
Similarly to brown rust, orange rust was considered to be economically unimportant in the Asian-Oceania region where the disease was restricted until the beginning of the 21st century (Magarey et al., 2001). However, in 2000, an outbreak of the disease occurred in Queensland (Australia) that caused extensive yield losses to the local sugar industry. Cultivar Q124, once considered resistant to orange rust, showed severe symptoms that were attributed to the appearance of new strain of the pathogen.

As a direct consequence, the local breeding program had to develop new cultivars resistant to the old and the new strain of the pathogen (*Puccinia kuehnii*) in order to replace highly susceptible cultivar Q124 by resistant cultivars.
After this outbreak of orange rust in Australia, the disease was identified for the first time in the Western hemisphere in Florida in 2007 (Comstock et al., 2008) and in Africa in 2010 (Saumtally et al., 2011). The genetic relationship between strains of the pathogen occurring in the Asian-Oceana region and those occurring now in the Western hemisphere is, however, not yet known. A comparison of orange rust strains has been started but results are preliminary, and it cannot be hypothesised where the strain originated that caused the outbreak in the Western hemisphere. Since then, the number of countries reporting occurrence of orange rust in Central and South America, and the Caribbean islands, continues to grow; and highly susceptible cultivars need to be replaced as soon as possible.

Another rust emergence in progress?
Furthermore, a new species of rust was recently observed on a number of sugarcane varieties in Swaziland and South Africa, suggesting that another world rust epidemic might develop in the near future (McFarlane et al. 2012). Future will tell!

A need to produce sugarcane cultivars resistant to diseases
If diseases can cause large direct losses to the sugarcane industry, they also cause indirect losses because there is a need to develop disease resistant cultivars in variety development programs. Furthermore, potentially high yielding varieties can be lost due to disease susceptibility. Breeding and screening for resistance to diseases that may cause damage in a given location is therefore essential. In order to be efficient, it is important to identify resistance sources and especially resistant germplasm that can be used in breeding programs.

Resistance of plants to diseases

Innate disease resistance in plants
A disease will develop when a plant cannot resist a microbial infection. However, most plant-pathogen interactions do not develop into a disease because plants have different forms and mechanisms of natural resistance to pathogen infection. Two forms of innate resistance have been identified in plants: general (= non-specific) resistance and specific resistance (Kiraly et al. 2007). General resistance is a durable form of resistance which is effective against several pathogenic species or several strains of a single pathogen. In contrast, specific resistance which includes gene-for-gene resistance (also called vertical resistance) is generally considered not durable because it confers resistance to only one or a few strains of the pathogen and the pathogen often can, at one time or another, breakdown or overcome this resistance. Selecting this race-specific resistance is therefore not an advisable strategy in plant breeding programs.

Disease resistance genes in sugarcane
Although resistance to diseases is often found in sugarcane germplasm, resistance mechanisms of sugarcane to diseases and their genetic support are currently poorly understood. Candidate genes for resistance to smut and eye spot have been identified but their role during the interactions between sugarcane and the causal agents of these diseases are not yet known (Borrás-Hidalgo et al., 2005; Que et al., 2011). However, although sugarcane has a highly complex genome, two major genes for resistance to brown rust have been identified (Daugrois et al., 1996; Raboin et al., 2006). Similarly, a major quantitative trait allele for resistance to Sugarcane yellow leaf virus, the causal agent of yellow leaf, was recently described (Costet et al., 2012b).

The legacy of history of sugarcane disease resistance

Durability of disease resistance
History has shown that durability of resistance of sugarcane to diseases varies according to the host cultivar and to the pathogen in a given environment or geographical location. Some sugarcane cultivars have been grown for decades without losing efficiency of resistance to the disease they were bred or screened for, others became susceptible and showed disease symptoms rapidly after being grown commercially. Cultivar R570, created in Reunion Island and released in
1978 for commercial production, has been grown commercially or as germplasm in numerous world locations where common rust exists (America, Africa, Caribbean Islands, Mascarene Islands, etc.), and so far no breakdown of resistance to the disease has been reported. This suggests that resistance to common rust in cultivar R570, although it is based on a major resistance gene called \textit{Bru}\textsubscript{1} (Costet \textit{et al.}, 2012a), cannot be easily overcome.

In contrast, in Florida, since brown rust was introduced, there has not been durable resistance to brown rust. A number of cultivars have been developed as resistant and then withdrawn from commercial production due to brown rust susceptibility. Races of brown rust were reported in Florida based on experiments in the early 1990s (Raid, 1989; Shine \textit{et al.}, 2005). Five brown rust isolates reacted differently on six sugarcane cultivars. Interestingly, these results appear to contrast with what is known with the \textit{Bru}\textsubscript{1} resistance gene. However, there is no conflict because five of the sugarcane clones that were used in the Florida brown rust race study tested negatively for the \textit{Bru}\textsubscript{1} resistance gene (the other clone has been lost). Thus, races were identified in the absence of this major resistance gene, and data indicate occurrence of other sources of minor resistance. Most of the brown rust resistant cultivars developed in the last decade in Florida were found to have \textit{Bru}\textsubscript{1} when tested for the presence of the \textit{Bru}\textsubscript{1} resistance gene using molecular techniques.

**Red rot resistance**

However, disease outbreaks and breakdown or overcoming of plant resistance suggesting changes in the pathogen populations have been observed for several sugarcane diseases. For example, in India, varieties that were screened for resistance to red rot caused by \textit{Glomerella tucumanensis} become susceptible to the disease within a few years after their release and commercial cultivation (R. Viswanathan, oral communication). This suggests gene-for-gene interactions between sugarcane cultivars and \textit{C. falcatum}, involvement of major genes in resistance of sugarcane to red rot, as well as rapid breakdown of these genes and the development of new races of the pathogen. Occurrence of several physiological and pathogenic strains of \textit{C. falcatum} has been reported in India (Malathi and Viswanathan, 2012).

**Smut resistance**

In contrast to red rot, only few breakdowns of sugarcane resistance have been reported for smut and resistance of sugarcane to this disease appears to be sustainable. Occurrence of two-three races of the smut pathogen was reported in Hawaii, Pakistan, The Philippines and Taiwan several decades ago (Ferreira and Comstock, 1989), but they apparently did not spread to other geographical locations although the spores of the pathogen can be easily disseminated by wind. It is therefore questionable if all strains/races of the pathogen are fit enough and able to survive and spread. A study of genetic diversity and structure of different populations of \textit{S. scitamineum} worldwide revealed that this pathogen was dispersed as a unique lineage from Asia to America and Africa (Raboin \textit{et al.}, 2007). Furthermore, a worldwide ISSCT project on sugarcane variability within sugarcane smut could not confirm race-cultivar interactions, except in Taiwan (Grisham, 2001).

**Dominant sugarcane cultivars and disease epidemics**

Emergence of new pathogens or new strains of a pathogen generally results in a change of the varieties grown in a sugarcane growing area because varieties that become susceptible to a disease are no longer sufficiently performing.

As mentioned above, appearance of an apparently new race of orange rust in Australia resulted in the replacement of cultivar Q124 that was cropped over 90% of the Central Queensland area and thousands of hectares. Indeed, when a single variety occupies most of the cultivated area in a given location, the risk of occurrence of an epidemic is very high. Growing an outstanding variety on large areas may be of great economic interest, but it may also result in tragic consequences, especially if replacement cultivars are not available when needed i.e. after occurrence of a serious epidemic!
At least six major epidemics significantly affecting the Queensland sugarcane industry occurred in the past 60 years (Magarey et al., 2011). All of these epidemics were related to the growth of dominant cultivars and concerned different diseases such as Fiji leaf gall, Pachymetra root rot, eye spot, orange rust and smut. This historical study of disease epidemics in Queensland conducted by Magarey et al. (2011) led these authors to conclude their work by the simple and following question: ‘What disease epidemic will occur next in Australia?’ This question can be asked in any location where very few varieties are cropped over large areas.

Sugarcane disease history has largely shown that pathogen populations can change and adapt, and more examples exist regarding this phenomenon in the literature (Ricaud et al., 1989; Rott et al., 2000). As a consequence, pathogen genetics must be taken into consideration for breeding and screening new sugarcane varieties for disease resistance, and for efficient management of plant resistance.

Genetics and virulence diversity of sugarcane pathogens and screening for resistance to diseases

Field screening for resistance

Screening of sugarcane for disease resistance can be performed under natural disease pressure or after artificial inoculation of plants with the pathogen. Inoculating plants has the big advantage that inoculum of the pathogen can be adjusted and controlled according to genetic diversity and/or variation in virulence of a pathogen in a given location. Studying and knowing these variations is therefore very important.

Although sugarcane cultivars were screened for resistance to *Xanthomonas albilineans* by artificial inoculation, outbreaks of leaf scald occurred in Florida in the late 1980s (Davis et al., 1997). These outbreaks were attributed to the appearance of a new strain of the pathogen that was genetically different from the strain that was present before the disease outbreaks.

Subsequently, this newly identified strain of *X. albilineans* was used to screen sugarcane for resistance to leaf scald after artificial inoculation of plants. Similarly, red rot can effectively be controlled thanks to the use of resistant cultivars but it is recommended to use virulent isolates of the pathogen from genetically different groups for screening (Singh and Sunita Lal, 2000). Mosaic viruses are another example of important genetic and virulence diversity within sugarcane pathogens. Mosaic symptoms are caused by two virus species: *Sugarcane mosaic virus* (SCMV) and *Sorghum mosaic virus* (SrMV). For both species, several strains have been identified based on leaf symptom expression after inoculation of differential host plants (Grisham, 2000). Although several strains of SCMV can exist in a geographical location, a strong correlation was found between genetic grouping and the geographical origin of SCMV isolates, suggesting specific adaptation of SCMV isolates to environmental conditions (Alegria et al., 2003).

Screening for resistance must take this genetic variation into consideration, especially when field screening is performed using spreader rows of susceptible infected plants near the test rows. Besides transmission by infected cuttings, mosaic viruses are spread by aphid vectors from infected plants to healthy plants. Providing a constant disease source and pressure, representative of the strain diversity of the pathogen, is therefore essential for successful screening of sugarcane cultivars resistant to mosaic.

Laboratory screening for resistance

The sugarcane genome is complex because sugarcane hybrids are complex aneu-polyploids (2n = 100–130) derived from inter-specific hybridisation between ancestral polyploid species. Sugarcane genome composition does therefore not facilitate the study of host-pathogen interactions at the gene or molecular level. Few disease specific resistance genes have been identified so far, and selection for these traits is also complex. However, when major resistance traits can be identified on the sugarcane genome, they can be used for developing molecular markers.
Identification of *Bru1*, a major resistance gene to brown rust, resulted in the design of primers that allowed the detection of this gene in sugarcane varieties by polymerase chain reaction (PCR). Using this molecular detection technique, Glynn and collaborators (2012) showed that over 75% of the commercial sugarcane acreage in Florida relies on *Bru1* to control brown rust. Although *Bru1* appears to be a very efficient resistance gene to brown rust (as shown by widespread resistance of cultivar R570), relying on a single gene, like relying on a single dominant cultivar on large areas, might be a serious risk and a threat to the sugarcane industry. Identification of different and alternative sources of resistance to disease in breeding programs is therefore highly suitable.

Brown rust is distributed worldwide and characterisation of resistance to the disease can generally be performed easily under natural disease pressure. However, the work on *Bru1* showed that it is also feasible, using a molecular detection technique, to rapidly screen sugarcane for putative resistance to a disease in the absence of the causal agent. Similarly, *Ryl1*, a major quantitative trait allele controlling resistance to *Sugarcane yellow leaf virus* (causal agent of yellow leaf) or SCYLV, was recently identified in disease resistant cultivar MQ76-53 (Costet *et al.*, 2012b). This resistance allele was found using a progeny assessed after natural infection of plants. It will therefore be necessary to determine the range of resistance conferred by this allele because variation in infection capacity and in virulence exists between the different genotypes of SCYLV (Abu Ahmad *et al.*, 2007). Anyway, identification in the future of genes of resistance to various diseases will most likely soon increase the impact of molecular breeding in sugarcane variety development programs.

If a few major resistance genes have been identified in sugarcane, no avirulence gene (= the interacting gene in a gene-for-gene relationship) has been identified to date in sugarcane pathogens. These genes, however, most likely exist based on these genes found in pathogens causing similar diseases (rust, smut) in other plants.

**Conclusion**

Diseases have caused significant direct and indirect losses to the sugarcane industry in the past. As history has shown, they most likely will continue to do so as sugarcane and pathogens are engaged in a continuing battle during which the pathogen will always try to overcome resistance of the host plant.

In some situations, genetic changes due to various mechanisms or changes in pathogen populations due to foreign introductions will allow the pathogens to attack previously resistant plants. New resistant plants have then to be developed and pathogen genetics, and especially variation of genetic factors, therefore can have a great impact on breeding for resistance to sugarcane diseases. However, if variation in virulence has been shown to occur in several sugarcane pathogens, the genetic support of this variation is so far poorly understood. Disease outbreaks and breakdown or overcoming of sugarcane resistance suggest occurrence of gene-for-gene interactions for some diseases such as common rust, brown rust, red rot and smut.

Thanks to high output and low cost sequencing, analysis of genome variation of sugarcane pathogens varying in virulence should result, in the future, in the identification and comprehension of the molecular determinants involved in these genetic changes, and subsequently also facilitate breeding for resistance.

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IMPACT DE LA GÉNÉTIQUE DES AGENTS PATHOGÈNES
SUR L’AMÉLIORATION VARIÉTALE DE LA CANNE À SUCRE
POUR LA RÉSISTANCE AUX MALADIES

Par

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MOTS-CLÉS: Agent Pathogène, Amélioration Variétale,
Diversité Génétique, Maladie, Résistance.

1.1 Résumé
LES MALADIES CONSTITUENT des facteurs limitants de la culture de canne à sucre, et la création de
variétés résistantes aux maladies est un objectif majeur de l’amélioration variétale. Les maladies
résultent d’interactions complexes entre les plantes, les agents pathogènes et l’environnement, y
compris l’homme et les insectes vecteurs d’agents pathogènes. L’histoire a montré que la durabilité
de la résistance de la canne à sucre aux maladies varie en fonction de la variété hôte et de l’agent
pathogène dans un environnement donné. Certains cultivars de canne à sucre ont été cultivés
pendant des décennies sans perdre l’efficacité de la résistance aux maladies pour lesquelles elles
avaient été créées ou sélectionnées. En revanche, d’autres sont devenus sensibles et ont montré des
symptômes de maladie rapidement après leur mise en culture commerciale. La recrudescence de
maladies et la chute ou le contournement de résistances de la plante hôte, suggérant des
modifications dans les populations de l’agent pathogène, ont été observés pour plusieurs maladies
de la canne à sucre. L’émergence de nouveaux agents pathogènes ou de nouvelles souches d’un
agent pathogène résulte généralement en un changement de la nature des variétés cultivées dans
une aire de culture. La génétique des populations d’agents pathogènes doit donc être prise en
considération lors de la création variétale et le criblage de nouvelles variétés de canne à sucre pour
la résistance aux maladies. La connaissance de la diversité génétique d’un agent pathogène dans une
aire de culture donnée est très importante, surtout quand les plantes sont inoculées avec l’agent
pathogène par voie artificielle lors des essais de criblage variétaux. De plus, la génétique de la
canne à sucre est très complexe et peu de gènes de résistance spécifique ont été identifiés à ce jour,
et la sélection pour ces caractères est aussi complexe. Le séquençage et l’analyse de la variabilité du
génome d’agents pathogènes dont la pathogénie est variable devrait, dans le futur, conduire à
l’identification et à la compréhension des déterminants moléculaires impliqués dans ces
modifications génétiques et, par voie de conséquence, aussi faciliter la création variétale pour la
résistance aux maladies.
IMPATÓ DE LA GENÉTICA DE LOS PATÓGENOS EN LA SELECCIÓN DE LA RESISTENCIA CONTRA ENFERMEDADES DE LA CAÑA DE AZÚCAR

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PALABRAS CLAVES: Diversidad Genética, Enfermedad, Mejoramiento Varietal, Patógeno, Resistencia.

1.1.3.1 Resumen
Las enfermedades son factores limitantes del cultivo de la caña de azúcar y la creación de variedades resistentes a las enfermedades es un objetivo mayor de la mejora varietal. Las enfermedades resultan de interacciones complejas entre las plantas, los patógenos y el medio ambiente, incluso el hombre y los insectos vectores de patógenos. La historia nos ha enseñado que la durabilidad de la resistencia de la caña de azúcar a las enfermedades varía dependiendo de la variedad de la caña y del patógeno en un medio ambiente dado. Algunas variedades de caña de azúcar han sido cultivadas durante decenas sin perder la eficiencia de la resistencia a las enfermedades para las cuales fueron creadas o seleccionadas. En cambio, otras presentaron síntomas de enfermedad rápidamente después de haber sido cultivadas comercialmente. El recrudecimiento de enfermedades y la ineficiencia de resistencias de la planta-huesped, sugiriendo cambios en las poblaciones del patógeno, han sido observados en varias enfermedades de caña de azúcar. La emergencia de nuevos patógenos o de nuevas cepas de un patógeno, suele ser debidas a un cambio de las variedades cultivadas en un área de cultivo. Hay que tener en cuenta la genética de las poblaciones de patógenos durante la creación varietal y la selección de nuevas variedades de caña de azúcar para la resistencia a las enfermedades. El conocimiento de la diversidad genética de un patógeno en un área de cultivo dado es muy importante, sobre todo cuando las plantas son inoculadas con el patógeno artificialmente durante la selección varietal. Además, la genética de la caña de azúcar es muy compleja y pocos genes de resistencia específicos han sido identificados hasta ahora, y la selección para estas características es también compleja. El secuenciado y análisis de la variabilidad del genoma de patógenos debería, en el futuro, llevar a la identificación y a la comprensión de los determinantes moleculares implicados en estas modificaciones genéticas y, por tanto, facilitar también la creación varietal para la resistencia a las enfermedades.
IMPACTO DA GENÉTICA DE PATÓGENOS NO MELHORAMENTO PARA RESISTÊNCIA A DOENÇAS DA CANA-DE-AÇÚCAR

Por

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PALAVRAS-CHAVE: Melhoramento, Doença, Diversidade Genética, Patógeno, Resistência.

Resumo

AS DOENÇAS SÃO fatores limitantes da produção de cana-de-açúcar e o melhoramento para resistência a doenças é um dos principais objetivos no melhoramento de variedades de cana. As doenças são resultantes de interações complexas entre plantas, patógenos e o ambiente, inclusive humanos e insetos vetores de patógenos. A história tem mostrado que a durabilidade da resistência da cana a doenças varia de acordo com a variedade hospedeira e o patógeno em um dado ambiente. Algumas variedades de cana têm sido cultivadas há décadas sem perder a eficiência de resistência a doenças a que foram condicionadas; outras tornam-se suscetíveis e apresentam sintomas de doenças rapidamente após serem cultivadas em escala comercial. Surtos de doenças e o descontrole ou a superação da resistência da planta indicando mudanças nas populações de patógenos foram observados em várias doenças de cana. A emergência de novos patógenos ou novas linhagens de um patógeno geralmente resulta em uma mudança nas variedades cultivadas em uma área de cultivo de cana. A genética de população de patógenos deve, portanto, ser levada em consideração para o melhoramento e a triagem de novas variedades de cana com resistência a doenças. Conhecer a diversidade genética de patógenos em um dado local é muito importante, especialmente quando as plantas são inoculadas artificialmente com patógenos para triagem. Além disso, a genética da cana-de-açúcar é muito complexa e poucos genes resistentes específicos foram identificados até o presente, sendo a seleção desses traços também complexa. O sequenciamento e a análise da variação do genoma em patógenos de cana-de-açúcar variando em virulência devem resultar, no futuro, na identificação e no entendimento dos determinantes moleculares envolvidos nessas mudanças genéticas e, subsequentemente, também facilitar o melhoramento para resistência.
MENDEL’S LEGACY LIVES THROUGH
MANAGEMENT OF SUGARCANE PESTS

By
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Abstract
ENTOMOLOGY AND CLASSICAL Mendelian genetics have had a long association and Mendel’s legacy continues to live through sugarcane pests. In this paper, we discuss examples of that legacy as applied to conventional and molecular approaches to breeding for insect resistance. We also discuss the application of genetics in pest management, systematics, and ecology. Conventional breeding for insect resistance is likely to continue to lag behind other traits as the realities of the high costs associated with a conventional breeding program and complexity of the sugarcane genome will continue to hold sway. Molecular breeding techniques offer many opportunities to overcome those limitations; however, the cost associated with this technology is high and gains that are obtained in pest management must be compared to more conventional strategies. Additionally, before the release of transgenic sugarcane with insect resistance can occur, various scientific, legislative, and public perception issues must be addressed. Many sugarcane industries lacking the resources are simply unable to overcome these obstacles. Genetic methods have revolutionised insect taxonomy and provided the means for rapid identification of closely related species, often without access to identified specimens. This is now impacting on our understanding of the ecology and biology of sugarcane pests and their natural enemies. Crop plants and pest insects can be genetically modified but paratransgenesis of closely associated microorganisms may allow better targeting and delivery of insecticidal compounds. Again, scientific, legislative, and public perception issues must be addressed.

Introduction
Mendel’s legacy has been the rise of genetics in modern biology. As a relatively obscure abbot in a relatively obscure central European monastery, Mendel did not know about chromosomes or DNA, nor did he know about genes as we do today. However, he performed many experiments in which he controlled the breeding of his pea plants. By observing the number and types of phenotypes in the offspring plants, he developed the rules of inheritance now known as Mendel's laws. It is that work that has laid the foundation of modern genetics.

Genetics plays an important role not only in the development of insect-resistant varieties of sugarcane, through both conventional and transgenic breeding, but also in diagnostics and phylogenetics that lead to better understanding of the biology, ecology and status of sugarcane pests. In this paper, we discuss recent advances in breeding for pest resistance in the areas of both conventional and molecular approaches. We also show how modern, genetics-based diagnostics have been used to provide reliable methods for differentiating groups of morphologically and ecologically similar pests such as canegrubs and borers, provide tools to better understand differences in biology, pest status and effectiveness of parasites in some borer populations, and to explain failures in classical biocontrol programs against borers.
Legacy to plant resistance

Conventional breeding

Many sugarcane breeding programs were founded by pathologists striving to incorporate disease resistance into locally adapted cultivars. For many diseases, prophylactic control measures were not available and the development of disease-resistant cultivars was the only reasonable option. So, it is not surprising that progress in the conventional breeding for resistance to pathogens has preceded those in breeding for insect resistance.

In addition, biological and chemical controls have provided the necessary means to minimise yield loss from insects. However, the innate appeal of plant resistance as a management component requiring no direct input from growers means that resistant cultivars can be an important goal for sugarcane breeding programs. This is particularly so where classical biological control is difficult to enhance, where chemical control requires prophylactic application, and in those industries invaded by new pest species but before new associations in biological control can be established.

The fact that variation exists among sugarcane cultivars in their response to insect pests has been known for nearly 100 years in Louisiana and Australia. The notion that resistance is heritable has been considered for nearly as long, although ‘resistance’ is used widely as a general term to encompass non-preference, antibiosis and tolerance components.

The sugarcane literature over the past 60 or so years is replete with research on procedures to quantify differences in cultivar response to insect feeding, yield losses associated with various damage levels, resistance mechanisms, and the documentation of cultivars that were insect resistant. However, it is probably accurate to conclude that those sugarcane cultivars released and having insect resistance were released for other reasons (e.g., yield and/or disease resistance) and were only later determined to also be insect resistant.

More recently, knowledge has been gained on the genetic nature of resistance (simple or quantitative inheritance), the narrow and broad sense heritabilities of insect resistance, sources of resistance outside the narrow genome of sugarcane cultivars, and the release of resistant germplasm (White et al., 2001; Allsopp and Cox, 2002; Milligan et al., 2003; Nibouche and Tibère, 2008). Regardless of the progress in important aspects of plant resistance few conventional breeding programs can afford to take on the additional selection trait of insect resistance.

Molecular breeding

Molecular breeding offers opportunities to overcome those seemingly impenetrable barriers to conventional breeding. Lakshmanan et al. (2005) identified five areas of advances in biotechnology pertinent to advances in sugarcane improvement:

1) cell tissue culture techniques for molecular breeding and propagation;
2) engineering novel genes into cultivars;
3) molecular diagnostics for sugarcane pathogens to improve exchange of Saccharum germplasm and the germplasm of related species such as Miscanthus and Erianthus;
4) developing genetic maps using molecular marker technology; and
5) understanding the molecular basis of sucrose accumulation in the stem.

We will discuss how items 1, 2, and 4 relate to breeding for insect resistance.

Cell tissue culture

Cell tissue culture is the oldest of the biotechnology techniques and also the basis for the development of other techniques that followed. One aspect of cell tissue culture that researchers have attempted to exploit is in vitro culture-induced variability, also referred to as somaclonal variation. Although infrequently beneficial, it is generally considered undesirable for both commercial propagation and germplasm storage. Here again, initial progress was realised in the area of obtaining disease resistance derived from propagation of susceptible cultivars.
Some work has been done in identifying insect resistant somaclones derived from an insect-susceptible cultivar (White and Irvine, 1987). However, the frequency of resistant phenotypes that occurred was no more than what would be obtained through conventional breeding. Unfortunately, it has also been shown that phenotypic variations in tissue-cultured sugarcane were frequently epigenetic and phenotype tended to revert to the parental phenotype as soon as the first-ratoon crop.

**Engineering novel genes into commercial cultivars**

As pointed out by Lakshmanan *et al.* (2005), the selective inclusion of a resistance trait is very difficult due to the complexity of the sugarcane genome. One of the most exciting areas of molecular breeding and an area where considerable progress has been realised is the introduction of novel insecticidal genes by transgenic methodologies. The first transgenic plants were obtained in 1984 using tobacco as the model plant (Horsch *et al.*, 1985). Since then, transgenic plants have been produced in more than 100 species (Lakshmanan *et al.*, 2005).

The first example of the successful application of this approach in sugarcane to obtain insect resistance was introduction of the *cry1A(b)* gene from the soil bacterium *Bacillus thuringiensis* (Bt) for control of the stem borer *Diatraea saccharalis* (Lepidoptera: Crambidae) (Arencibia *et al.*, 1997).

More recently, the genetic manipulation of the *Cry* genes in Bt offers opportunities to improve the efficiency of Bt-based bioinsecticide products. Weng *et al.* (2011) synthesised a truncated insecticidal gene *m-cry1Ac* by increasing its GC content from 37.4 to 54.8%. Increasing the GC content of the Bt *cry1Ac* from 37.4 to 47.5% enhances its protein expression level in sugarcane plants by two- to three-fold (Weng *et al.*, 2006).

Another category of transgenes having insecticidal activity is plant-derived genes such as proteinase inhibitors. This group of transgenes are of interest because these inhibitors are part of the natural plant defence system against insect attack. The first example of the application of this approach was successful transfer of the gene encoding a trypsin inhibitor (*CpTi*) (Hilder *et al.*, 1987). Other plant-derived genes with insecticidal activity include genes encoding α-amylase inhibitors, lectins, and chitinases. Lectins such as those purified from snowdrop (*Galanthus nivalis*) or garlic (*Allium* sp.) are toxic to insects but not mammals.

Transgenic sugarcane engineered with the snowdrop lectin has been shown to have antibiosis to canegrubs (Nutt *et al.*, 1999) and also to sugarcane stemborers (Legaspi and Merkov, 2000). Falco and Silva-Filho (2003) reported resistance to *Diatraea saccharalis* with soybean proteinase inhibitors and Nutt (2005) investigated the use of proteinase inhibitors from the guts of canegrubs as potential pest-derived transgenes.

As attractive as this new technology may appear, it must be kept in mind that an insecticide is still being administered to the insect, albeit in a non-traditional manner, and is therefore still subject to the same concerns for the development of resistance.

As pointed out by Babu *et al.* (2003), the long-term impact of transgenics on development of resistance, environmental and public concerns, and biosafety issues should be carefully examined before the release of any transgenics. In addition, these transgenes often come with third-party ownership restrictions on their use, usually making their commercialisation difficult.

**Molecular marker technology**

Genetic markers are heritable entities that are associated with economically important traits. Ever since Mendel’s discoveries, plant breeders and associated disciplines have been monitoring, inducing, and mapping single gene markers in higher plants. Unfortunately, most traits of economic importance in sugarcane are polygenic.

Although advances in quantitative genetics have made many important contributions to the basic understanding of the genetics of polygenic traits, ultimately the inability to describe and study quantitative traits has seriously hampered breeding for such traits.
The advent of molecular markers in quantitative genetics began with the discovery that the allelic forms of enzymes (isozymes) can be separated on electrophoretic gels. This meant that it was no longer necessary for a gene to cause a discrete visible change in the phenotype of an organism for it to be scored. The next advance in molecular markers came with the introduction of DNA-based genetic markers.

Several areas of sugarcane improvement have been impacted by molecular markers. One area that has been explored by entomologists is the identification of quantitative trait loci (QTL). A number of studies have recently been published reporting markers for several stemborer species – *Eldana saccharina* (Butterfield *et al.*, 2004), *Eoreuma loftini* and *Diatraea saccharalis* (da Silva *et al.*, 2005), *Sciraphaga excerptalis* (Selvi *et al.*, 2008), *Chilo sacchariphagus* (Nibouche *et al.*, 2012), and *Diatraea saccharalis* (Liu *et al.*, pers. communication). However, to our knowledge, none of the markers identified are actively being used in a sugarcane improvement program.

### Legacy to other management components

#### Diagnostics and phylogenetics

Accurate identification of a pest species is critical in framing appropriate management measures. Classically, identification rests on morphological characters, but these may show little variation among species and/or may be variable within species. A classic case is that of two groups of Australian whitegrubs where larval morphology and overlapping geographic distributions do not allow morphological separation among members of each group.

Miller *et al.* (1999) used species-level base-pair differences in the cytochrome oxidase II gene (COII) to develop polymerase chain reaction restriction fragment length (PCR-RFLP) protocols for robust identification of larvae of each species. The technique has proved particularly useful in insecticide-control trials where accurate identification of target species is mandatory, and the phylogeny developed matches well with those derived from morphological characters (Allsopp and Lambkin, 2006).

The same technique was used by Lange *et al.* (2004) to develop DNA-based diagnostics to identify sugarcane borers at any developmental stage. Rapid and accurate identification of larval borers is vital in managing any incursion of exotic species, particularly for the Australian industry where there are no major endemic or established borer species.

Lange *et al.* genetically profiled borers from around the world and established protocols that allowed rapid identification of the most common stage found in any incursion, the larvae. The technique was subsequently tested in a suspected incursion of a *Chilo* sp. in the Torres Strait area of northern Australia. Young larvae were rapidly identified as not being one of the major borer species and, after comparisons with DNA from adults in collections, were shown to be an endemic species and unlikely to cause significant damage to sugarcane (Allsopp *et al.* 2005).

Six species of *Mythimna* armyworms occur in Mauritian cane fields and, because adults and larvae are similar, morphological distinction among species is difficult. Joomun *et al.* (2010) used polymorphisms in the 5’ end of the COI gene to identify a combination of four enzymes, *RsaI, TaqI, PvuII* and *SacI*, that gave a simple and quick method for differentiating the three species tested, *M. insulicola*, *M. phaea* and *M. pseudoloreyi*. These and similar data, e.g. from the American borer *Diatraea saccharalis* (Bravo *et al.* 2008; Li *et al.* 2011), could be included in the ‘Barcodes of Life’ project with the intent to identify each of the species on Earth.

The difficulty is in securing funding for a project that would benefit all sugarcane growing countries, but which does not have an immediate impact on productivity.

Lange *et al.* (2004) also used that sequence data to construct molecular phylogenies. The Noctuidae were found to be monophyletic, providing molecular support for the current taxonomy within the family. However, the Pyraloidea appear paraphyletic, with the Galleriinae and Schoenobiinae separated from the Crambinae.
This supports the separation of the Pyralidae and Crambinae, but does not support the incorporation of the Schoenobiinae in the Crambidae. Of the three crambine genera examined, *Diatraea* appeared monophyletic, *Chilo* paraphyletic, and *Eoreuma* basal to those two.

Within the Noctuidae, *Sesamia* and *Bathytricha* were monophyletic, with *Busseola* basal to *Bathytricha*. Many species had different biotypes within collection localities and across their distribution. These data highlight the need for taxonomic revisions at all taxonomic levels.

The African borer *Eldana saccharina* occurs throughout sub-Saharan Africa, but populations from West Africa have distinct behavioural differences and parasitoid guilds from those in East and southern Africa (King et al. 2002; Assefa et al. 2006).

DNA analysis using the cytochrome oxidase I gene (COI) showed that Ethiopian specimens differ genetically from both West and southern African specimens, while in each area there is little variation (Assefa et al. 2006).

Ugandan specimens, however, show high genetic diversity, presumably mirroring the geological changes in the Rift Valley area during the Miocene and Pleistocene. Overall, the genetic results reflect and explain the differences in behaviour, biology and parasitoids seen previously.

Similar variation in the borer *D. saccharalis* was found between North American-Caribbean populations and Central-South American populations (Lange et al. 2004). The differences could reflect two dispersals (presumably human-assisted), one to the east and one to the south, from an original evolution on grasses, perhaps the wild ancestor of maize, in Central America.

Other analysis of variation in the same species (Palacio Cortés et al. 2010) showed similar geographical differences in DNA and in the ratios of the two components of the sex pheromone—a clear case of genetics reflecting physiology and behaviour.

**Population markers**

Genetic markers are useful for monitoring changes in genetic profiles, for example in monitoring changes in the genetic variability of laboratory colonies used to generate parasites for inundative release programs or changes in wild populations exposed to chemical or genetically modified controls.

A simple application is for monitoring changes in gender ratios in laboratory colonies of the borer *Diatraea saccharalis* (Heideman et al., 2010). One DNA fragment of about 700 bp is a useful female marker for that species. It would be interesting to determine if this same marker is consistent over a range of other borers.

Ruvolo-Takasusuki et al. (2002) investigated the profiles of different forms of esterases in *D. saccharalis* as possible population markers for the study of that borer. They could show that laboratory populations maintained for at least four generations still behaved as if the moth was randomly mating. This indicates that the genetic diversity of populations used for rearing parasites is maintained.

One concern with the use of any insecticide, whether a synthetic chemical or one delivered through genetically modified plants, is the development of resistance in target populations. How to monitor the development of resistance so that controls are not overused or so that they can be replaced before an insecticide loses its field efficacy is a central question.

Yang et al. (2010) showed that the expression of three aminopeptidases from the midgut of *D. saccharalis* decreased as the insects developed resistance to Cry1Ab toxin from *Bacillus thuringiensis*, potentially forming a marker for the development of field resistance to transgenic plants expressing Cry1Ab.

This provides a guide to the development of other resistance-monitoring systems, although difficulties in developing a laboratory-based resistant strain of a target insect, such as a whitegrub that has a 2-year lifecycle and that must be reared in soil in individual containers, are considerable.
Parasitoid effectiveness

The success of biological control programs depends on accurate identification and biosystematics of both natural enemies and target pests. However, in reality, such programs are often confounded by cryptic species and interspecific groupings (superficially similar) that differ in their relationships with hosts. Terms such as ‘biotypes’, ‘races’ and ‘strains’, commonly used in sugarcane entomology, reflect this variation.

The *Cotesia flavipes* species complex of parasitoid wasps are gregarious endoparasitoids of stemborers of sugarcane and other grasses. Populations of these wasps have been introduced widely and are used in many sugarcane industries to control stemborers, but not all introductions or programs have been successful. Limited work indicated genetic variation within and among species of the complex, consistent with variation in host range, habitat preferences and biology.

Muirhead *et al.* (2012) provided a comprehensive molecular phylogeny of the complex using both mitochondrial and nuclear DNA. Their analyses provided strong support for the monophyly of the complex and of the presence of at least four species: *C. chilonis* (from China and Japan), *C. sesamiae* (from Africa), *C. flavipes* (originating from the Indo-Asia region but introduced into Africa and the Americas), and *C. nonagriae* (from Australia and Papua New Guinea). The latter was previously synonymised with *C. flavipes* but was reinstated based on molecular, morphological and biological differences (Muirhead *et al.* 2008, 2010).

There is obvious potential for new introductions based on *C. chilonis* and/or *C. nonagriae*. Diversity of geographic populations relates to historical biogeographic barriers and biological control introductions, and reflects previous reports of ecological variation in these species. Strong discordance was found between the mitochondrial and nuclear markers in the Papua New Guinea material—this suggests recent hybridisation and introgression of *C. flavipes* and *C. nonagriae*, although the biological and ecological implications of this are unknown.

The study also indicated that Japanese populations of ‘*C. flavipes*’ may represent a further, cryptic species. Some clades showed specific host associations, but Muirhead *et al.* (2012) considered that this could be due to localised host availability, rather than host specificity. The overall message from this work was that, given the limitations of morphological-based identification for this complex, molecular identification should be used prior to any biological control introductions – in other words, know what you are dealing with!

Paratransgenesis

Genetic modification for pest management has classically been directed at improving plant antibiosis (see above). Pest insects can be genetically modified, but this is technically challenging and may meet social constraints – although the impact on food quality would be negated. A third alternative utilises microorganisms that are closely associated with the pest to deliver compounds that directly harm the host insect. This is termed paratransgenesis. Indigenous gut bacteria are favoured as delivery vehicles because resident bacteria are usually unable to become established outside the gut environment, because non-residents are unable to colonise the gut, and there is no impact on fitness as there is in transgenic insects.

Pittman *et al.* (2008a) compared the bacterial community profiles associated with the hindgut walls of the Australian sugarcane whitegrub *Dermolepida albohirtum* and those associated with the insect’s plant root food. They used denaturing gradient gel electrophoresis (DGGE) and specific 16S rRNA primers to reveal a number of taxa that were found consistently in the larvae, but not in their food source. That is, bacteria specific to the gut of the larvae.

These taxa were related to others found in the intestines of other scarab larvae and termites. They managed to isolate pure cultures of eight of these bacteria (Pittman *et al.* 2008b) and fed them to larvae. DGGE analysis showed that at least one strain persisted in the hindgut for 19 days post-consumption.
Using the EZ::Tn5 transposon system, they inserted a kanamycin resistance gene into the chromosome of that strain and again fed the transformed bacteria to the larvae. These transformants were maintained in the hindgut for at least another 12 days, demonstrating the ability of paratransgenesis to deliver a gene product potentially lethal to the host insect. It is surprising that this approach has not been developed further despite its clear potential. Bacteria are not the only potential carriers.

Hughes et al. (2011a) isolated two yeasts from the sugarcane planthopper Perkinsiella saccharicida, a vector of Fiji leaf gall virus. One, a Candida sp., was cultured and genetically transformed to confer resistance to the antibiotic nourseothricin and expression of green fluorescent protein. However, stably transformed yeast lines could not be isolated as the integrative plasmids presumably replicated within the yeast without integration into the genome. Only with stable transformation could the yeast be a useful agent for paratransgenic control of Fiji leaf gall.

Wolbachia pipientis is a maternally inherited endosymbiotic bacterium that infects a wide range of arthropods and nematodes. It is known for inducing dramatic reproductive phenotypes in the host insects, such as cytoplasmic incompatibility and parthenogenesis, that manipulate host reproduction to favour the bacterium.

DNA analysis of populations of *P. saccharicida* and *P. vitiensis* showed low-titre infections, albeit variable, and high phylogenetic diversities of associated Wolbachia (Hughes et al. 2011b). How these affect the reproduction of the planthoppers is unknown, but it is interesting to speculate, firstly, how they may be associated with the dramatic decline in numbers of *P. saccharicida* in eastern Australian sugarcane since the late 1980s, and, secondly, if they have a paratransgenic potential for control of Fiji leaf gall.

**Conclusions**

Entomology and classical Mendelian genetics have had a long association. The elucidation and expansion of Mendel’s classic work in genetic inheritance was done using an insect (the fruit fly) as the experimental animal. Contrariwise, many approaches to insect control have a genetic basis (i.e., screwworm eradication program).

Mendel’s legacy continues to live through sugarcane pests. In this paper we discussed examples of that legacy as applied to conventional and molecular approaches to breeding for insect resistance. We also discussed the application of genetics in pest management, systematics, and ecology.

Conventional breeding for insect resistance is likely to continue to lag behind other traits as the realities of the high costs associated with a conventional breeding program and complexity of the sugarcane genome will continue to hold sway.

Skinner et al. (1987) warned that to increase the numbers of characters with no increase in budget or resources was to provide a mechanism for overloading the breeding program with requirements and destroying its productivity. Molecular breeding techniques offer many opportunities to overcome those limitations; however, the cost associated with this technology is high and gains that are obtained in pest management must be compared to more conventional strategies.

Additionally, before the release of transgenic sugarcane with insect resistance can occur, various scientific, legislative, and public perception issues must be addressed. Many sugarcane industries lacking the resources are simply unable to overcome these obstacles.

Genetic methods have revolutionised insect taxonomy and provided the means for rapid identification of closely related species, often without access to identified specimens. This is now impacting on our understanding of the ecology and biology of sugarcane pests and their natural enemies. Crop plants and pest insects can be genetically modified but paratransgenesis of closely associated microorganisms may allow better targeting and delivery of insecticidal compounds. Again, scientific, legislative, and public perception issues must be addressed.
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LES LOIS DE MENDEL S’EXPRESSMENT A TRAVERS LA GESTION DES INSECTES RAVAGEURS DE LA CANNE A SUCRE

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MOTS-CLES: Résistance aux Insectes, Gestion des Ravageurs, Systématique, Écologie.

Résumé
L’ENTOMOLOGIE ET LA GÉNÉTIQUE classique mendélienne ont eu une longue association et les lois de Mendel continuent de vivre à travers la gestion des ravageurs de la canne à sucre. Dans cet article, à l’aide d’exemples, nous discutons de la façon dont ces lois s’appliquent aux approches conventionnelles et moléculaires pour la sélection des variétés résistantes aux insectes. Nous discutons aussi de l’application de la génétique, la systématique et l’écologie et dans la gestion des insectes. La sélection conventionnelle de variétés pour la résistance aux insectes va certainement continuer de rester en retrait par rapport à d’autres traits agronomiques car la réalité des coûts élevés associés à ce type de sélection conventionnel et la complexité du génome de la canne à sucre reste dominante. Les techniques de sélection moléculaire offrent de nombreuses opportunités de maîtriser ces limites; cependant le coût associé à cette technologie reste élevé et les gains obtenus avec la gestion des insectes doivent être comparés à ceux des méthodes plus conventionnelles. De plus, avant la libération des variétés de canne à sucre transgéniques pouvant être résistantes aux insectes, les perceptions scientifiques, législatives, publiques qui posent problème doivent être considérées. De nombreuses industries sucrières par manque de ressources ne peuvent pas faire face à ses obstacles. La génétique a révolutionné la taxonomie des insectes et apporté les moyens rapides d’identification des espèces proches, souvent sans avoir accès au matériel identifié. Cela impacte maintenant notre compréhension de l’écologie et de la biologie des insectes ravageurs de la canne à sucre et leurs principaux ennemis naturels. Les plantes cultivées et les insectes ravageurs peuvent être génétiquement modifiés mais la paratransgenèse des microorganismes associés à ces insectes peut permettre de mieux cibler et produire des composés à propriété insecticide. Et là encore il est nécessaire de prendre en compte les problèmes de perception scientifique, législative et publique.
EL LEGADO DE MENDEL VIVE A TRAVÉS DEL MANEJO DE PLAGAS DE CAÑA DE AZÚCAR

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PALABRAS CLAVE: Resistencia para Insectos, Manejo de Plagas, Sistemática, Ecología.

Resumen
LA ENTOMOLOGÍA Y LA GENÉTICA clásica mendeliana ha tenido una larga asociación y el legado de Mendel continua viviendo en las plagas de la caña de azúcar. En este trabajo discutimos ejemplos de este legado referidos a abordajes convencionales y moleculares para el mejoramiento para resistencia a insectos. Discutimos también la aplicación de la genética en el manejo de plagas, la sistemática, y la ecología. El mejoramiento convencional para resistencia a insectos muy probablemente continúe rezagándose en relación a otros tratamientos en la medida que continúen dominando los altos costos asociados a los programas de mejoramiento convencional y la complejidad del genoma de la caña de azúcar. Las técnicas de mejoramiento molecular ofrecen numerosas oportunidades para superar estas limitaciones; sin embargo, los costos asociados a esta tecnología es alto y las ganancias que se obtienen en el manejo de plagas se debe comparar con estrategias de control más convencionales. Además, antes de que se pueda liberar una caña de azúcar transgénica con resistencia a insectos, se deben abordar varios temas de índole científica, normativa y de percepción pública. Muchas de las industrias de la caña de azúcar que no cuentan con los recursos no pueden superar estos obstáculos. Los métodos genéticos han revolucionado la taxonomía de insectos y proporcionado los medios para una rápida identificación de especies estrechamente relacionadas, a menudo sin acceso a especímenes identificados. Esto está impactando ahora en nuestra comprensión de la ecología y biología de plagas de caña de azúcar y sus enemigos naturales. Las plantas cultivadas y los insectos plaga pueden ser transformados genéticamente pero la paratransgénesis de microorganismos estrechamente asociados pueden permitir un mejor direccionamiento y distribución de compuestos insecticidas. Nuevamente, se deben abordar temas de índole científica, normativa y de percepción pública.
O LEGADO DE MENDEL SOBREVIVE AO MANEJO DE PRAGAS DA CANA-DE-AÇÚCAR

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PALAVRAS-CHAVE: Resistência a Insetos, Manejo de Pragas, Sistemática, Ecologia.

Resumo

A ENTOMOLOGIA E A GENÉTICA clássica mendeliana estão associadas há muito tempo e o legado de Mendel sobrevive a pragas da cana-de-açúcar. Neste trabalho, discutiremos exemplos desse legado, aplicado a abordagens convencionais e moleculares para melhoramento para resistência a insetos. Também discutiremos a aplicação da genética em manejo de pragas, sistemática e ecologia. O melhoramento convencional para resistência a insetos deve continuar a retardar em relação a outros traços, ao passo que as realidades dos altos custos associados a programas de melhoramento convencionais e a complexidade do genoma da cana continuará a predominar. Técnicas de melhoramento molecular oferecem muitas oportunidades para superar essas limitações, mas o custo associado a essa tecnologia é alto e os ganhos que são obtidos no manejo de pragas devem ser comparados ao de estratégias mais convencionais. Além disso, antes que ocorra o lançamento da cana transgênica com resistência a inseto, devem ser tratadas várias questões científicas, legislativas e de percepção pública. Muitas indústrias de cana-de-açúcar com recursos insuficientes simplesmente não conseguem superar esses obstáculos. Os métodos genéticos revolucionaram a taxonomia de insetos e ofereceram meios para identificação rápida de espécies relacionadas, em geral sem acesso a espécimes identificados. Esse fato tem impacto no nosso entendimento da ecologia e da biologia das pragas de cana e de seus inimigos naturais. As culturas e as pragas podem ser modificadas geneticamente, mas a paratransgênese de microrganismos intimamente associados pode ser um melhor alvo e oferecer compostos inseticidas. Novamente, devem ser tratadas questões científicas, legislativas e de percepção pública.
KENDEL’S GENETICS IN A COMPLEX GENOME IN THE GENOMICS ERA

By

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Abstract
MENDEL’S 1865 PAPER ‘Experiments in Plant Hybridisation’ would later transform the study of inheritance, and usher in the new science of genetics. The study was the outcome of eight years of experimentation using a plant species and phenotypic traits carefully selected to be suitable to generate useable results: ‘The value and utility of any experiment are determined by the fitness of the material to the purpose for which it is used, and thus in the case before us it cannot be immaterial what plants are subjected to experiment and in what manner such experiment is conducted.’ Beyond his ‘Laws’ of Segregation and Independent Assortment, Mendel’s greatest legacy may be regarded as the introduction of reductionist methodology to biological science, and the concept of the model system to derive more widely applicable inferences; his peas were the forerunner of today Arabidopsis. The complex hybrid auto-allo-aneu-poly-ploid genome of sugarcane hardly makes it an attractive subject as a model system, yet we still need to deepen our understanding of genome structure and functioning in order to make progress in sugarcane breeding and biotechnology. This presentation will highlight some of the key knowledge gaps and challenges in sugarcane genetics, and outline how a model-system approach could assist in shedding light on these areas.

Introduction
In 1865, Gregor Mendel read his paper ‘Experiments in Plant Hybridisation’, describing the inheritance of phenotypic traits in peas, at two meetings of the Natural History Society in Brno, Monrovia, which was later published in the proceeding of the Society in 1866. He summarised his findings in two ‘laws’, which later became known as the Law of Segregation, and the Law of Independent Assortment.

In the paper, he introduced the notation of $A$ and $a$ to denote dominant and recessive characters, and $Aa$ to denote the hybrid, and demonstrated that the result of crossing a dominant with a recessive parent would result in progeny $A$, $Aa$ and $a$ in the ratio of 1:2:1. In addition, he extended the analysis to 2 and 3 characters (denoted by $B$, $b$ and $C$, $c$), demonstrating the more complex ratios obtained when combinations of characters are observed.

The paper was the results of eight years of experimentation, observation and mathematical analysis, as he understood the need for a rigorous, methodical approach, as evidenced in his introductory remarks.

‘Those who survey the work done in this department will arrive at the conviction that among all the numerous experiments made, not one has been carried out to such an extent and in such a way as to make it possible to determine the number of different forms under which the offspring of the hybrids appear, or to arrange these forms with certainty according to their separate generations, or definitely to ascertain their statistical relations. It requires indeed some courage to undertake a labour of such far-reaching extent; this appears, however, to be the only right way by which we can finally reach the solution of a question the importance of which cannot be overestimated in connection with the history of the evolution of organic forms.’
Although initially locally well received, the paper had little impact for the next 35 years, until independently ‘re-discovered’ in 1900 by Hugo de Vries and Carl Correns, and promoted by the English scientist William Bateson, who introduced the term ‘genetics’ in 1905, and was the co-founder of the Journal of Genetics in 1910. The new science of genetics was characterised by vigorous disagreement between the Mendelians, led by Bateson, and the ‘Biometric school’ of the study of inheritance led by the prominent statistician Karl Pearson, until the two fields were unified by R.A Fisher, who laid the foundation for modern quantitative genetic analysis, based on Mendel’s principles.

Nowadays, ‘mendelian genetics’ or ‘mendelian traits’ commonly refer to simple situations, typically in diploid organisms, where a trait is controlled by one or two genes with dominant/recessive alleles, in which case the genotypes (and phenotypes) of progeny of a cross can be predicted based on the genotype/phenotype of the parents. This is in contrast with polygenic or quantitative traits, which are influenced by many loci/alleles.

**Mendelian genetics and sugarcane**

Sugarcane has a hybrid, polyploid and aneuploid genome. The ancestral species, *S. officinarum* (2n = 80, x = 10) and *S. spontaneum* (2n = 40–128, x = 8) are both polyploids, and differences in the base chromosome number results in abnormal chromosome pairing during meiosis in the hybrid (Butterfield *et al*., 2001). Modern cultivars generally have chromosome numbers ranging from 100 to 120, with 9 to 15 chromosomes in each hom(e)ology group. At first glance, it may appear that the apparent complexity of the sugarcane genome would mean that a classical Mendelian approach would have little application in sugarcane genetic research and breeding.

This, however, is not the case. The simple ratio of 1AA: 2Aa : 1aa described by Mendel was later shown to be a special case of the more general form (A + a)^n; where n = the ploidy level, in Mendel’s case 2 for diploid peas, and in the case of sugarcane, 8 or 10. The same extension applies for cases with more than one locus, e.g. (AB + Ab + aB + ab)^n. Although algebraically more laborious to detail, the Laws of Segregation and Independent assortment apply equally to sugarcane as to peas. In fact, the application of Mendel’s laws extended to the polyploid case made it possible to develop the approaches to creating genetic maps in sugarcane (Wu *et al*., 1992); a basic tool fundamental to modern genetic analysis and molecular breeding applications.

A simple Mendelian trait has also been described in sugarcane, and its usefulness demonstrated in breeding. A major resistance gene to brown rust, Bru1, has been identified (Dugrois *et al*., 1996; Asnaghi *et al*., 2000) and characterised in a range of germplasm (Costet *et al*., 2012). It is possible that other major genes may be discovered for some disease resistance traits, facilitating their use in breeding, but the majority of economically important traits in sugarcane such as cane yield and sucrose content are quantitative in nature. Improving these traits currently relies on quantitative genetic approaches, but it is conceivable that, with improvements in sugarcane molecular marker technologies, Genomic Selection (GS) or Genome Wise Association Analysis (GWAS) using large numbers of markers (mapped using Mendelian approaches) will be used in the future to improve the efficiency of breeding.

**A Mendelian approach to understanding sugarcane**

Beyond his ‘Laws’ of Segregation and Independent Assortment, Mendel’s greatest legacy may be regarded as the introduction of reductionist methodology to biological science (Falk, 2005), and the concept of the model system to derive more widely applicable inferences; his peas were the forerunner of today’s *Arabidopsis* used for functional genetic studies. In describing the selection of the experimental material, Mendel commented: ‘The value and utility of any experiment are determined by the fitness of the material to the purpose for which it is used, and thus in the case before us it cannot be immaterial what plants are subjected to experiment and in what manner such experiment is conducted.’
The importance of the type of experimental material in relation to the type of questions or hypotheses that can be posed and investigated is crucial, and is the key to developing approaches to answer fundamental questions. This is even more crucial when the context is complex – as in the case of sugarcane genetic analysis. With this in mind, it is useful to reflect back on the fundamental questions that need to be answered to deepen our understanding of modern sugarcane, and develop experimental approaches from ‘first principles’ in order to address them. Some of these questions include the following:

(1) **What makes *Saccharum officinarum* sweet?**

*S. officinarum*, the original sugarcane cultivated until the development of modern hybrids, is native to New Guinea and Indonesia, but only found in cultivated conditions in garden plots of the indigenous people of the region. It is presumably derived from *S. robustum* (2n = 60, x = 10), a *Saccharum* species that is found growing wild, although no sweet forms of *S. robustum* are known. Although they differ in ploidy level, this is unlikely to be the cause of the dramatic increase in sucrose storage ability between the two species.

There has been some speculation suggesting that limited molecular data may not support a direct origin of *S. officinarum* from *S. robustum*, and that introgression of genes of other genera (e.g. *Miscanthus*) may be involved (Lu *et al.*, 1994) but, until an exhaustive study involving the genetic mapping and genome sequencing of ‘pure’ *S. officinarum* and *S. robustum* is carried out, the mystery of the origin of *S. officinarum* will not be solved. Analysis of simpler systems with better developed genetic resources – e.g. the comparison of sweet and non-sweet stalked germplasm of sorghum and maize – may shed further light on this question.

(2) **Why are few ancestral *S. officinarum* clones present in modern germplasm?**

The early accounts of hybridisation work between *S. officinarum* and *S. spontaneum* in Java (now Indonesia) show that a relatively large number of *S. officinarum* clones were used in the first sugarcane breeding experiments. However, most of these did not produce desirable progeny, with the consequence that the genealogies of modern hybrids can be traced back to a small number of successful *S. officinarum* parents (Arceneaux, 1965). Subsequent ‘base-broadening’ attempts in different countries using alternative sources of *S. officinarum* as parents have not met with much success. What characterises the difference between the successful and un-successful *S. officinarum* parents? The answer to this may be partly found in the answer to Question 1 above, but a thorough comparison of the genomes of diverse *S. officinarum* genotypes, in conjunction with *S. robustum*, would shed light on the key domestication genes involved in the development of modern sugarcane.

(3) **What is the ideal mix of *S. officinarum* and *S. spontaneum* genomes in hybrids?**

The F1 hybrid generation resulting from ‘regular’ 2n + n chromosome transmission of a cross between 2n = 80 *S. officinarum* and 2n = 64 *S. spontaneum* have 112 chromosomes; 80 (71%) from *S. officinarum*, and 32 (29%) from *S. spontaneum*. F1 hybrids generally resemble *S. spontaneum*, with thin stalks and low sucrose content.

With subsequent crossing events, either with *S. officinarum* or other hybrids, the proportion of *S. spontaneum* drops, and modern cultivars have about 15% of their genome derived from *S. spontaneum* (10% comprised of *S. spontaneum* chromosomes, with another 10% of chromosomes showing recombination between the two species (D’Hont *et al.*, 1996).

For this, it seems that there may be an optimum proportion of *S. spontaneum* genome that gives rise to superior performance in the hybrid. Aneuploidy could result in the further erosion of *S. spontaneum* genome in subsequent generations of breeding beyond this optimum level (Butterfield *et al.*, 2001), which would have important implications on breeding strategies.

High-density genetic maps containing species specific markers for a range of sugarcane hybrids of different generations would shed light on this question. To interpret these fully, in addition to genetic maps and genome sequence of *S. officinarum* (obtained from Question 1), similar genetic map and sequence resources would be needed for *S. spontaneum.*
Conclusions

Thorough experiments designed to answer the 3 basic questions posed above would go a long way to expand our knowledge of the genetics of sugarcane, the driving forces behind domestication of *Saccharum officinarum* and the factors contributing to the yield and quality parameters of modern germplasm.

These are all essentially Mendelian hypotheses; based on aligning knowledge of the species with the key questions needing answers, and requiring Mendelian analyses; genetic mapping using polyploid segregation ratios, and ratios of alleles within hybrids derived from different parents. Conceptually, they are not difficult questions to answer, but they are not quick questions to answer, requiring detailed planning and several years of population development, mapping, sequencing etc. Like Mendel’s experiments, a time frame of 8 years does not seem an unreasonable amount of time required (assuming the experiments are run concurrently) to obtain solid answers.

But these are not cheap answers to obtain, principally because of the long time required. To date, sugarcane research has been driven largely by small industry-based research institutes, with some larger government-funded institutes and universities making important contributions.

As everywhere, funding for research, especially basic research, is an issue, and researchers have tried to balance basic versus applied research, often having to take short-cuts in experimental design or place more emphasis on applied aspects.

It should not be forgotten, however, that the global sugarcane production is around 1.7 billion tonnes per annum (FAOSTAT: data for 2010).

Using a hypothetical global cane price of $30/tonne, this would translate to an annual raw cane value (i.e. not considering the value of sugar or ethanol) of around $50 billion per year.

Increasing productivity of the raw material—cane and recoverable sugars per hectare—is key for the economic development of the sugarcane industry. Investment in basic research to gain fundamental knowledge about the raw material, following the example of Mendel set more than 150 years ago, is one path to achieve this.

REFERENCES


LA GÉNÉTIQUE DE MENDEL DANS UN GÉNOME COMPLEXE À L’ÈRE GÉNOMIQUE

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Résumé

Le papier de Mendel “Expérimentation sur l’hybridation des plantes” publié en 1865 allait ultérieurement transformer l’étude de l’hérédité, et ouvrir la voie vers une nouvelle science de la génétique. L’étude a été la culmination de huit années d’expérimentation utilisant une espèce de plante et des caractéristiques phénotypiques soigneusement choisis capables de générer des résultats utilisables: “La valeur et l’utilité de toute expérimentation sont déterminées par la convenance du matériel suivant l’objectif pour lequel il est utilisé, donc pour le sujet qui nous intéresse il ne peut être immatériel de savoir quelles sont les plantes qui sont soumises à l’expérimentation et la manière dont l’expérimentation est menée”. Au-delà de ses “Lois” de ségrégation et d’assortiment indépendant, le plus grand héritage de Mendel peut être considérer comme l’introduction de méthodologie réductionniste de la science biologique, et le concept du système modèle pour tirer des inférences plus largement applicables; ses petits poids ont été le précurseur de l’Arabidopsis d’aujourd’hui. L’hybride complexe auto-allo-poly-ploïdie du génome de la canne à sucre ne permet guère un sujet attrayant comme un système modèle, pourtant on a toujours besoin d’approfondir nos connaissances de la structure du génome et son fonctionnement pour accomplir des progrès dans l’amélioration génétique de la canne à sucre et de la biotechnologie. Cette présentation va mettre en évidence quelques-unes des principales lacunes et les défis de la génétique de la canne, et définir dans les grandes lignes comment une approche modèle- système peut aider à éclairer ces zones.
LA GENÉTICA MENDELIANA EN UN GENOMA COMPLEJO EN LA ERA DE LA GENÓMICA

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Resumen

El artículo de Mendel, publicado en 1865 con el título “Experimentos en hibridación en plantas”, se transformaría más tarde en el estudio de la herencia, marcando la nueva ciencia de la genética. Su reporte fue el resultado de ocho años de experimentación, usando una especie de planta y caracteres fenotípicos cuidadosamente seleccionados y apropiados para que generen resultados usables: “El valor y la utilidad de cualquier experimento dependen de la aptitud del material para el propósito por el cual se utiliza; entonces, en el caso anterior a nosotros este no puede ser irrelevante de qué plantas son sometidas a experimentar y de qué manera se lleva a cabo tal experimento.” Más allá de sus “Leyes” de la Segregación y el Apareamiento al Azar, el mayor legado de Mendel podría ser mirado como la introducción de la metodología del reduccionismo a las ciencias biológicas, y el concepto de un sistema de modelo para direccionar inferencias de aplicación más amplia; sus guisantes fueron los predecesores del Arabidopsis de hoy. El complejo genoma híbrido auto-allo-aneu-poli-ploide de caña de azúcar, difícilmente hace a este organismo como modelo atractivo de estudio, ya que todavía necesitamos profundizar nuestro entendimiento de la estructura y funcionamiento del genoma para hacer progresos en mejoramiento y biotecnología de caña. Esta presentación resumirá algunos de los espacios vacíos claves del conocimiento y los retos en la genética de caña de azúcar, y resumirá como un sistema-modelo método podría asistir en mostrar luces en estas áreas.
A GENÉTICA DE MENDEL EM UM GENOMA COMPLEXO NA ERA GENÔMICA

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Resumo

O TRABALHO DE MENDEL de 1865 intitulado “Experiments in Plant Hybridization” transformou o estudo da hereditariedade e abriu as portas a uma nova ciência da genética. O estudo foi o resultado de oito anos de experimentação utilizando espécies de plantas e traços fenotípicos cuidadosamente selecionados como adequados para gerar resultados úteis: “O valor e a utilidade de qualquer experimento são determinados pela adequação do material para o fim a que é utilizado e, nesse caso, não deixa de ser relevante o que as plantas estão sujeitas a experimentar e de que maneira tal experimento é conduzido.” Além de suas “Leis” de Segregação e Variedade Independente, o maior legado de Mendel pode ser considerado como a introdução da metodologia reducionista à ciência biológica e o conceito de sistema de modelo ter gerado inferências mais largamente aplicáveis, suas ervilhãs foram as precursoras do Arabidopsis atual. O genoma híbrido complexo auto-alo-aneupoliploide da cana-de-açúcar pode não ser um assunto atraente como um sistema modelo, mas ainda precisamos aprofundar nosso conhecimento sobre a estrutura e o funcionamento do genoma para progredir em melhoramento e biotecnologia de cana-de-açúcar. Esta apresentação destacará algumas das principais lacunas no conhecimento e os desafios na genética da cana, além de esboçar como uma abordagem de sistema modelo poderia lançar luz sobre essas áreas.