Chapter

Sugarcane Breeding for Enhanced Fiber and Its Impacts on Industrial Processes

Pietro Sica

Abstract

For centuries, sugar has been virtually the only commercialized product derived from sugarcane. Traditionally, sugarcane breeding programs focused exclusively on the increase of the sucrose content, abandoning characteristics such as biomass yield and fiber content. Recently, sugarcane gained prominence also for its potential in terms of biomass production. As a result, some sugarcane breeding programs began to look for ways to increase fiber content and biomass yield instead of sugar content. In the 1980s, Alexander created the concept of energy cane. Here we review the changes in the sugarcane breeding programs related to enhanced fiber instead of sugar content. Compare the energy generation of energy cane with other biomass crops. Also, the recent changes in the biomass and biofuels scenario, focusing on topics as 2G ethanol and the RenovaBio program, from the Brazilian Government, which will give carbon credits to biofuels. Although several studies demonstrate its potential for biomass production, energy cane is still a new technology on an experimental scale and has been struggling to reach and establish on a commercial scale. However, policies and new technologies are increasing the demand for lignocellulosic material. Therefore, this chapter connects these points and shows the potential of this new plant material for the coming years.

Keywords: energy cane, bioenergy, 2G ethanol, RenovaBio, cane breeding, biomass

1. Introduction

Sugarcane is the most produced crop in the world, yielding about 1,890 million tons on approximately 26.8 million hectares. About 40.6% of the world's production was in Brazil. Asia (38.2%) also stands out, especially with countries such as India (18.4%) and China (6.5%), which are the second and third largest producers in the world, respectively. However, due to its high yields (70.6 tons/ha), the sugarcane harvested area is lower than other production main crops such as wheat, maize, and rice [1].

Dry matter of sugarcane is composed of sugar, mostly sucrose, and fiber (cellulose, hemicelluloses, and lignin) [2]. Studies have shown that sugarcane commercial hybrids stem is composed of about 14–18% sucrose and 12–15% fiber. The rest consists of water, minerals, and other substances [3, 4].

Worldwide, sugarcane is primarily grown as a source of sugar, providing around 70% of the world's sugar demand [5]. In 2018/2019, the world sugar production is expected to yield about 188 million metric tons of raw sugar, of which 68 million will be produced in Brazil and India [6]. In 2017, world ethanol production was about 27.05 billion gallons—the United States was the world's largest producer (58%), followed by Brazil (26%). However, the vast majority of US ethanol is produced from corn, while Brazil primarily uses sugarcane [7]. For this reason, traditionally, sugarcane breeding programs have focused on increasing the sugar content.

Sugarcane bagasse and straw have a high content of fiber and can be used for energy purposes according to four platforms: cogeneration, production of second-generation bioethanol, gasification to produce syngas, or generation of biogas, and pyrolysis to produce bio-oil and biochar [8–10]. In 2018, in the Brazilian final energy consumption sugarcane products represented 17.2% of all energy consumed in Brazil, of which 10.8% was from the sugarcane bagasse and 6.4% from ethanol, those products together were higher than mineral coal (14.4%), natural gas (11.4) and firewood (9.1%) [11].

Thus, sugarcane has great potential as a source of bioenergy. This review will present and discuss the traditional breeding programs that aim to increase sucrose content and the shift of this paradigm, focusing on the increase of biomass and fiber for bioenergy generation. In addition to the prospects for the use of biomass as a renewable and sustainable source of energy in the coming years.

2. Sugarcane breeding

Sugarcane is a crop that belongs to the genus *Saccharum L.* in the Poaceae family. Its genus includes six different species with variable sizes and numbers of chromosomes: *S. officinarum, S. spontaneum*, *S. robustum*, *S. barberi*, *S. sinense*, and *S. edule.* There are four genera closer to *Saccharum L.* that can readily interbreed (*Sclerostachya, Miscanthus, Narenga,* and *Erianthus*), forming the '*Saccharum* complex`. Three gene pools for sugarcane were proposed (**Table 1**).

One of the biggest challenges for taxonomists and molecular biologists is that '*Saccharum* complex' genera have a high level of polyploidy and aneuploidy, that is, an unbalanced number of chromosomes. Therefore, the complexity and size of the sugarcane genome are limitations in genetic improvement [12, 14]. Excessive non-flowering is one of the desirable characteristics of a sugarcane cultivar because flowering causes a pithing process in the stalks. However, flowering is a crucial characteristic in a breeding program, making it necessary for breeding stations to be built in specific locations where these phenotypes may flower regularly and have fertility. Another challenge for sugarcane breeders is the time. In Brazil, the breeding program takes from 11 to 13 years starting from the first crossbreeding performed until the release of a cultivar, since it is necessary to evaluate the clones on diseases and pests, as well as their productivity in different environments [15].

Gene pool	Genera examples	Ease of crossing	Hybrids
GP-1	*S. officinarum* clones, *S. robustum*, *S. spontaneum*, *Erianthus* and *Miscanthus*	Easy	Fertile
GP-2	Remainder of '*Saccharum* complex'	Some biological barriers make it more difficult	Tend to be sterile
GP-3	*Sorghum* and *Zea*	Needs techniques to enable gene transfer	Weak, lethal, or completely sterile

Table 1.
Proposed gene-pools for sugarcane and potential genera to be used in sugarcane breeding programs (adapted from [12, 13]).

2.1 Traditional sugarcane breeding

Until the 19th century, the most cultivated species was *Saccharum officinarum* because of its high sugar content [12]. Thereafter, sugarcane breeders that were interested in increasing disease resistance and yield crossed *S. officinarum* with a wild and vigorous relative, *S. spontaneum*, and then backcrossed the hybrids to *S. officinarum* [16]. *The* hybridization of both genera resulted in modern cultivars with chromosome numbers ranging from 100 to 130 [17], of which 80% originate from *S. officinarum* and 10–15% from *S. spontaneum*, with about 5–10% being recombinant chromosomes [18, 19].

S. officinarum was first found growing in gardens in the aborigines of New Guinea, a humid and high-temperature region. Later, it began to be used as raw material for sugar production, playing an important social, economic, and cultural role during the colonial period [20]. *S. spontaneum* is a grassy wild species found in diverse environments from Africa to Southeast Asia and the Pacific Islands. Since it evolved in such different environments, it has a wide gene pool, can adapt to different climate characteristics and is resistant to diseases to which *S. officinarum* is susceptible [21, 22].

Later, during the 20th century, sugarcane breeding programs were expanded, and all the efforts were still concentrated on increasing the sugarcane yield for sugar. Current levels of sugar yields are difficult to overcome, especially when considering the management systems and the carbon partition between the accumulation of sucrose and plant growth [23, 24]. The initial success of some breeding programs and subsequent stagnation in the genetic gains of sugarcane can be seen in the yield variation in the US, Brazil, and the World in the last fifty years, especially in the last decade [25].

In 1989, [22] described the 'modern' (1890–1989) sugarcane breeding process by dividing it into three phases. The first phase involved crossing and selecting among *S. officinarum* clones. By that time several clones were used by sugar industries worldwide. Those clones had commercial milling qualities such as sugar content, low fiber, and low impurity levels. However, they were susceptible to some diseases and had low vigor and ratooning performance. The second phase required developing interspecific hybrids by crossing the selected clone in the first phase with other species, which is normally part of the '*Saccharum* complex'. *S. spontaneum* has high adaptability to diverse environments, disease resistance, high vigor, and ratooning capacity. Because of this, it was mostly used in the interspecific cross with *S. officinarum.* To increase sugar content and stalk size, breeders used a process called "nobilization". Nobilization was based on backcrossing the initial hybrids with *S. officinarum* clones to increase the sugar content and the stalk size. The third phase was the multiplication and exploitation of the hybrids obtained in the second phase [12].

This breeding process, however, led to the narrowing of the genetic base of sugarcane breeding programs [21, 22]. Backcrossing sugarcane hybrids with *S. officinarum,* despite increasing the sugar content reduces fiber content and vigor, as the varieties are more susceptible to abiotic stresses and diseases [26]. Thus, the commercial average yield of sugarcane is about 25% of the potential field yield of fresh biomass in optimum conditions, 400 tons per hectare [27]. Because of these concerns, the interest in genetic diversity increased and sugarcane breeders saw a potential opportunity to introgress new genes into commercial hybrids [28]. The '*Saccharum* complex' fiber and sugar content is presented in **Table 2** [29].

2.2 Sugarcane breeding for fiber and the energy cane concept

After more than 100 years of looking to increase sugar yield, by the beginning of this century sugarcane breeding programs started to search for a new type of cane,

Species (n)	Sucrose (%)	Reducing sugar (%)	Fiber (%)
Erianthus maximus (3)	2.24 ± 0.44	0.73 ± 0.23	26.4 ± 0.9
Erianthus arundinaceus (2)	0.62 ± 0.16	0.61 ± 0.17	30.3 ± 0.3
Miscanthus floridulus (5)	3.03 ± 0.56	0.79 ± 0.24	51.0 ± 2.0
Saccharum spontaneum (30)	5.35 ± 0.38	1.66 ± 0.06	31.8 ± 0.9
Saccharum robustum (10)	7.73 ± 0.83	0.27 ± 0.02	24.8 ± 1.6
Saccharum sinense (2)	13.45 ± 0.02	0.38 ± 0.08	12.8 ± 2.0
Saccharum officinarum (25)	17.48 ± 0.35	0.32 ± 0.02	9.8 ± 0.4

n = number of evaluated accessions.

Table 2.
Levels of sucrose, reducing sugars, and fiber in access of ancestral genera and species of sugarcane [9, 29].

focusing on high yield and fiber for bioenergy generation [9, 30]. Now the goal of some breeding programs is to produce hardy plants with less juice and higher fiber productivity. A new introgression process is being used, this time replacing sugar plants with fibrous plants (see **Tables 1** and **2**). Reducing the sugar and increasing the fiber content would make plants more rustic, bringing about economic and environmental benefits as well as increased resistance to pests and diseases [9].

In the 1970s, in Puerto Rico, Alexander [31] already drew attention to "changing the focus on the 'qualitative side' features of sugarcane, as sugar yield, to the 'quantitative side,' such as green yield." He was one of the first breeders to use the energy cane concept in 1985. By that time, Alexander affirmed that if the energy cane were harvested with leaves and the top, it would increase the total biomass by 100%, with a penalty of 25–35% of sucrose [30, 31]. Energy cane can also be cultivated on marginal soil, optimizing the use of land [30] because it has a deeper root system, exploring better the soil's nutrients and water. For this reason, it has a big potential to be cultivated in 32 million hectares of degraded pastures in Brazil, more than the agricultural area of Europe [32].

Energy cane also differs from sugarcane in terms of the stalk morphology and the population. **Figure 1** summarizes the differences between energy cane and sugarcane on the stalk morphology and population. Energy cane stalk height is from 4 to 6 m, whereas sugarcane stalk is smaller, from 2 to 2.5 m [33, 34]. However, the sugarcane stalk is thicker than the energy cane. The diameter of the sugarcane stalk is, on average, 3.5 cm, whereas the energy cane ranges from 1.5 to 2 cm [32]. In terms of population, the cultivation of energy cane can have from two to three times more plants per area when compared to the traditional cultivation systems of sugarcane [32].

According to [35] to obtain energy cane cultivars, breeding programs should:

i. maintain a germplasm collection with high genetic diversity in sugar and fiber content.

ii. perform genetic crosses between modern hybrids of sugarcane (high sugar) and accesses of the genus Saccharum (high fiber).

iii. produce large amounts of seedlings and select superior individuals.

To better understand sugarcane as an energy crop and to facilitate well-focused and effective genetic improvement programs, [36] classified the energy cane into three distinctive types. The first is sugarcane, composed primarily of sugars, with

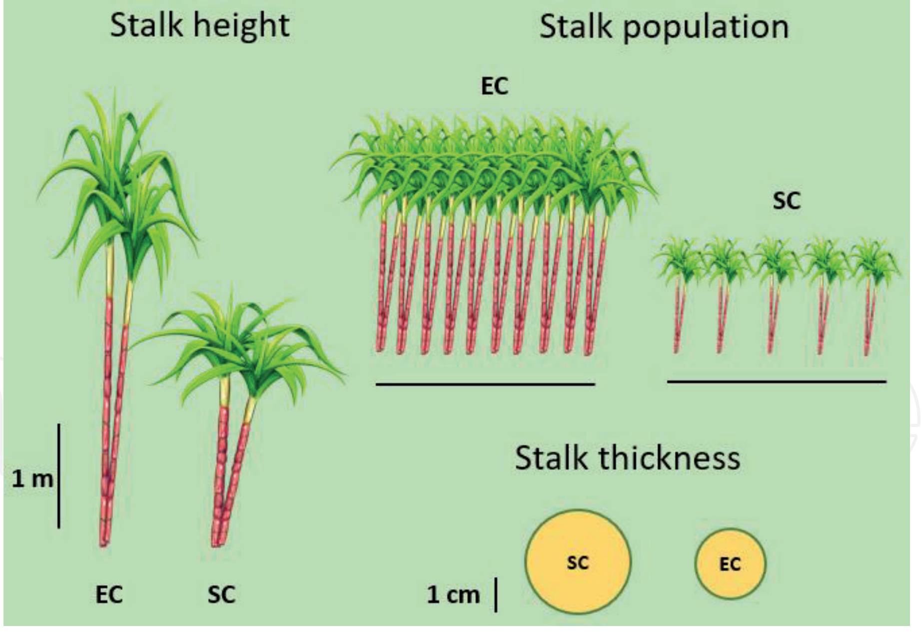

Figure 1.
Comparison between the characteristics of the stalks of sugar cane and energy cane: height, thickness, and population. EC: energy cane and SC: sugarcane. Sources: adapted from [32–34].

a juice with a high concentration of sucrose, high purity, which can be used in both sugar and ethanol production. Type I energy cane is like conventional sugarcane but has higher fiber content and less sucrose. Its juice's purity is lower and is not recommended for sugar production. Type II energy cane has only a marginally content of sugar and higher fiber than that of Type I, and it should be used exclusively for biomass production.

One of the pioneer programs for introgression in energy cane started in the 1980s in Barbados. One hybrid, WI79460, achieved yields of 112 tons of biomass and 46 tons of dry mass per hectare, a gain of 73% when compared to a commercial cultivar used in sugar production, B77602 (26.7 tons of dry mass per hectare). WI79460 also had a relatively high sucrose production per hectare of 10.4 tons, 77.03% of the sucrose produced by the B77602 [4, 9].

In Brazil, CanaVialis has started an introgression program for fiber content, and preliminary studies already show enormous potential. A commercial hybrid was crossed with *S. spontaneum* and the best F_1 clone was reproduced and compared with one of the most used commercial hybrids in Brazil, RB72454. The number of stalks per linear meter was 40, which is a high value when compared with the commercial hybrid that has 14 stalks per linear meter. The total fiber per hectare was also higher. The selected clone produced 40.25 tons of fiber per hectare, which was 136% higher than that of the commercial hybrid (17 tons per hectare). However, the sugar production per hectare and the purity of the extracted juice was lower in the energy cane [3]. **Figure 2** compares the production and potential production of energy cane and sugarcane in tons of stalks, fiber, and sugars per hectare.

Since 2001, USDA scientists at the Sugarcane Research Laboratory in Houma, Lousiana, are assessing the energy potential of high-fiber sugarcanes. In 2007, in the Louisiana sugar belt, three sugarcane varieties with fiber content higher than 16% were released for use as feedstocks for the production of bioenergy. These varieties, however, are disqualified for use in commercial sugar production operations [37].

Based on the above, energy cane is a result of recent breeding programs and may be an alternative to be integrated with the traditional ethanol and sugar production processes.

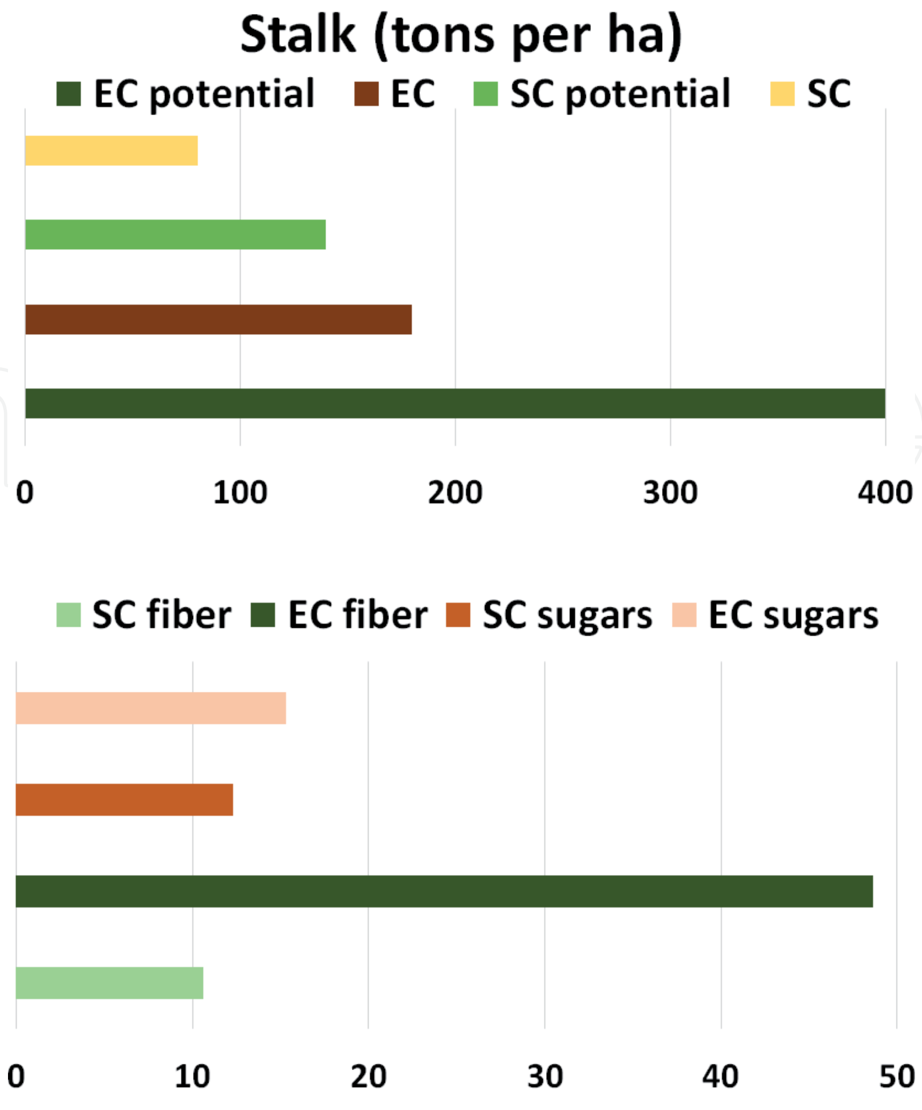

Figure 2.
Energy cane and sugarcane biomass, fiber, and sugar production and potential production per hectare. EC: energy cane and SC: sugarcane. Sources: adapted from [4, 25, 30, 32].

3. Fiber as a source of energy

To be considered a sustainable biomass source, the plant should meet humanity's energy needs, without competing with food production. For that, fibrous plants should be prioritized, instead of starch and oilseed plants [38]. In 2014, in the review "The potential of energy cane as the main biomass crop for the cellulosic industry", [9] listed five characteristics of the use of fibrous plants as biomass, citing [38–43]:

i. C4 plants with high efficiency in assimilate the solar energy and convert it into biomass, with the less possible amount of water, nutrients, and other inputs.

ii. possibility of application of agricultural technology in large-scale production.

iii. perennial but growth and long-term canopy to allow harvest during most of the year.

iv. easily and efficiently processed into usable forms of energy.

v. sustainable economically and environmentally, that is, not compete with food production, being able to be cultivated in marginal lands, with social-benefit consequences and having a high rate of carbon (C) balance.

The fibrous stem with low sugar content makes the energy cane more valuable to produce 2G ethanol and bioelectricity. However, the sugarcane price in Brazil is determined based on the sugar content and purity, and the sugarcane's end use, either sugar or ethanol [44, 45]. Thus, this payment method still encourages the production of the traditional sugarcane, to produce sugar and ethanol, being an obstacle to the cultivation of energy cane by sugarcane suppliers. Therefore, it is still necessary to have policies and to develop a payment method that considers the fiber content and the production of bioelectricity and 2G ethanol.

3.1 Energy cane as biomass and 2G ethanol

In the last decades, due to the increasing prices of electricity sold to the grid, specific incentive policies, and public-private initiatives, the Brazilian sugarcane industry increased its focus on cogeneration [35]. From 2013, the amount of commercialized surplus electricity from the plant is higher than the self-consumed, achieving a ratio of 60% and 40% in 2015 [46].

Cellulosic ethanol is a biofuel produced from extracted cellulose from the fibers of a vegetable. In the case of sugarcane, the primary input used in Brazil to produce 2G ethanol is obtained by processing the bagasse after extracting the juice or even the straw. As about half of the energy from sugarcane is present in its lignocellulosic fibers (bagasse and straw), it would be possible to produce more ethanol and electricity with the same amount of material and planted area [47, 48]. The energy cane can provide more fiber for the industrial process, supplying the cogeneration and bioelectricity production, and increasing the amount of bagasse that can be used for the 2G ethanol production. In Brazil, three companies already started to use the second-generation ethanol technology, with a total capacity of 124 million liters of second-generation ethanol per year:

i. Raízen, in a plant located in Piracicaba-SP, since 2014 producing ethanol from bagasse and straw, being able to increase by 50% the ethanol production without expanding the area of cultivation, producing biofuel even during the off-season for sugarcane, from December until March, and reducing carbon emissions during production, creating a cleaner fuel. The plant can produce 42 million liters of ethanol [49];

ii. GramBio, also started the commercial plant in 2014. The plant, Bioflex 1, is in Sao Miguel dos Campos, in the state of Alagoas, in the Northeast region, and its initial production capacity is 82 million liters of ethanol per year from energy cane bagasse and straw [50].

iii. CTC (Sugarcane Technology Center) has a pilot plant in Sao Manoel-SP, producing about 3 million liters of 2G ethanol per year from sugarcane straw and bagasse [51].

The 2G ethanol substrate is more diluted than the 1G ethanol, generating higher volumes of vinasse per liter of ethanol produced with a chemical composition different than the traditional 1G vinasse [52–54]. However, due to the high acetic acid concentration and to the low content of furans, which can inhibit the anaerobic digestion process, biogas production from 2G ethanol vinasse can have satisfactory performance, when compared to 1G ethanol vinasse [54]. The filter cake is rich in nutrients and can also be used integrated with the vinasse to increase the biogas production efficiency [55]. If ensiled, the energy cane can be stored for up to six months and be used to feed the biogas process in the period when the ethanol plant is not in operation [56]. Also, according to [56], in terms of energy generation per cultivated area, the production of biogas from sugarcane bagasse is more advantageous than the production of 2G ethanol Thus, it is also possible to consider a biogas production plant integrated with a 2G ethanol plant to increase the bioenergy generation.

The second-generation ethanol has great potential to increase the biofuel production in Brazil without increasing the sugarcane cultivation area [57]. However, this technology is not considered viable yet, needing to overcome some challenges, including the pretreatment and hydrolysis conditions to release the fermentable sugars [58]. Although these challenges need to be faced, the second-generation ethanol from sugarcane and energy cane can become a reality in Brazil for three reasons:

i. the Federal Government has incentive programs, and the commercialization of carbon credits is going to be one more economical and environmental advantage for this product [59–61];

ii. this technology is still in a learning curve period, and it is expected that 2G technologies are going to become more competitive in the future [62, 63];

iii. the cultivation of energy cane will boost the availability of fiber in the industry [64].

However, to process the energy cane in the ethanol plant is still challenging. Different conditions for milling and pretreatments may be required [9, 37]. Although the primary energy and sugar production per hectare is higher for energy cane when compared to the traditional sugarcane, the sugar concentration in the juice is lower and fiber content is higher. All the extraction process in the plant are adapted for sugarcane, thus, these differences raise concerns about processing energy cane, as mentioned by [65]:

i. sugar extraction: still need to be studied which process is better for it: mill or diffuser; the amount of water required for imbibition; the energy requirement for the extraction; and the extraction efficiency, which is expected to be reduced as the % of fiber increases;

ii. steam consumption; more imbibition water and increase in % fiber will require more steam for the processing of energy cane. However, it is also expected that a greater amount of fiber will be supplied to the cogeneration, having a positive balance in the steam generation:consumption;

iii. processing: needs to be reevaluated to maximize the products revenue

3.2 RenovaBio and energy cane

It is expected that the second-generation ethanol production in Brazil will increase and achieve about 2 billion liters in 2030, almost 20 times more than the current production [59] due to a new Federal Government program, the RenovaBio. In the RenovaBio, biofuel producers will receive one financial title

	Sugarcane[a]	Energy cane[a]	Sweet sorghum[b]	Eucalyptus[c]
Crop cycles (months)	10 to 12	10 to 15	3.5	96
Number of cycles year^{-1}	1	1	2	0.125
Yield (t ha^{-1} year^{-1})	70	200	60	24
Brix (% juice)	13 to 15	10 to 12	11 to 13	—
Fiber (% cane)	13.5	26.7	13	—
Biomass (t ha^{-1} year^{-1})	17.5	50	15.6	24
Calorific power (Mcal t^{-1})	2,275	2,275	3,281	4,600
Mcal ha^{-1} year^{-1}	39,813	113,750	51,184	110,400

[a] [3, 25, 66, 69, 70].
[b] [66, 71].
[c] [72–74].

Table 3.
Comparison of the potential energy generation per hectare per year among biomass crops.

equivalent to carbon credits called CBIO, which corresponds to one ton of CO_2 that is no longer emitted due to the biofuel production. Fuels distributors will have an obligation to buy CBIOs and it will also be available to any interested investor [60, 61]. The energy cane juice contains 9.8% of fermentable sugars, less than half of the traditional sugarcane. With these incentives of the Brazilian government and advances on the 2G technologies, the energy cane can potentially triple the productivity of biomass per hectare and reduce the production costs, also increasing the production of biofuel in the same area. The theoretical ethanol yields of sugarcane is 3,609 kg per hectare, while the energy cane are 12,938 kg of ethanol per hectare [61, 66]. However, it is important to find ways to ensure that these incentives reach the sugarcane producers, and not just stop in the sugarcane industry.

Regarding the amount of energy per area per year, the energy cane has almost four times more energy content than the traditional sugarcane, more than double of the sweet sorghum content, and almost the same as eucalyptus. However, the energy cane also provides the juice with a considerable amount of fermentable sugars and the eucalyptus cycle can take more than eight years (**Table 3**). The energy cane also has higher yields than the elephant grass and erianthus [67, 68].

4. Final remarks

Sugarcane breeding programs began in the 19th century when a focus on increasing sugar yield surfaced and have continued until recently. However, in the last few decades, various policies around the world have started aiming to reduce dependence on petroleum and other fossil energy sources. Thus, many breeders around the world have turned their attention to increasing productivity and fiber content. In this scenario, Brazil appears as the ideal country to start its commercial cultivation, because, in addition to being tropical, the RenovaBio program will give financial incentives to increase the production of second-generation ethanol. The energy cane is a crop with higher fiber production potential in marginal soil. In addition to that, the literature presented in this chapter shows that the energy cane can be stored and used to keep a continuous biogas production from December until March when the ethanol plant is not operating, and vinasse is not being produced.

However, energy cane faces several challenges to be implemented commercially. In the RenovaBio context, it is still necessary to find ways that the incentives do not end in the industry. CBIOs should also achieve producers, as a form of incentive for more sustainable production, closing the producer-industry-consumer cycle, and stimulating a more sustainable biomass production in the field and, consequently, the adoption of energy cane. The industrial processes and sugarcane management in the field have already been established for decades, and the implementation of energy cane would imply several changes throughout the chain—this is still a reason for resistance from producers and mill managers. Also, the low purity of its juice does not allow it to be used for sugar production and the current sugarcane method valorizes high sugar content and purity, to produce sugar and ethanol. In this sense it is also necessary to develop a new payment method, considering the fiber content in order to stimulate producers to adopt the energy cane. In addition, cellulosic ethanol is still a very new technology and needs adjustments to reach industrial scales and become profitable.

Energy cane is still an experimental technology and its cultivation is starting to be adopted on larger scales; however, it demonstrates the potential to be expanded to commercial scales. To do this, further steps need to be taken in breeding programs and new technologies, and changes will be necessary for its implementation in the field as well as its processing in the industry.

Author details

Pietro Sica
University of Sao Paulo, Piracicaba, Sao Paulo, Brazil

*Address all correspondence to: pietros0394@gmail.com

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