Facts Series

Sugarcane in Africa

VIB | International Plant Biotechnology Outreach

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Abstract

Sugarcane is an important crop for food and energy production, thanks to its capacity to accumulate high levels of sugar in its stems and its typical high-biomass yield. While sugarcane was first dedicated to sugar production, advances in technology have ensured that nowadays, all parts of the sugarcane plant can be converted into energy. To date, producing bioethanol from the sugar in sugarcane (first-generation biofuels) has been one of the world's most commercially successful biofuel production systems.

The residue obtained after the pressing of sugarcane stalks to extract juice at sugar factories is called 'bagasse'. Bagasse is typically used to produce heat and electricity, but it is currently underutilized in Africa. Sugarcane bagasse has potential as a carbohydrate source for the production of second-generation biofuels. Ethanol produced in this way is seen as a viable option for decreasing any perceived competition between food production and bioenergy.

As a source of income and employment, sugarcane-based agriculture could play a role in in the economic development of Sub-Saharan Africa. Energy represents an urgent need for all Sub-Saharan African countries. In these regions, locally produced energy is an attractive option for addressing the energy gap. With its tropical and subtropical climate, Sub-Saharan Africa is well-suited in many ways to expand sugarcane production. To unlock sugarcane industry potential in Sub-Saharan Africa, a number of

enabling conditions need to be reached vis-à-vis, for instance, environmentally sustainable production, infrastructure, trade policy, research and development, and financial services.

A possibility to meet the growing demand for energy is to improve sugarcane yield and accelerate the selection of desirable traits, including herbicide tolerance, disease and pest resistance, and cold and drought tolerance. Sugarcane's tolerance to drought is an important trait, especially in Africa, where cultivation expands into water-limited regions. However, sugarcane's large and complex genome has long hampered efficient, conventional, selective breeding of the crop, as well as the development of crucial domains such as genetics to support breeding for crop improvement programs. To maximize the efficiency of conversion of sugarcane biomass into biofuels, it is imperative to generate improved sugarcane cultivars with not only high biomass yield and fiber content, but also better biomass degradability for conversion into biofuels.

South Africa is the only African country currently active in genetically modified technology-assisted sugarcane research. Substantial institutional and regional strategic reforms and international support can leverage science and technology in Sub-Saharan Africa and close the gap between the regional and international sugarcane biotechnology research communities.

Facts and figures

Sugarcane is a global agricultural crop of commercial significance, with the potential to support developmental and societal needs of the many countries that grow it, including Sub-Saharan Africa.

Sugarcane accounts for about 80% of the sugar produced worldwide; the remaining 20% is produced from sugar beet.

Sugarcane is considered one of the best converters of solar energy into biomass and sugar, with a conversion efficiency of 2.24-2.29%, compared to maize at 0.2%.

Compared to the three major cereal crops (maize, rice and wheat), which collectively occupy 41% of the world's cropland, sugarcane is the highest-yielding crop in tonnage worldwide (1.9 billion tons) while it occupies only 2% of the world's cropland.

Africa contributes only 5% to the current global sugarcane production, and 83% of this is in Sub-Saharan Africa. The Sub-Saharan African region, with its tropical and subtropical climate, is well-suited in many ways to expanding the production of sugarcane.

The crop is emerging as a versatile resource, diversifying into a wide range of value-added products that go beyond food/sugar, particularly bioethanol and bioelectricity but also bioplastics, biohydrocarbons and biochemicals. As such, it favors low carbon development.

Ethanol production does not necessarily require additional cane production, or does not impact sugar production, because ethanol can be produced from sugarcane bagasse, which is an underutilized by-product of sugar factories.

Cellulosic ethanol has the potential to nearly double the amount of fuel that can be produced without increasing the area planted with sugarcane and without competing with food security.

The development of high sugar and biomass-yielding sugarcane is key for improving the value and sustainability of the sugarcane industry in Sub-Saharan Africa.

The competitiveness of biofuels over other options can be helped by biotechnology to improve the biomass yield and the feedstock composition for biofuels.

Sugarcane has one of the most complex genomes among cultivated plants, with a high level of polyploidy, high heterozygosity and large amounts of repetitive DNA sequences. This complexity renders our understanding of sugarcane genetics, and our ability to improve the crop, laborious.

Despite sugarcane's economic importance and significant efforts made by several international research groups, a reference genome is still unavailable today.

The sugarcane plant at a glance

Sugarcane is an industrial crop essentially because of its ability to store high concentrations of sucrose, or sugar, in the stem, and also because it is a valuable resource for the production of bioethanol and bioelectricity.[1] It predominantly grows in tropical and subtropical regions due to its need for sufficient sunlight and rainfall. It is also highly adapted to a wide range of soils and agricultural conditions.

Source: *SASRI South African Sugarcane Research Institute, 2017 collection*

The sugarcane plant forms stools of stalks or culms that can be several meters (up to 4 meters) in length. The stalks are juicy, with high concentrations of sucrose (Figure 1.1). Sugarcane is a semi-perennial crop, meaning that it can persist for many growing seasons. Commercial sugarcane is vegetatively propagated using stalk pieces that are planted. There are two basic sugarcane production cycles (Figure 1.2).[2] The plant-cane cycle starts with planting and ends after the first harvest, generally 8-24 months after planting. The portion of the stalk that is left underground gives rise to the succeeding crop known as the stubble or ratoon-cane, which is usually harvested at 12-month intervals. Although several ratoon-canes are possible, cumulative stool damage from harvesting, weed control operations and the impact of pests and diseases eventually lead to declining yield. A complete cycle of a sugarcane field may last between 4 to 10 years.[3, 4]

The inflorescence of sugarcane is a ramified, cone-shaped panicle with a main stem, called the rachis, which is the continuation of the last stalk internode. The time and intensity of flowering is influenced by environmental and physiological conditions such as day length, temperature, moisture, altitude, stress, and nutrition. The ability of sugarcane to reproduce sexually was not recognized until the mid to late 1800s.[5] Genetic improvement of sugarcane could then start (see text box 'Sugarcane breeding history'). However, sugarcane pollen has low viability. Thus, little seed set usually occurs, making genetic improvement of sugarcane laborious (see Chapter 7). Flowering is actually not desirable in commercial cane, as it uses both energy and sugar and can thus be detrimental to cane productivity.[4, 6]

Figure 1.1: *(A) A Kenyan worker harvesting sugarcane by hand; (B) sugarcane stalks.*

Between sugarcane cycles, a rotational crop such as leguminous crops (e.g. peanuts and soybeans) can be grown to improve and/or restore soil condition. Leguminous crops can accumulate over 5 tons/hectare of dry mass during a short period of time and fix large amounts of atmosphere nitrogen into the soil. In this way, they increase the soil nitrogen content naturally. Therefore, crop rotation with legumes can partially or totally replace the nitrogen mineral fertilization required to grow sugarcane.[7]

Because of its high photosynthetic efficiency (C_4 photosynthesis[a]), sugarcane is among the most efficient converters of solar energy into chemical energy, with a conversion efficiency of 2.24-2.29%.[3] In comparison, maize, which is also a C_4 crop, has a conversion efficiency of only 0.2%.[8] Sugarcane carbon fixation rates are as high as 28 mg CO_2/m/s.[3] A high efficiency of CO_2 fixation into biomass is of chief importance for energy crops, although biomass yield is determined by a number of other factors as well.

[a] *C_4 photosynthesis is a carbon concentration mechanism used by some plants to improve the efficiency of photosynthetic carbon fixation.*

In addition, the C_4 mechanism is intrinsically linked to 1.3 - 4 times higher nitrogen use efficiency and water use efficiency.[9] For that reason, C_4 photosynthesis has facilitated the adaptation of plants to arid conditions, high temperatures and marginal environments. This is also why sugarcane is considered to have high resilience to adverse climatic factors and environments.

Sugarcane originated in prehistory and is among the oldest cultivated plants. The evolutionary history and taxonomy of sugarcane are complex due to extensive prehistoric distribution of sweet canes by humankind and wide hybridization (crossing) among them.[10] Today, cultivated sugarcanes are hybrids derived from crossings between *Saccharum officinarum*, known as the 'noble cane' because it contains high sugar and low fiber content, and *Saccharum spontaneum*, known for its resistance to biotic (e.g. insects, bacteria, viruses) and abiotic (e.g. water, temperature) stresses (for details, see text box 'Sugarcane breeding history').[11]

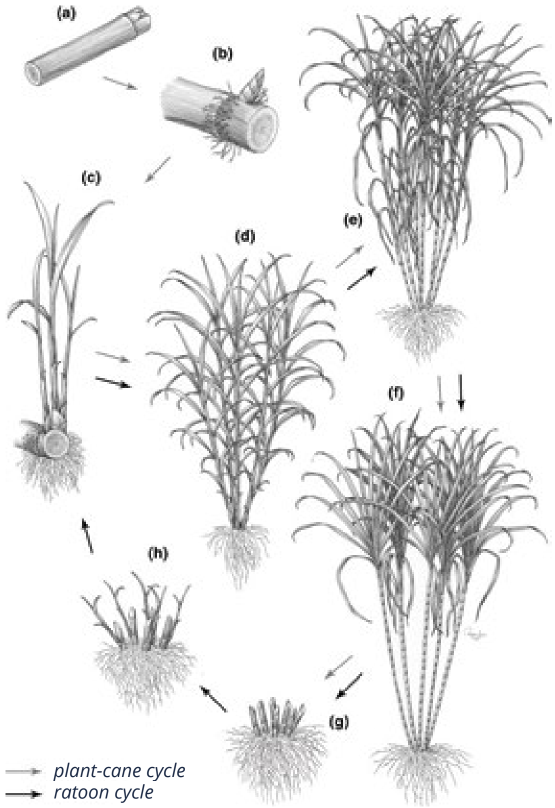


Figure 1.2: *Sugarcane has two production cycles. (a) Stalk pieces used in planting; (b) beginning of bud sprouting and rooting; (c) tillering initiation; (d) intense tillering; (e) beginning of maturation; (f) manufacturable stalks in optimal sucrose concentration; (g) harvesting; (h) ratoon sprouting (source: reprinted from [2]).*

SUGARCANE BREEDING HISTORY *(source: based on the data of [12])*

The 1888 discovery that sugarcane can produce fertile seeds, along with the onset of interspecific hybridization, are the two main events that allowed to start sugarcane genetic improvement. Sugarcane improvement has developed in four stages:

(1) Breeding among noble canes[b] to produce noble cultivar

In the early 1900s, progenies of Saccharum officinarum *varieties, considered as noble canes, were selected for sugar production. However, noble canes were found to be susceptible to disease and insects.*

(2) Breeding through nobilization to produce hybrid cultivars

During the period of 1920-1930, breeders broadened the genetic base of noble canes to improve their adaptability as well as disease and insect resistance. Crosses with Saccharum spontaneum, *known for resistance to biotic and abiotic stresses, were realized. The resulting hybrids were then backcrossed to* Saccharum officinarum *to recover the high-sugar-producing phenotype, a process known as 'nobilization'.*

(3) Breeding of nobilized canes

From 1930 until today, crosses among nobilized lines have produced hybrid cultivars and have permitted the introgression of specific traits into the hybrid cultivars. Breeders have found that interspecific hybridization not only produced disease-resistant offspring, but also brought about unexpected improvement in vigor, cane and sugar yields, ratooning ability, and adaptability to stress conditions. All present-day cultivars are essentially derivatives of no more than 15-20 nobilized cultivars that in turn trace back to the initial nobilized genetic base developed in Java and India.

(4) Breeding with a broadened genetic base

Following more than 100 years of selection, the genetic diversity of today's commercial varieties is narrow. Efforts to invert the narrow base include the so-called Base-Broadening program (BB-program) that started in Barbados in 1965 using clones different from those initially used in Java and India. The program has produced many semi-commercial type clones that have been incorporated into the gene pool. BB-programs in other countries have not been so successful. Although there is large favorable genetic variation among clones of Saccharum *species, a breeding tool to follow the incorporated germplasm is missing.[13] Recent developments in biotechnology could help the breeders incorporate useful genes from any source into the gene pool of advanced cultivars.*

Sugarcane has a large (10 Gb) and one of the most complex genomes known among cultivated plants, with a high level of polyploidy[c], high heterozygosity[d] and large amounts of repetitive DNA sequences.[14] This complexity renders our understanding of sugarcane genetics, and our

[b] *Noble cane contains high sugar and low fiber content.*

[c] *Multiple (more than two) sets of homologous chromosomes.*

[d] *Presence of different alleles at one or more loci on homologous chromosomes.*

ability to improve the crop, laborious (see Chapter 7). Most sugarcane production regions have their own breeding programs to develop and they improve local varieties adapted to regionally specific environments and agricultural practices.

Sugarcane is susceptible to many pests and diseases. Table 1.1 provides examples of common pests and diseases of sugarcane in Africa. Insect damage accounts for approximately 10% of sugarcane crop loss worldwide.[15] In addition to direct damage, insects can damage the crop indirectly by acting as vectors for the transmission of other pathogens. Stem borers are the most important insect pests of sugarcane. Vertebrates such as rats can also infest sugarcane fields.[15] Sugarcane presents more than 200 types of diseases that contribute to significant yield losses worldwide.[16] Among these diseases, viruses can be particularly damaging. Sugarcane is also susceptible to some bacterial and fungal diseases. For instance, sugarcane ratoon stunting was reported to cause 5% to 15% crop losses without growers even realizing their fields are infected.[17] Moreover, losses of up to 62% were reported to be caused by sugarcane smut (Figures 1.3 and 1.4).[18]

Figure 1.3: *(A) Sugarcane smut disease caused by the fungus* Sporisorium scitamineum*; (B) damages caused by the African sugarcane stalkborer inside a stalk.*
(source: SASRI South African Sugarcane Research Institute, 2017 collection).

Table 1.1: *Examples of common pests and diseases of sugarcane in Africa.*

PESTS OF SUGARCANE	
African armyworm *(Spodoptera exempta)*	The African armyworm can cause serious crop losses. Larvae can eat entire leaves and destroy the plant to ground level. African armyworm is widespread in Sub-Saharan Africa, being most prevalent in the eastern central regions of the continent.
African sugarcane stalkborer *(Eldana saccharina)*	The African stalkborer is the most serious sugarcane pest in tropical and sub-tropical Africa. Situations of high pest pressure can cause total crop failure. Larvae feed extensively as scavengers inside the cane stalks, causing severe loss in cane quality.
Spotted cane borer *(Chilo sacchariphagus)*	The spotted cane borer is a serious sugarcane pest, particularly in Mozambique and South Africa. Larvae mainly bore into the softer elongating internodes at the tops of canes, causing reduced growth, constriction of the stem, shortening of internodes at the point of attack, and death of the top, which may kill the whole cane.
African pink stem borer *(Sesamia calamistis)*	The African pink stem borer is found in Sub-Saharan Africa, commonly in wet localities from sea level to 2400 m altitude. The damage caused is similar to that of the African sugarcane stalkborer, but younger tissue is attacked.
Pink sugarcane mealybug *(Saccharicoccus sacchari)*	The mealybug occurs in warm regions wherever sugarcane is grown. Pink sugarcane mealybugs are usually found in large colonies on the stem beneath the sheath. Most damage is caused by honeydew excreted by the mealybugs and the gum exuded from the wounded parts, which interferes with the synthesis of raw sugar juice. Severe attacks decrease the general vitality of the plants, which become more susceptible to diseases.
Termites *(White ants)*	Termites are small, soft-bodied, creamy-colored insects resembling ants, which inhabit nests. They attack cane at soil level, sometimes causing the stalks to collapse. Yield losses can be very high. In Sudan, losses of 18% have been recorded and in Central Africa, losses of 5-10% are common. In Nigeria, plant germination failure of up to 28% has been reported. The most common damage to sugar cane is the destruction of the planting material (setts).

Figure 1.4: *Sugarcane brown rust disease in a South African field caused by the fungus Puccinia melanocephala (source: SASRI South African Sugarcane Research Institute, 2017 collection)*

DISEASES OF SUGARCANE	
Bacterial diseases	
Sugarcane ratoon stunting	Ratoon stunting is considered to be the most important disease affecting sugarcane production worldwide. It is caused by a bacterial pathogen and has no easily recognized external symptoms, only stunting of growth that may not always be apparent in the field. Infection can be identified with certainty only by submitting tissue samples for laboratory diagnosis.
Sugarcane leaf scald	Leaf scald is a prevalent disease in South Africa and in the most productive sugarcane areas of the world. Caused by a bacterial pathogen, it is potentially a very serious disease that can lead to plant death. The disease is insidious because it may have a latent (asymptomatic) period that lasts for months and sometimes years. The most typical visual symptoms are leaf chlorosis, with narrow and sharply defined white lines on the leaves.
Viral diseases	
Mosaic disease virus	Mosaic is the most important viral disease of sugarcane in South Africa. It is transmitted by aphid species and causes systemic infection of the sugarcane plant. The whole plant, including roots, contains viruses. The symptoms (mosaic and/or necrosis) are observed on the leaves and sometimes the stems.
Fiji disease virus	The virus is transmissible by leafhoppers and causes 'Fiji disease' with stunting, elongated swellings or even galls along the veins on the lower surfaces of the leaves and leaf sheaths. Susceptible plants do not recover from the disease: they become grass-like on ratooning and eventually die.
Fungal diseases	
Sugarcane brown rust *(Puccinia melanocephala)*	Initial symptoms of sugarcane brown rust are elongate yellowish leaf spots, increasing in size and turning reddish-brown in color. Multiple spots on leaves give a reddish appearance to plants from a distance.
Sugarcane smut *(Sporisorium scitamineum)*	Smut is the most important fungal disease of sugarcane in Africa. Dark brown, whip-like structures usually develop from the tops of infected stems. Other symptoms include stunting and production of thin horizontal leaves. Smut is spread by infected cuttings and spores released from the whip-like shoot.
Sugarcane red rot *(Colletotrichum falcatum)*	The pathogen mainly infects the stalk tissue, which is the storehouse of sucrose. Infected stalk tissues turn reddish, the leaves wither, and the entire clump subsequently dries. Upon colonization inside the stalk, the pathogen produces large amounts of an enzyme – invertase – which breaks the sucrose molecule into its components, glucose and fructose. As a result, the sucrose content from the infected canes is significantly reduced. It is appropriately called the 'cancer' of sugarcane.[19]
Sugarcane pineapple set rot *(Ceratocystis paradoxa)*	Pineapple disease is essentially soil-borne, being transmitted by fungal spores present in the soil. The fungus enters the setts through the cut ends. The internal tissues turn red, and then brownish-black. It is called pineapple disease because of the characteristic odor of the rotting cuttings, which is like that of decaying pineapples. The interior of affected seed pieces becomes sooty black. Eventually, the vascular bundles (tissues conducting fluids in the plant) become fibrous strands in hollow blackened cores.

In addition to various agronomic traits and pest and disease tolerance, sugarcane breeding and selection has been traditionally geared toward maximizing sugar production and has resulted in the generation of varieties with reduced fiber content. This is because high fiber content was considered an undesirable characteristic, as it reduces the mill throughput and increases sugar losses in the bagasse. Sugarcane bagasse is the residue obtained after pressing sugarcane stalks to extract juice at sugar factories (Figure 1.5).

Recently, consideration is given to developing new cultivars on the basis of traits that might increase sugar content for first-generation bioethanol production and fiber content for second-generation bioethanol (see Chapters 2 and 5 for a detailed description of first- and second-generation bioethanol). As a result, energy cane breeding programs have emerged and are separated from sugar cane breeding programs, though both breeding programs employ interspecific hybrids from crosses between species primarily within the genus *Saccharum*. Sugar cane cultivars are selected primarily for high sugar content and energy cane for high biomass and fiber.

Figure 1.5: *(A) Sugarcane field for sugar factories; (B) sugarcane bagasse, an underutilized by-product of sugar factories in Africa.*

2 Sugarcane, one of the most important crops worldwide

Today, sugarcane is an important cash crop in the tropical and subtropical regions of the world and together with sugar beet (grown mostly in the temperate zones of the northern hemisphere), they form the basis of the sugar industry worldwide.

Source: *SASRI South African Sugarcane Research Institute, 2017 collection*

Sugarcane has been an integral part of African agriculture since the 15th century, when Spanish and Portuguese explorers introduced the crop (Figure 2.1). Sugarcane accounts for about 80% of the sugar produced worldwide. The remaining 20% is produced from sugar beet. Cane sugar provides the cheapest form of energy-giving food, requiring the smallest unit of cultivated land area per unit of energy production.[20] Cane sugar is prevalent in the modern diet and ranks at the third-highest quantity of human consumed plant calories (164 Kcal/capita/day) following rice and wheat (Table 2.1).

From its origin, the sugarcane plant has been widely dispersed as it followed human migrations. The craving for sweet food is so strong that control of the trade in sugar has historically been an important driver of the fortunes of men and empires, similar to salt and tobacco. The rise in sugar consumption and the rise of the slave trade are inextricably bound together. The increasing demand for sugar was a starting point in the development of large European trading fleets during the early Renaissance period and the propagation of African slaves around the world between the 17th and 19th centuries (Figure 2.1). Slavery fundamentally changed the way sugar was produced, decreasing its price and turning it into a bulk commodity that is used by everyone.[21] The industrial processing of food, together with the requirement for sugar as a preservative, has also been associated with the Industrial Revolution in Britain.[10]

In 2014, sugarcane was the 11th-most extensive crop in terms of cultivated area worldwide, covering 27 Mha, equivalent to 2% of the total global cropland area (Table 2.1). Cultivated in over 100 countries on all continents worldwide, the top global sugarcane producers are Brazil and India. In 2014, Brazil and India together were responsible for 57% of the world's sugar production. Africa contributed only 5% to global sugarcane production, of which 83% occurred in Sub-Saharan Africa (Figure 2.2). Whereas most Sub-Saharan African countries grew sugarcane in 2014 (Figure 2.3), six countries accounted for more than half of the total production: South Africa (23%), Kenya (8%), Sudan (7%), Swaziland (7%), Mauritius (5%), and Zambia (5%) (Figure 2.2).[24]

Compared to the three major cereal crops (maize, rice and wheat), which collectively occupy 41% of the world's cropland, sugarcane is the highest-yielding crop in tonnage worldwide while it occupies only 2% of the world's cropland (Table 2.1). The tonnage recorded is not necessarily an indication of sugarcane's exchange value because it takes wet weight into account, while the dry matter of cereals and tuber crops are much higher. However, this measurement reveals the large amount of biomass produced via sugarcane agriculture and suggests the potential gains from making and monetizing other use-values than sugar from the plant.[25]

Although Sub-Saharan Africa represents a small part of the world's total sugarcane production (Figure 2.2), it is considered a promising region for continued expansion due to its high production potential, low cost and proximity to European markets.[26] Five countries are consistently ranked among the lowest-cost sugar producers in the world, namely Zimbabwe, Malawi, Zambia, Swaziland and South Africa.[21] Costs of production in Sub-Saharan Africa are relatively low. This is mainly due to the ideal growing conditions for sugarcane in the region (topography, soils, availability of irrigation, wet/hot summers and cool/sunny/dry winters), which support high plant growth rates and sugar conversion.

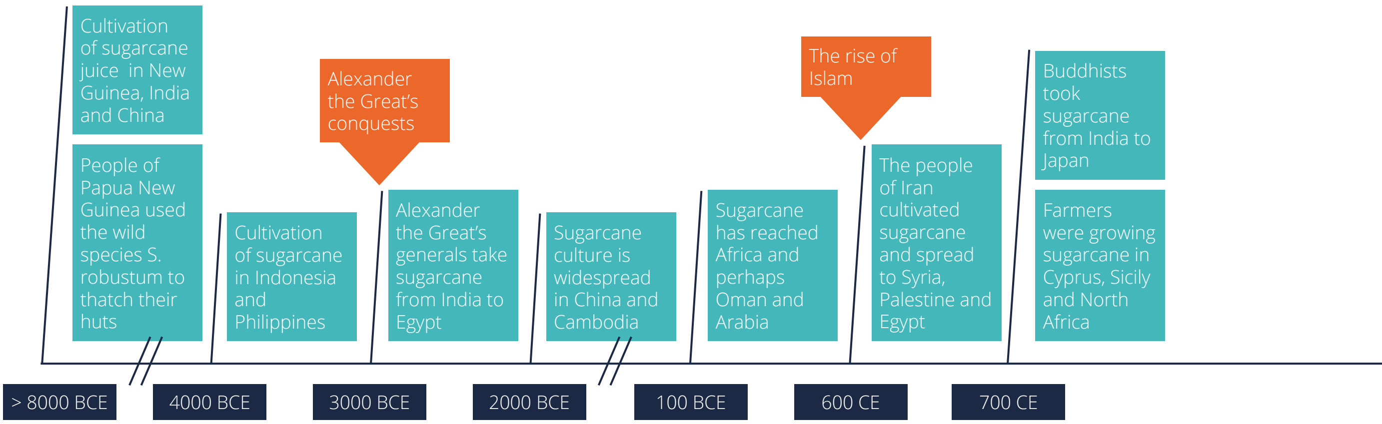


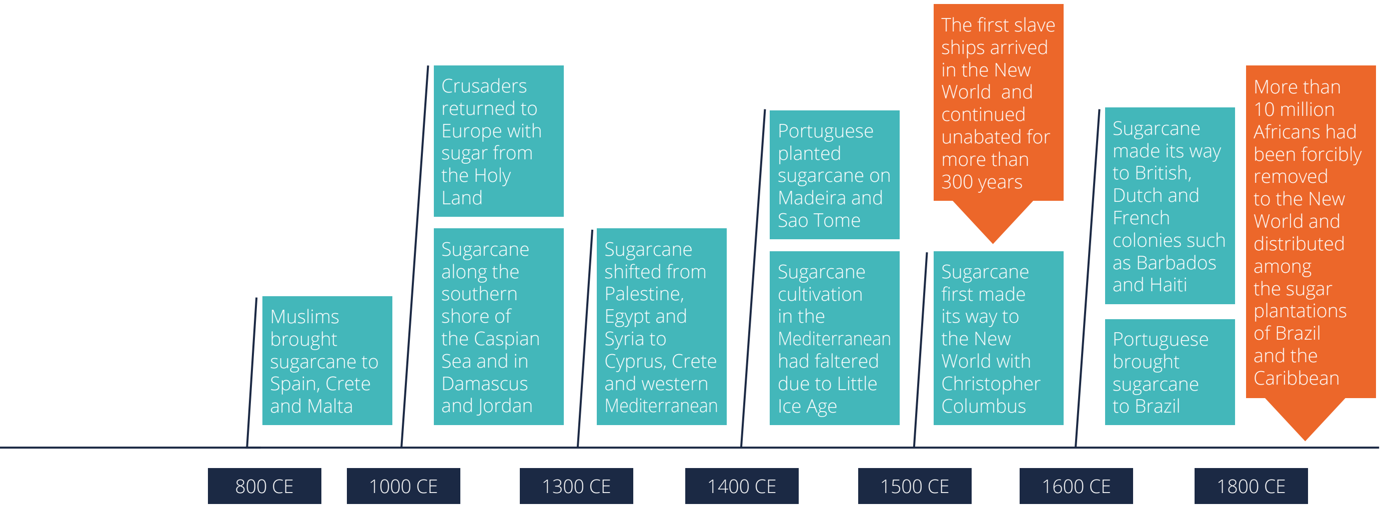
Figure 2.1: *Sugarcane expansion goes hand-in hand with military conquest, exploration and colonial expansion (source: based on the data of [22 and 23]).*

Most Sub-Saharan African countries have high sugarcane yield (Figure 2.3). Sugar production of southern African sugarcane, for instance, typically averages > 1 ton/hectare/month, whereas the global average is 0.5 tons/hectare/month.[21] It shows that the Sub-Saharan African region has high sugar production potential and that it can attract significant international interest and investment as a commodity crop.[26]

As one of the world's main crops, sugarcane production has major repercussions on agricultural land use, water resources, biodiversity, livelihood, food security and ecosystem services. At the same time, it can potentially provide major infrastructure and economic benefits (see Chapters 3 and 4).

Crop	Ranking by tonnage produced	Production (Mt)[a]	Area (Mha)[a]	Fraction total crop land (%)	Consumption (Kcal/capita/day)[b]
Sugarcane	1	1884	27	2	164
Maize	2	1038	185	13	147
Rice	3	741	163	12	541
Wheat	4	729	220	16	527
Potatoes	5	381	19	1	64
Soybeans	6	306	117	8	14
Oil, palm fruit	7	274	19	1	52
Sugar beet	8	270	4	0.3	40
Cassava	9	268	24	1.7	37
Barley	10	144	49	4	7

Table 2.1: *Crop production and area ([a]: in 2014) and daily caloric consumption ([b]: in 2013) of some of the world's cultivated food crops (source: [24]; Mt, million tons; Mha, million hectares).*



Further development of the sugarcane sector will take place within a changing climate, greater rainfall uncertainty and increased drought risk. On one hand, this will put pressure on yields in rainfed production[27], and on the other hand, it will raise demand for irrigation, reducing available water supplies.[28]

Therefore, sugarcane's potential to help satisfy global energy demand (for details, see Chapter 3) could be limited in part by poor production practices generating severe impacts on freshwater availability and quality, which indirectly could convert land and emit greenhouse gases.[29]

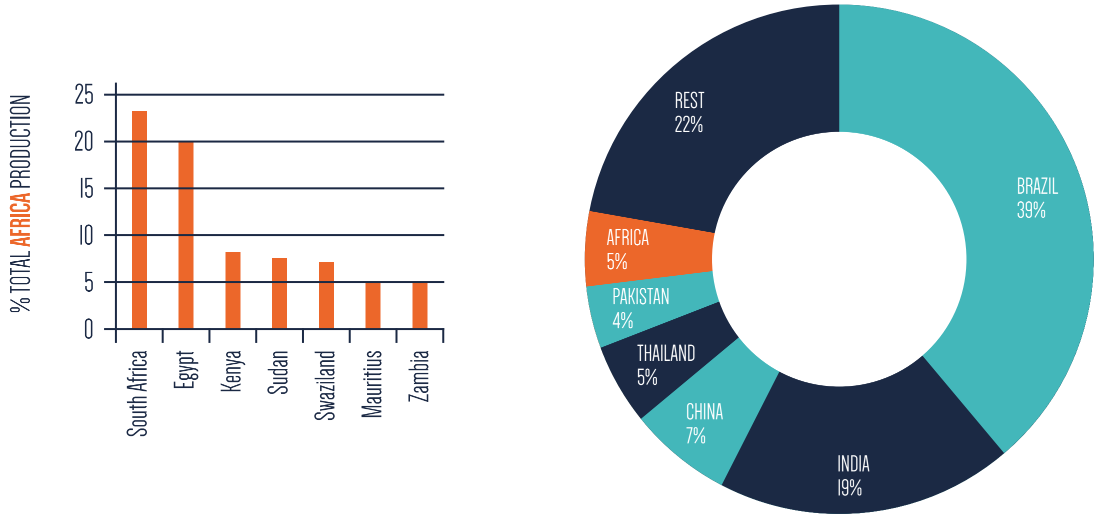


Figure 2.2: *Global sugarcane: percentage of world production and main African producing countries in 2014 (source: based on [24]).*

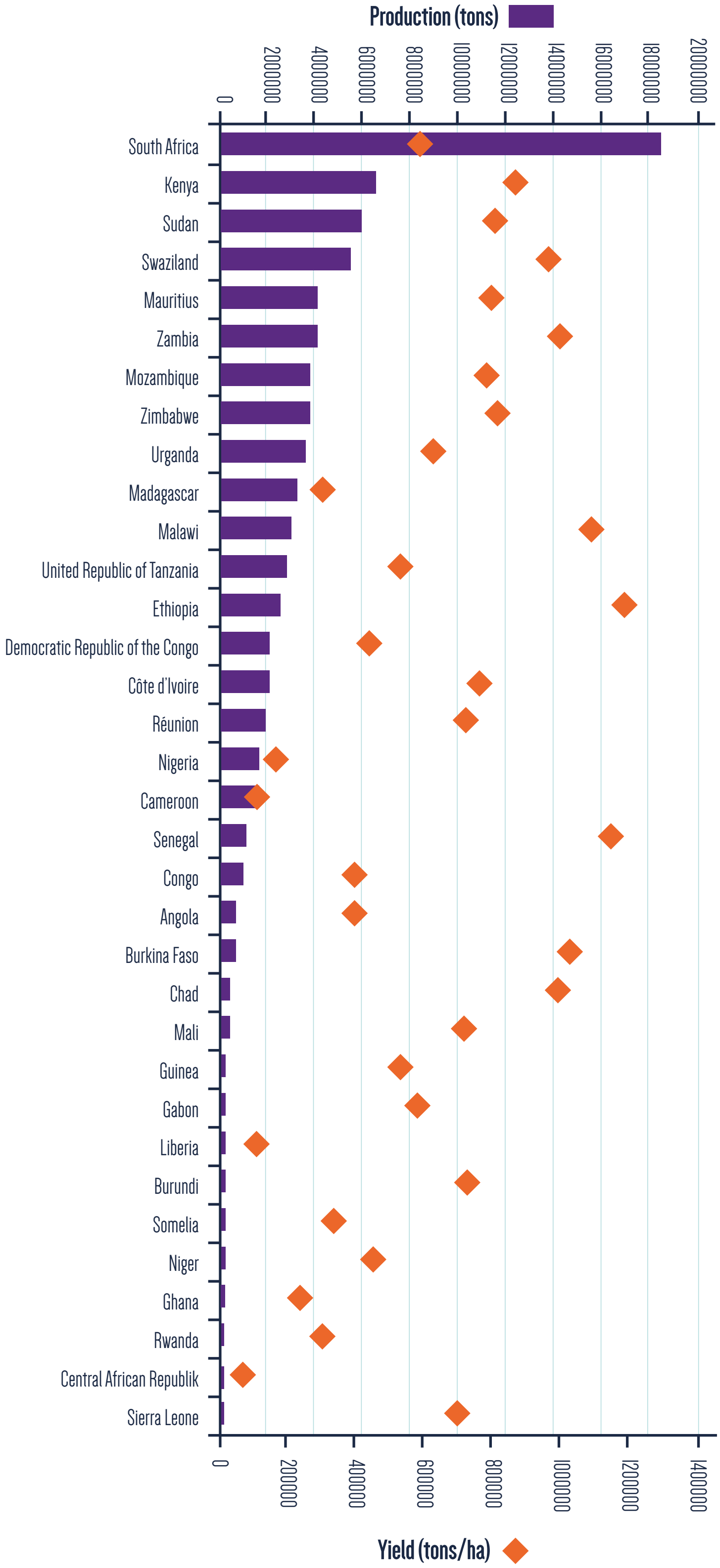


Figure 2.3: *Average sugarcane production and yield by Sub-Saharan country in 2014 (excluding Cabo Verde, Benin, Guinea-Bissau, and Djibouti, which grew less than 30,000 tons) (source: based on [24]).*

The wide range of value-added products from sugarcane

Historically, sugarcane has been used in multiple ways. Sugarcane juice, the sweet liquid contained in sugarcane stalks, can be processed into sugar. Sugar has been variously seen as condiment, preservative, decoration and medicine before finally taking hold as a major industrial food product. Beyond industrial sugar, sugarcane juice is also used to produce artisanal products such as muscovado sugar[e], sugarcane syrup, rapadura[f] and other similar sugarcane candies. The juice may also be fermented and then distilled to produce rum (Figure 2.4).

While sugarcane was first dedicated to sugar production, technological advances have ensured that nowadays, all parts of the sugarcane plant are converted into energy. Sugarcane is now diversifying into an extraordinarily wide range of value-added products that go beyond food, particularly bioethanol and bioelectricity but also bioplastics, biohydrocarbons and biochemicals. For instance, bioplastics have the same properties as regular plastics (the most common type is known as PET) but are more environmentally friendly and 100% recyclable. Expanding the production of clean, renewable sugarcane products may have the potential to enhance energy security, reduce global dependence on fossil fuels and create jobs.[30, 31] Moreover, the multiple uses of sugarcane allow companies to diversify their product portfolios, reduce risks associated with price oscillations and volatility, and exploit market opportunities.

[e] *Muscovado sugar is a type of partially refined to unrefined brown sugar with a strong molasses content and flavor.*
[f] *Rapadura sugar is an unrefined cane sugar that preserves the natural caramel taste of the sugar.*

In Brazil and the United States (the largest producers of ethanol from sugarcane), sugarcane ethanol is used in the transport sector as a renewable fuel that cuts greenhouse gas emissions by an average of 90% compared to gasoline.[30, 32, 33] From a global yield of around 1.9 billion tons of sugarcane per annum (Table 2.1), approximately 131 million tons of sugar and over 27 billion liters of ethanol are produced. The exact ratios depend on a range of additional factors, specifically the price of oil. Roughly 35% of sugar production is traded internationally.[29]

Biofuels made from sugarcane are classified into two different generations depending on their biomass feedstock and processing technology. Sugarcane ethanol is an alcohol-based fuel produced by the fermentation of sugarcane juice and molasses, referred to as first-generation bioethanol. The process taps only one-third of the energy sugarcane can provide. The other two-thirds are locked in the bagasse (the fibrous residue that remains once cane is crushed) and the straw, which is removed mechanically from the harvested cane before it is processed. New techniques are under development (based on biochemical or thermochemical processes) to produce what is known as cellulosic ethanol. This is referred to as second-generation bioethanol produced from leftover plant material, also known as lignocellulosic feedstock. Once these processes are commercially viable, second-generation bioethanol has the potential to nearly double the amount of fuel that can be produced without increasing the area planted with sugarcane and without competing with food security.[34, 35]

Figure 2.4: *(A) Hand-cranked press to remove sugarcane juice for distillation; (B) woman carrying and chewing sugarcane poles in Mozambique; (C) rum and sugar production in South Africa; (D) sugarcane juice sold at the Stone Town market in Tanzania.*

3 Opportunities and threats for sugarcane production in Sub-Saharan Africa

Sub-Saharan Africa is showing impressive economic growth and positive economic and social developments. However, economic growth in the region has still not been translated into much higher income per capita, nor has it reduced the poverty rate of over 40%.[36] The share of the population living on less than USD 1.25 per day has changed little over the last decade.[36]

For sustainable development to occur in Sub-Saharan Africa, access to secure, sustainable and affordable energy is a prerequisite. Indeed, energy sufficiency and security is key to development and prosperity because it provides essential inputs for socio-economic development at regional and national levels. Therefore, energy sufficiency and security provide vital services that improve the quality of life.[37] A study conducted by the International Energy Agency[38] showed that, in 2010, of the estimated population of one billion people in Africa, about 470 million rural inhabitants, representing 47%, had no access to electricity or clean water (Figure 3.1).

Industrialization and population growth have been highlighted as major drivers affecting energy demands in most developing countries. However, in African countries, energy demands will intensify mainly because of the growing population, which is projected to reach 1.6 billion in 2030.[39] This implies that, in 2030, 592 million people will still not have access to electricity in rural areas (corresponding to 37% of the total African population), whereas 704 million urban inhabitants will have access to electricity, as shown in Figure 3.1 (corresponding to 44% of the total African population).

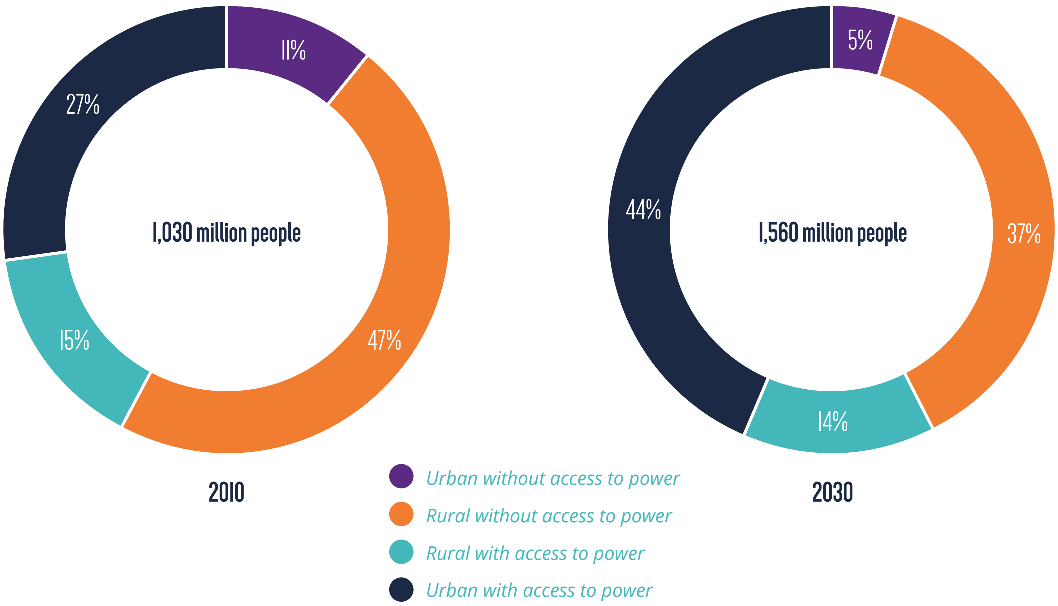


Figure 3.1: *Rural and urban electricity access for people living in Africa for the years 2010 and 2030 (source: adapted from [38]).*

In addition, around 70% of Sub-Saharan African nations are dependent on energy imports, predominantly liquid fuels, to fulfil their energy demands.[40] They import petroleum products at a cost that inflicts a heavy economic burden and reduces energy security and sovereignty. The difficulties are more significant in landlocked countries, where transportation and fuel costs are high, and supply lines are vulnerable to disruption in the case of natural disasters, geopolitical instability or civil unrest.[41] In these regions, locally produced energy is an attractive option for addressing the energy gap. World total transport energy use and CO_2 emissions are projected to be 80% higher by 2030 than current levels.[42] The volatile nature of the international oil market, depleting fossil fuels and global environmental concerns associated with the increasing use of fossil fuels have challenged most countries, including those of Sub-Saharan Africa, to seek alternative forms of energy. The production of biofuels, biopower and bioproducts using locally available biomass resources which do not compete with food security is therefore an important area that Sub-Saharan Africa could focus upon to meet future energy requirements, thus reducing its dependency on oil imports.

In Sub-Saharan Africa, agriculture is the key to broad-based economic growth, poverty reduction and food security. This is due to the importance of the sector for Sub-Saharan African economies, the extent of rural poverty and the dependence of 50 million smallholder farms on agricultural income. Agriculture generates an average of 25% of the Gross Domestic Product of many African economies.[36] Agriculture has huge potential in Sub-Saharan Africa. The region contains around 50% of the uncultivated cropland available globally, of which a substantial fraction is well-suited for the production of rainfed crops. It has untapped water resources and significant room for improvement in inputs to increase yields. Developing the agricultural value chain is a way to promote structural transformation and diversification of the economy in the region.

In this context, sugarcane production and processing are well-positioned to support a flourishing value chain for sugar and biomass derivatives as well as the development of bioenergy strategies in Sub-Saharan Africa. Ethanol production from sugarcane is currently the most attractive alternative to fossil fuel. It is obtained from renewable biomass: sugarcane and bagasse. Brazil and the United States are the largest producers of ethanol from sugarcane, with both countries accounting for about 86% of total bioethanol production in 2010.[24]

Food security first

Recent food security crises have reinforced the debate of biofuel production potential in African countries, since most of them depend on local agriculture for subsistence.[39] Bioenergy and food security are considered mutually incompatible and in direct competition for land and other inputs. There is the logical fear that growth in first-generation bioethanol will increase the price of food in Sub-Saharan Africa. As more land, water, fertilizers and other resources are channeled away from food production into biofuel production to meet growing energy demands and reduce reliance on fossil fuels, food insecurity will become more prevalent, especially in the most vulnerable regions.[35] For example, in Swaziland, poorer growers were unable to meet their food requirements after converting all their land to rainfed sugarcane.[43] In Kenya, the Mumias sugar scheme has raised concerns that a shift to sugarcane by small-scale producers could result in increased food insecurity.[21] Women in particular lose access to land for food crops and would also have less control over household income. However, there is no evidence that sugarcane production is associated with an increase in malnutrition.[26]

Land plays a crucial role in the livelihoods of Africans. Therefore, food security and poverty alleviation will be achieved when the land is first prioritized to meet people's needs, and then used for biofuel industries. Nevertheless, ethanol production does not necessarily require additional cane production, or does not impact on sugar production, because ethanol could be produced from sugarcane bagasse, an underutilized by-product of sugar factories (see Chapters 2 and 5).[44]

Reducing the dependence on imported petroleum by maximizing domestic biomass resources for biofuel production should be achieved sustainably with minimal environmental and socio-economic impact.

4 Sustainability assessment of sugarcane production in Sub-Saharan Africa

Sugarcane production has characteristics that are associated with significant economic, environmental and social outcomes, such as the crop's water requirements, especially in Sub-Saharan Africa. Large-scale direct and indirect land use change, which can impact water, energy and nutrient cycles, have been associated with commercial sugarcane production.[26] Sugarcane cultivation is also criticized for impacting the environment through deforestation and pollution (e.g. air pollution caused by the burning prior to harvest of sugarcane fields). Another sensitive point is the claim that sugarcane production systems rely heavily on low-paying jobs and labor abuse worldwide (e.g. child labor and slavery regimens).[45]

Environmental impacts

In Sub-Saharan Africa, sugarcane is considered a particularly 'high-impact' crop. The production and processing of sugarcane can have negative as well as positive impacts on the air, water, soil, flora, fauna, human population and global climate. Thus, its production is generally not considered explicitly sustainable or unsustainable. These impacts vary from country to country, as they are dependent on considerations such as e.g. small versus large producers, use of irrigation, the level of mechanization and harvesting practices, and environmental regulations.[26] Long-standing experience in sugarcane cultivation and processing has led to agricultural management practices that, if adopted, can significantly reduce the negative and improve the positive environmental impacts. For instance, good agricultural management practices can reduce nutrient loss[46] and atmospheric pollutants such as N_2O emissions due to nitrogen fertilizer applications.[47] Carbon sequestration can be increased [48] and the impacts of burning can be significantly reduced when the crop is harvested 'green'.[49]

Land use change and water impact

Sub-Saharan Africa has abundant land for sugarcane crop expansion and could contribute to meeting projected global energy demands that would require an estimated 49% increase in land area under sugarcane cultivation by 2050.[29] It has been estimated in southern Africa alone, almost 6 million hectares of suitable land are available for sugarcane production.[50] This hectarage is significantly larger than the current 0.37 million hectares under sugarcane cultivation in the region and the 1.5 million hectares cultivated across the entire African continent in 2014.[24] Mozambique, with over 2.3 million hectares of suitable land, offers the best potential for expanding sugarcane production, followed by Zambia and Angola, each with over 1.1 million hectares.[51] An assessment of constraints to production and yield performance determined that Angola, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe have good potential for expanding sugarcane production.[51]

Sugarcane development in Sub-Saharan Africa can occur through the conversion of existing agricultural land previously used by small-scale producers, or through the development of large, previously uncultivated tracts of land and forests. Any of these two routes imply direct and/or indirect land use change. Both need careful consideration. The former may involve dispossession, displacement and disrupted livelihoods, which can reduce food production and threaten food security. The latter may disrupt long-established grazing patterns, threaten biodiversity and disrupt other land-related ecosystem services.[26]

One of the most crucial resources to the sugarcane industry is water, both for cane cultivation and for processing/refining.[52] Approximately 36% of the water consumed in mills is used to wash sugarcane stalks to remove soil particles and debris prior to the fermentation phase.[53] Sugar mill outflows have a high Biological Oxygen Demand[g] as well as high levels of suspended particles and ammonium. As sugar mills generate about 1,000 liters of wastewater per ton of sugar crushed, it can pose water quality issues (Figure 4.1).[54] This was the case for three sugar factories next to River Nyando in Kenya, which led to a decline in the quality of drinking water for many families along the river's course to Lake Victoria and caused nutrient-enrichment of Lake Victoria as well.[55]

In general terms, Sub-Saharan Africa cannot be considered water poor.[56] The region holds 9% of the world's freshwater resources and has a lower per capita rate of water withdrawal (Sub-Saharan Africa comprises only 11% of the global population). It also has less irrigated area than any other region in the world. Yet, the irrigated sugarcane was shown to have approximately three times the productivity (98 tons/hectare) of rainfed sugarcane (32 tons/hectare).[26] The region is characterized by a range of hydro-climatic zones with high rainfall variability [57] and land with rainfall suitable for rainfed production of sugarcane is abundant in Sub-Saharan Africa. The Food and Agriculture Organization of the United Nations (FAO) estimated – based on an Agro-Ecological Zones methodology (Figure 4.2A) – that the Democratic Republic of Congo, Cameroon, Republic of the Congo, Gabon, Equatorial Guinea

Figure 4.1: *Washing of sugarcane stalks in a bioethanol manufacturing plant.*

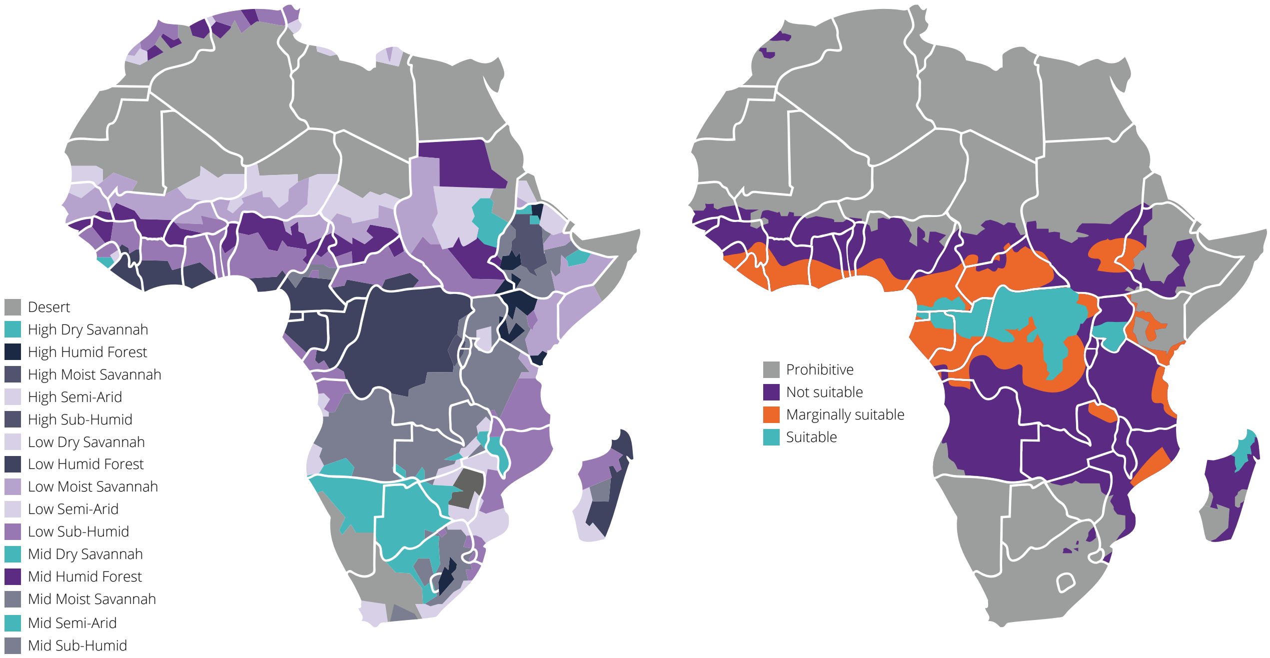


Figure 4.2: *(A) Agro-ecological zones in Africa (source: adapted from [58] and reproduced with permission, © World Bank, License: https://openknowledge.worldbank.org/terms-of-use). (B) Suitability for rainfed sugarcane production in Africa (source: adapted from [59] and reproduced with permission).*

and Uganda offer the best prospects for planting sugarcane (Figure 4.2B).[51]

However, it is important to raise attention that part of the land identified as suitable in the above-mentioned countries is under closed evergreen lowland forest, which are forests characterized by multiple layers of vegetation and generally having very high species diversity. This type of land should be considered unavailable for sugarcane production in order to preserve both biodiversity and water resources.[51] Therefore, the booming demand for sugarcane-derived products has to be managed with proper land use planning, while at the same time protecting precious natural resources. Brazil recognizes this challenge and has taken the lead in establishing Agro-Ecological Zones across its territory to allow for the sustainable expansion of food and bioenergy production. Figure 4.2B shows areas marginally suitable for sugarcane: e.g. southern Nigeria, southern Togo and Benin, southwestern Chad, Sudan, Ethiopia and Kenya and northeastern Zambia. All the other countries are shown as not suitable or even prohibitive, although sugarcane is actually grown under irrigation, for instance, in Swaziland, Zimbabwe, Malawi, Senegal, Morocco and Egypt.

The Agro-Ecological Zones methodology developed by FAO can be fine-tuned to identify smaller areas with adequate rainfall for sugarcane growth. For example, South Africa produces rainfed sugarcane and is shown as prohibitive on Figure 4.2B. More precise mapping of land suitability and availability would greatly benefit

[g] Biological Oxygen Demand is the amount of dissolved oxygen, expressed in milligrams of oxygen per liter of water, consumed by micro-organisms to decompose the organic matter present in water.

Figure 4.3: *Sugarcane plantation with leaf trash covering the field.*

African sugarcane production. Such assessments should include analysis of long-term climatic data so that the major influences of radiation, temperature and water availability on plant growth can be incorporated into the suitability score for each unit of land considered.[51]

Considering future rainfall uncertainty and potential for yield uplift, it seems inevitable that future agricultural developments will increasingly depend on irrigation to ensure crop water demands through the growing season.[26] South Africa as well as Tanzania and Zambia are determined to commit adequate water resources to supplying agricultural development projects in recognition of their economic contribution.[60] On the other hand, some studies, such as one conducted in the Mozambique's Limpopo River Basin, have recommended limiting sugarcane developments.[61]

As with any other large-scale commercial crops, sugarcane production involves the application of fertilizers and pesticides. Herbicides are the most widely used agro-chemicals in sugarcane production.[62] An increase in nutrient loads and salinity as well as dissolved and suspended particles are the most common threats to water quality, which can have an impact from the field to catchment levels through rivers and lakes, shallow and deep groundwater, and even reaching coastal areas. Agrochemical monitoring at catchment scale is still limited in Africa.[26]

Insufficient environmental and regulatory controls could pose a threat to water quality in Sub-Saharan Africa. However, new environmental regulations, including the implementation of ISO standards and participation in BONSUCRO[h], a multi-stakeholder certification accreditation, are helping to mitigate these impacts, particularly for new cane developments.[29]

Soil impact and land management

Long-term production of sugarcane may have a negative impact on soil properties and crop productivity.[63] However, it may also have a positive

[h] *www.bonsucro.com*

Figure 4.4: *Sugarcane truck full loaded in the field.*

effect in the case of green cane harvesting, which leaves a layer that can increase the amount of organic matter and available nitrogen and phosphorus in the soil, enhance soil biodiversity, reduce risks of erosion, protect soil moisture and suppress weeds (Figure 4.3).[64] On the other hand, the use of leaf trash covering the sugarcane fields can favor some pests. Long-term sugarcane cultivation can then lead to increased soil acidification, nutrient depletion and reduced soil microbial activity and biomass, compared to other agricultural land uses or natural vegetation.[55] The over-application of fertilizers can also have a negative impact on soils.[65]

Large commercial plantations generally use intensive farming methods, which are often semi-mechanized. Driving or operating heavy machinery in-field can lead to compaction and reduced soil porosity, decreased soil aeration and increased soil resistance with consequences to the physical, chemical and biological properties of the soil, and ultimately to root growth and yield (Figure 4.4).[66]

Smallholder systems tend to be less mechanized but their practices can also be detrimental to soil conditions. For instance, soil erosion has been associated with sugarcane growing on slopes.[26]

The quantification of the effects of soil impact on cane yield and economics is not easy to determine. The South African Sugar Association has developed comprehensive standards and guidelines on soil conservation with indication of best practices at the local level.[55]

Air quality impact and greenhouse gas emissions

The burning prior to harvest of sugarcane fields (to facilitate manual harvesting) and the emissions from either sugar or ethanol processing are the main activities in the sugarcane industry that cause air pollution. Besides contributing to greenhouse gas emissions, both burning and processing have effects on public health and ecosystems (Figure 4.5). A practice that has spread from Cuba, Brazil and Australia consists of harvesting the green cane. Burning is in this way avoided. The South African Sugar Association standards and local environment committees regulate burning of cane prior to harvesting, restricting it to certain hours per week.[55]

Greenhouse gas emissions from soils under cultivation are highly dependent on soil conditions (moisture, nitrate content, etc.) and field management practices. These emissions are essentially nitrogen compounds associated with fertilizer decomposition. Greenhouse gas emissions associated with sugar production can reach 2.4 tons of CO_2 equivalent/hectare.[67] Burning prior to harvest is a far more important source of greenhouse gas emissions (44%), followed by the utilization of synthetic fertilizers (20%) and fossil fuel combustion (18%).[67] Thus, improving green harvest can increase soil organic carbon and reduce CO_2 emissions from sugarcane production.

When calculating the effect of conversion to sugar on greenhouse gas emissions, the net emissions of the previous land use is taken into account. The replacement of other agricultural land uses with sugarcane can result in a net decrease in emissions, while where natural forests have been converted to sugarcane, net emissions may increase.[26]

Biodiversity impact

Sugarcane is grown as a monoculture and, as such, can have a negative impact on biodiversity, particularly if the plantation is located in an area with a high biodiversity, such as unmanaged wetlands.[68] On the other hand, biodiversity is likely to remain unchanged or even increase if sugarcane replaces grasslands or annual agricultural crops. To preserve the crucial edge habitat of a diversity of species, it is important to leave a buffer zone between the plantation and established woodland or hedgerows. Sugarcane plantations can also provide corridors between isolated habitats.[55]

As with any large-scale use of land, careful planning and management are needed to

Figure 4.5: *(A) Burning prior to harvest of a sugarcane field in Senegal; (B) manual sugarcane harvesting on a plantation in Malawi.*

mitigate negative impacts on biodiversity. It is important to observe relevant national laws and regulations on conservation and nature protection and thus to avoid growing sugarcane on protected or vulnerable areas. In some cases, growing sugarcane in more marginal or degraded areas (e.g. steep slopes or wetlands with high biodiversity) where other crops fail or are too difficult to farm, may avoid food conflicts.

Social impacts

Because of the large volume of material required and the short viability of the freshly-cut harvested cane (3–4 weeks), sugarcane transport is often not practical and expensive. Therefore, to limit costs, cane is generally grown close to the factory site and can dominate the land use in the locality of the mill, with potentially high labor demands for both cane production and processing. This concentration of activity results in a need for significant infrastructural support (e.g. houses, roads, schools) for people employed in the production and processing of cane.[26] The needed close proximity of cane production areas to processing factories renders the relationships between farms, factory, workforce and the local economy tightly intertwined. Thus, it is clear that the main social impacts are through employment and livelihoods, food security, land availability and health.[26]

Employment and livelihood

There are currently no comprehensive and robust estimates of employment benefits associated with sugarcane production and processing in Sub-Saharan Africa. Sugar estates and mills directly employ thousands of individuals across Sub-Saharan Africa. Indirect work associated with sugar production includes: (i) independent farms contracted to grow sugarcane on their own land (outgrowers) and the individuals who work for them, and (ii) the provision of the many goods and services that support sugar production. Besides that, earnings from sugarcane indirectly support many other local businesses and small-scale economic activities. According to the South African Sugar Association estimates [69], 79,000 direct jobs and 350,000 indirect jobs are associated with sugarcane production and processing in South Africa. Projection based on these estimates would suggest as many as 1.8 million jobs associated with the sugarcane industry in Sub-Saharan Africa (Figure 4.6).[26]

Working conditions of employees vary tremendously; manual cane cutting is known to be particularly arduous. Seasonal employment excuses employers from the responsibility of providing benefits such as pension contributions, health and social services and employment security. Also, within the southern African sugar industry, there is increasing casualization of labor associated with industry restructuring, changing aid frameworks and market incentives, and mechanization.[70]

Figure 4.6: *(A) Kakira sugar factory in Uganda; (B) women selling sugarcane on a market in Ethiopia.*

Health impacts

In Sub-Saharan Africa, extraneous cane material is removed mostly by burning sugarcane before harvest.[71] This has direct impacts on the environment and human health through the amount of atmospheric pollutants emitted. Research has shown that sugarcane burning is the cause of major health problems related to lung function and the respiratory system [72], including the development of certain types of cancer, such as lung cancer.[73]

Links have been observed between sugarcane production and malaria: use of the insecticide Malathion in sugarcane fields has been associated with the increasing resistance of mosquitos, specifically those which are malaria vectors.[74] In Zambia, cane cutters constitute the largest migrant labor group and through visiting prostitutes have contributed significantly to high HIV infection rate, which is estimated at 16–22%.[75] Other health issues include the physical stresses associated with cane cutting over extended periods, and risk of disease from the poor quality of housing provided to plantation workers. However, it is important to point out that many sugar estates in Sub-Saharan Africa provide healthcare facilities for both employees and local residents.[26] Further attentions to potential health impacts are crucial when expanding sugarcane cultivation in Sub-Saharan Africa.

Global climate change

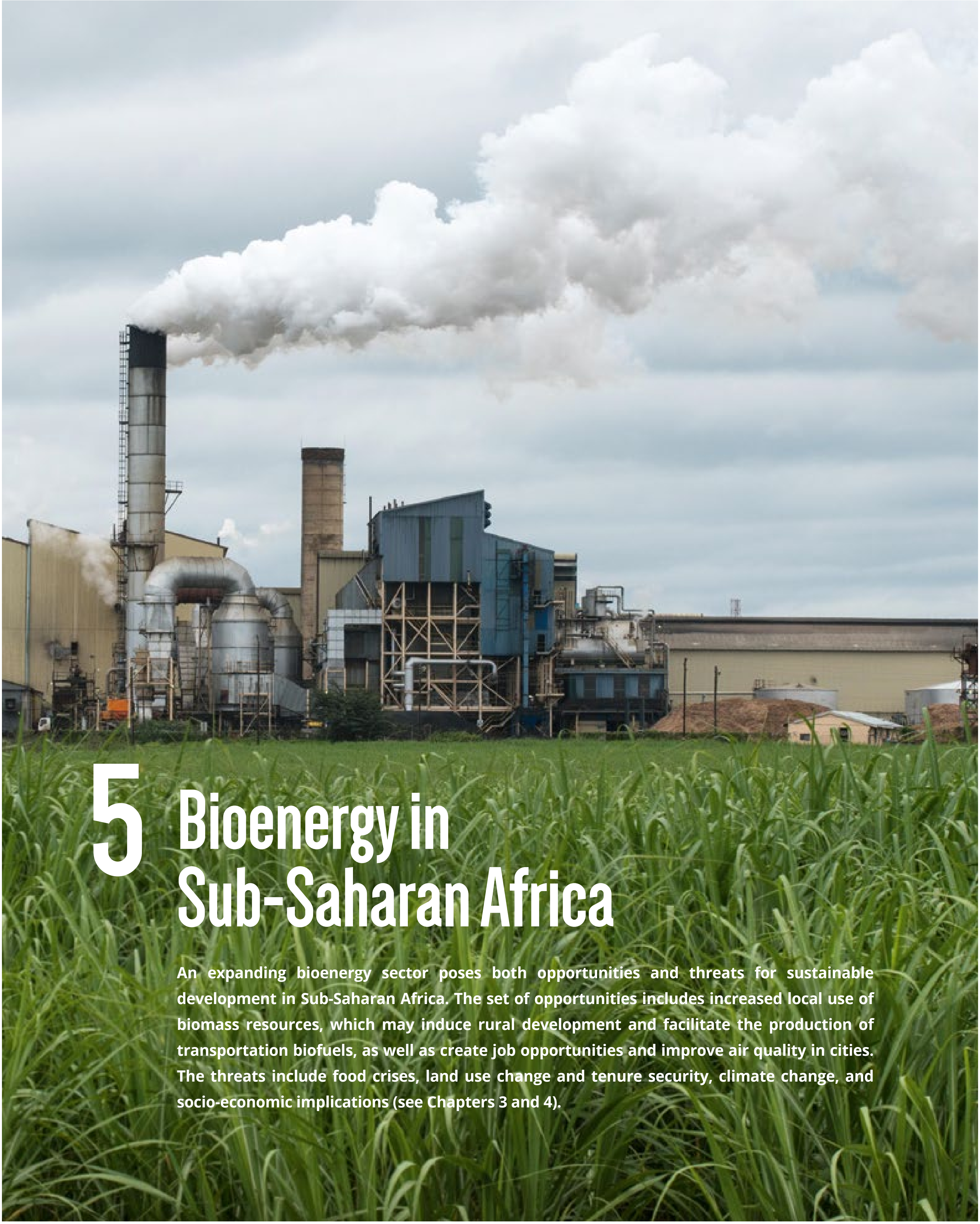
Natural processes (e.g. volcanic eruptions) and human activities (industrial, domestic and agricultural) cause long-term changes in weather patterns worldwide (so called global climate change). Agriculture is vulnerable to climate change through the direct effects of changes in temperature and/or precipitation, as well as through the indirect effects arising from changes in the severity of pest pressures, availability of pollinators and performance of other ecosystem services that affect agricultural productivity. As a consequence, crop productivity is directly affected by climate change.[76] On a continental scale, substantive impacts from climate change are expected to affect Africa's cropping systems, with severe high temperature episodes and increasing frequency and severity of droughts and floods potentially causing catastrophic failures in production.[77]

Climate change is expected to have important consequences for sugarcane production in the world. Sub-Saharan African countries are particularly vulnerable, mainly because of their relatively low adaptive capacity to cope with climate change, their high vulnerability to natural hazards, as well as their poor forecasting systems and mitigating strategies.[78] A negative effect of increased temperature may occur in the tropical regions, where cool winters are required to slow sugarcane growth and increase sugar storage.[76] However, it is important to recognize the uncertainty in assessing climate impacts on productivity. Indeed, some studies suggest that the impacts on future yield could be much less dramatic to rainfed sugarcane production in South Africa, Australia and Brazil.[78, 79, 80, 81]

We have seen above that one of the most crucial resources for the sugarcane industry is water, both for cane cultivation and processing/refining. Changes in the water cycle and water availability are often highlighted as major problems facing sugarcane production mainly in Sub-Saharan Africa [28], perhaps because the region is more vulnerable due to the highly variable climate and lack of irrigation infrastructure (Figure 4.7A).[82] In general, drought in early and mid-growth stages reduces cane yield, leading to low sugar yield. Some mitigation and adaptation strategies for climate change in sugarcane production have been proposed in Zimbabwe. These strategies include planting drought-tolerant varieties, investing in irrigation infrastructure (Figure 4.7B), improving irrigation efficiency and drainage systems, and improving cultural and management practices.[83] Adaptation strategies in South Africa, based on long-term data, focus special attention on technologies and management regimes that will enhance sugarcane tolerance to warmer temperatures during winter, especially in the harvesting phases.[84] Studies have shown that some genotypes/cultivars are better than others at tolerating water deficit and low temperature stresses[85], in radiation use efficiency[86] and in nutrient use efficiency.[87]

The severity of most sugarcane diseases is associated with climate-related factors. More extreme climate change-dependent weather events have led to more overwintering pests (weeds and insects), more disease pathogens, and consequently more costs related to acquiring pesticides that help reduce these risks and maintain a certain level of sugarcane production.[76] For example, the incidence of smut disease is likely to increase due to high temperatures, and prolific dry weather exacerbates the symptoms of ratoon stunting disease.[88] On the other hand, severe storms and hurricanes can spread leaf scald.[89]

Figure 4.7: *(A) Smallholder farmer irrigating his sugarcane field in Zambia; (B) irrigation of sugarcane fields in the region of Beira in Mozambique.*



5 Bioenergy in Sub-Saharan Africa

An expanding bioenergy sector poses both opportunities and threats for sustainable development in Sub-Saharan Africa. The set of opportunities includes increased local use of biomass resources, which may induce rural development and facilitate the production of transportation biofuels, as well as create job opportunities and improve air quality in cities. The threats include food crises, land use change and tenure security, climate change, and socio-economic implications (see Chapters 3 and 4).

The environment for bioenergy-related business is recently showing encouraging signs in Sub-Saharan Africa, where governments have recognized the effect of the energy gap in economic growth.[31] Indeed, if designed with the involvement of local communities and sensitivity toward local environmental constraints, bioenergy has the potential to substitute a significant amount of energy used in transport, electricity and household sectors. Besides, local agricultural systems may profit from rural investments and relatively high labor demands, hence ramping up family income opportunities while boosting local crop production. New regulatory and institutional frameworks have been implemented in order to stimulate bioenergy production, notably in South Africa, Mozambique, Swaziland, Zambia and Zimbabwe.[90]

Sugarcane production provides a wide range of renewable energy services, from bagasse pellets and alcohol gels for cooking to bioethanol fuel for transportation and the generation of electricity from sugarcane bagasse. Sub-Saharan African countries with established industrial infrastructure for sugar production could, with relatively low investment capital, start bioenergy production by integrating new distilleries into traditional sugar mills (Figure 5.1). This kind of energy production in sugar mills can be an important diversification alternative, reducing economic risks and increasing industrial efficiency with better use of both molasses and sugarcane bagasse. With the European sugar market regime due to end in 2017 [91], this kind of combined sugar and ethanol mill offers interesting business perspectives. Indeed, the European sugar market policy, including quotas and a minimum price system, underpins much of Africa's sugar production. If the changes come to pass, only the most competitive sugar producers in Sub-Saharan Africa will be able to continue selling to Europe. Therefore, the others will need to re-orient themselves towards regional and other external sugar and/or biofuel markets.[26]

According to the World Bank, more than 60% of the Sub-Saharan African population was living in rural areas in 2014.[92] Most of them (80%) are stuck in the poverty trap, with living conditions deeply impacted by constraints on energy supplies. Given these figures, the logical priority for bioenergy should be small-scale projects targeting local markets, aiming at rural electrification, water pumping and assuring the availability of transport fuels for agriculture. At the local level, the sugarcane milling industry in Sub-Saharan Africa can become a platform for renewable energy production in rural areas. An average-sized mill processing one million tons of sugarcane a year is estimated to provide electricity to 210,000 households (during the milling season), while supplying 150,000 people with modern cooking fuels.[90] Up to 3,300 hectares per year of deforestation might be avoided and conflicts over firewood resources minimized. At the regional level, significant gains, especially for electricity production and ethanol, are possible without compromising

Figure 5.1: *(A) and (B) factory for sugar production from sugarcane in Senegal.*

Figure 5.2: *An ethanol plant located in Chikwawa on the west bank of the Shire River in Malawi.*

sugar production. The implementation of similar structures in suitable areas for sugarcane could extend electricity access to 400 million people, reducing the energy gap by 65%.[90]

These estimates concern the use of sugarcane as a feedstock in a first-generation bioethanol production system, which primarily consists of concentrating and extracting sugar from juice expressed from the culms and then subjecting the residual molasses to fermentation and distillation. Sugarcane ethanol is the only biofuel currently produced at a commercial scale available to meet advanced non-cellulosic renewable fuel targets (see Chapter 2).[93] Sugarcane ethanol is one of the only renewable fuels recognized by United States Environmental Protection Agency as an advanced biofuel, cutting carbon dioxide emissions by up to about 61% compared to gasoline.[94]

Ethanol and other renewable energy carriers from sugarcane remain poorly exploited in Sub-Saharan Africa due to various constraints, such as financial barriers, lack of technical expertise, land availability, and government policies.[39] Large-scale biofuel production and electricity cogeneration are yet to be widely developed in the region. Apart from Malawi and Mauritius, where sugarcane has proven to be a viable way to achieve energy security (Figure 5.2), there is limited experience with large-scale production and use of biofuels in Sub-Saharan Africa, although a number of projects and programs are under development.[90]

Kenya, Madagascar, Mozambique, Senegal, South Africa, Tanzania and Zambia are among those countries that are planning to introduce the large-scale use of fuel ethanol.[41, 95] Some African countries, notably Mozambique, have attempted to emulate Brazil's success in sugarcane bioethanol production by relying heavily on Brazilian biofuel technology expertise and development assistance (see text box 'Brazil's pioneering experience'). Demand for technical and financial support has coincided with Brazil's desire to increase south–south cooperation and leverage its historical and cultural ties with Africa for mutual economic benefit.[96]

Moreover, ethanol produced from lignocellulosic feedstocks (second-generation bioethanol) is seen as a viable option for decreasing any perceived competition between food production and bioenergy.[97] There is a continuous and potentially advantageous path from fermenting both the soluble sugars present in sugarcane and cellulosic residues. Second-generation bioethanol produced from cheaper and abundant plant biomass residues has been viewed as one plausible solution (see Chapter 2). Lignocellulose is present in sugarcane at about a 2:1 ratio relative to sugar. Converting both lignocellulose and sugar fractions in sugarcane would substantially increase yields of energy and revenue per ton. In addition, growing 'energy cane' with high fiber content would have the boosting effect of increasing biomass per hectare.[97] The permanence of sugarcane as a major source of bioenergy will depend largely on using sugarcane bagasse for second-generation bioethanol coupled with the first-generation bioethanol plants already in operation, minimizing logistical and energy costs. If the sugarcane industry were to adopt this technology, up to 37% more bioethanol would be produced without affecting sugar coproduction.[98]

SUGARCANE ETHANOL – BRAZIL'S PIONEERING EXPERIENCE *(sources [53 and 99])*

Sugarcane agriculture in Brazil began about 500 years ago, but the expansion in crop area and yield over the past 20 years or so has been unprecedented. Between 1990 and 2011, for instance, the area cultivated with the crop increased by 45% and yields increased in average by 1.5 billion tons per year. Brazil's favorable conditions and tradition in cultivating sugarcane were essential in the development of the sector. Large scale production of ethanol biofuel in Brazil started in the late 1970s, among concerns about energy security and the economy. Essentially, an international oil crisis doubled Brazil's expenditure on oil imports and propelled Brazil to invest in large-scale ethanol fuel production to decrease its dependence on foreign oil and stimulate the economy by reducing imports and promoting agro-business. With that in mind, the government launched the National Alcohol Programme (Pro-Álcool) in 1975 to increase ethanol production as a substitute for gasoline. It invested massively in infrastructure and research, increasing agricultural production, modernizing and expanding distilleries, and establishing new production plants. It also introduced subsidies to lower prices and reduced taxes for ethanol producers. Over the next 15 years, production of ethanol increased hugely from 0.6 billion liters in 1975 to 11 billion liters in 1990. Today, Brazil is the world's largest producer of sugarcane ethanol.

The science behind the achievement

Behind the success of the program were important scientific and technological advances in agriculture and industry. Researchers produced varieties adapted to different soil and climate conditions, with better yields and tolerance to water scarcity and pests (such as the devastating fungus that caused sugarcane rust in the 1980s). In production, new grinding systems were developed and the fermentation process adapted to use different microorganisms and enzymes to produce more ethanol faster. A problem at the time was waste. The vinasse, a corrosive liquid by-product of ethanol distillation, was dumped in rivers, causing environmental damage. But the vinasse was found to be a good fertilizer, and in the 1980s, the Sugarcane Technology Centre developed a transportation system involving a combination of trucks, pipes and ducts to carry it from the distilleries to the fields. Researchers at the center and other institutions also found ways to use leftover sugarcane fiber, known as bagasse, to produce energy, building on existing methods of burning the bagasse to power steam turbines for electricity generation.

The expansion of sugarcane cultivation in Brazil

For the past 50 years, most of the sugarcane cultivation in Brazil has been concentrated in the southeastern region in the states of São Paulo and Minas Gerais because it is where most of the sugarcane mills are located. In these regions, sugarcane agriculture has occurred mostly over areas of degraded pastureland, citrus agriculture, and annual crops. However, sugarcane is now quickly expanding into the Cerrado region (a vast tropical savannah region), not only over pastureland but also to a lesser extent (1%) in areas of natural vegetation. Although the area of natural vegetation converted to sugarcane is not significant in comparison to the other land cover types, the expansion of sugarcane over this area has significant environmental relevance. The Cerrado region includes some of the most threatened tropical biomes on Earth.

6 Sugarcane is more than sugar and bioenergy

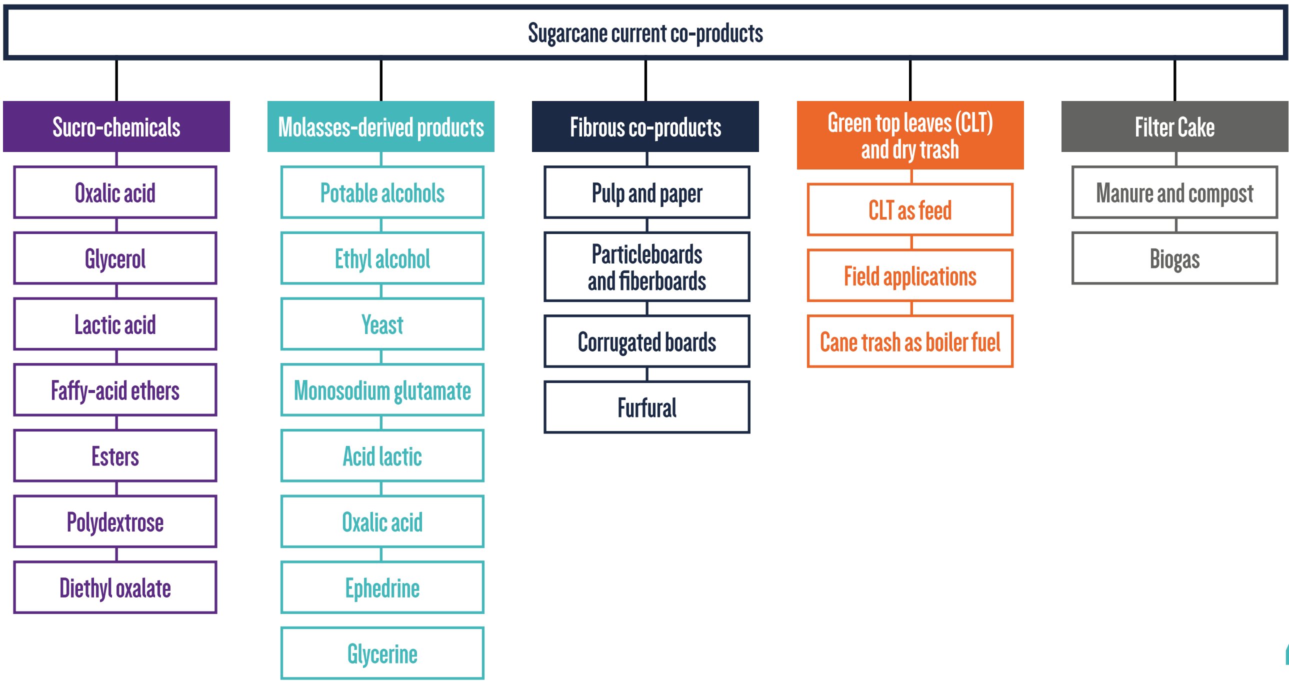
Besides sugar and bioethanol production and the use of bagasse for power and heat generation, there are many sugarcane resource streams and co-products from which value-added products can be developed. Final products relying on commercially proven technologies include, for instance, specialty sugars, fibrous co-products and other manufactured goods (Figure 6.1). A number of agro-industrial industries based on sugarcane derived products have been established worldwide. Such complexes utilize sugarcane and its co-products in an integrated manner.[100] Godavari in India is a good example of a sugar company diversifying into biobased chemicals while obtaining social, environmental, and financial sustainability gains.[101] Godavari manufactures refined sugar, ethanol, chemicals and even flavor and fragrance ingredients. From bagasse, electricity is cogenerated and used to power the sugar and chemical factories and plants. In this way, biobased chemicals are efficiently produced to be able to compete pricewise against the same chemicals produced from fossil sources.[102]

Bagasse co-products under research include for instance, cellulose fiber (rayon pulp), additive for improving product and processing characteristics of food (carboxymethyl cellulose) and xylitol which is an alternative sweetener used in food and pharmaceutical preparations. Biogas and biochar produced from the thermochemical decomposition of sugarcane biomass are co-products of sugarcane. Biochar is suggested to improve the water- and fertilizer-retaining capacity of agricultural soil. There are also plastics and other petrochemical-based products.[100] Other fractions of sugarcane biomass which are available in significant amounts consist of the green top leaves and dry trash. Potential products from the green top leaves and trash under development include fiber for building, furfural for pharmaceuticals, pulp and paper, and chemicals.[100]

A number of downstream products are currently produced in facilities operating in Africa, mainly multinationals. These include fertilizers; furfural (used mainly in oil refineries for the purification of oils); furfural alcohol (used mainly to produce resin in the foundry industry); diacetyl and 2,3-pentanedione (both used as high-quality natural flavorants); agricultural nematocide; ethyl alcohol and lactulose (as a natural laxative).[100]

Sugarcane has also turned into a target crop for biosynthesis, through genetic engineering, of novel products. These products include proteins with pharmaceutical properties such as the bovine lysozyme to control pathogenic bacteria [103] and the His-tagged cystatin, a human protein used for identification and prevention of various diseases.[104] There are also novel carbohydrates and sugar substitutes such as nutraceuticals which are derived from food sources and have extra health benefits.[45] Many challenges must still be overcome before these innovations become commercial realities. Although it is possible to obtain the novel bio-products in sugarcane, they are not obtained at competitive levels yet. For instance, protocols for protein extraction and purification from vegetative tissues at the industrial level still represent a challenging task, as do practical knowledge and skills that are still in their infancy, especially in sugarcane industries.[12]

Figure 6.1: *Sugarcane is more than sugar and bioenergy. Current co-products from cane resources (source: based on the data of [100]).*



7 Unlocking the potential for genetic improvement of sugarcane

The main characteristics that make sugarcane a unique crop are its capacity to accumulate high levels of sugar in its stems and its typical high yield. Thus, a key goal in meeting growing demand is to improve biomass yield and accelerate selection for desirable traits. Sugarcane biotechnology has been receiving considerable global attention over the last several years. New breeding programs and germplasm collections are being established and an increasing arsenal of tools are expected to improve this crop.

Source: *SASRI South African Sugarcane Research Institute, 2017 collection*

A major barrier in sugarcane improvement for many years has been the lack of biotechnological tools. This is because the complex and large genome of sugarcane (see Chapter 1) has long hampered efficient, conventional, selective breeding of the crop, as well as the development of crucial areas such as genetics to support breeding for crop improvement programs. In addition, breeding for new sugarcane varieties takes between 10 and 15 years.[14] Genetic improvement of sugarcane has mainly been based on the production of hybrids by controlled pollination techniques[105] relying on careful hand-pollination, a process that is labor-intensive and potentially uneconomical (see VIB Facts Series issue 'From plant to crop: the past, present and future of plant breeding').[106] Because of the small number of sugarcane species involved in the primary original crosses (see Chapter 1), the genetic diversity of modern hybrid varieties was shown to be narrow, which could be one of the reasons for the slow progress in sugarcane breeding.[107] With the advent of molecular techniques, the sugarcane genome has become less mysterious, although its complexity has been confirmed in many aspects.[108] The development of commercial sugarcane varieties may take a further 8 to 10 years due to the slow multiplication and limited availability of seeds at the time of release of the new variety.[14]

Sugarcane genome resources

Deciphering the sugarcane genome is a major goal for improving genome-wide assisted selection breeding and genetic engineering opportunities. It will contribute to improving the understanding of the genetic basis of sugar content and physiology. It will also provide molecular tools for breeding purposes and gene discovery related to traits such as biomass yield, plant defenses, metabolism, flowering, and responses to biotic and abiotic stresses.

Despite the complexity of the sugarcane genome, a large array of genomic tools has been developed, unveiling new ways to define the genetic architecture of the sugarcane genome and to explore its functional system. Physical maps and molecular markers are being routinely used in the sugarcane research community for genetic studies. Detecting a specific DNA fragment (also called a 'marker') which is linked to a trait (e.g. disease resistance) in a crossing product can help to determine at a very early stage whether or not a plant will be disease resistant (see VIB Facts Series issue 'From plant to crop: the past, present and future of plant breeding').[106] Molecular markers associated with relevant agronomic traits could significantly reduce the time and costs involved in developing new sugarcane varieties. Although some genetic maps linking DNA markers and traits have been developed, marker-assisted breeding is still in its infancy for sugarcane. Sugarcane genome-wide analyses have found few molecular markers associated with relevant traits at plant-cane stage.[109]

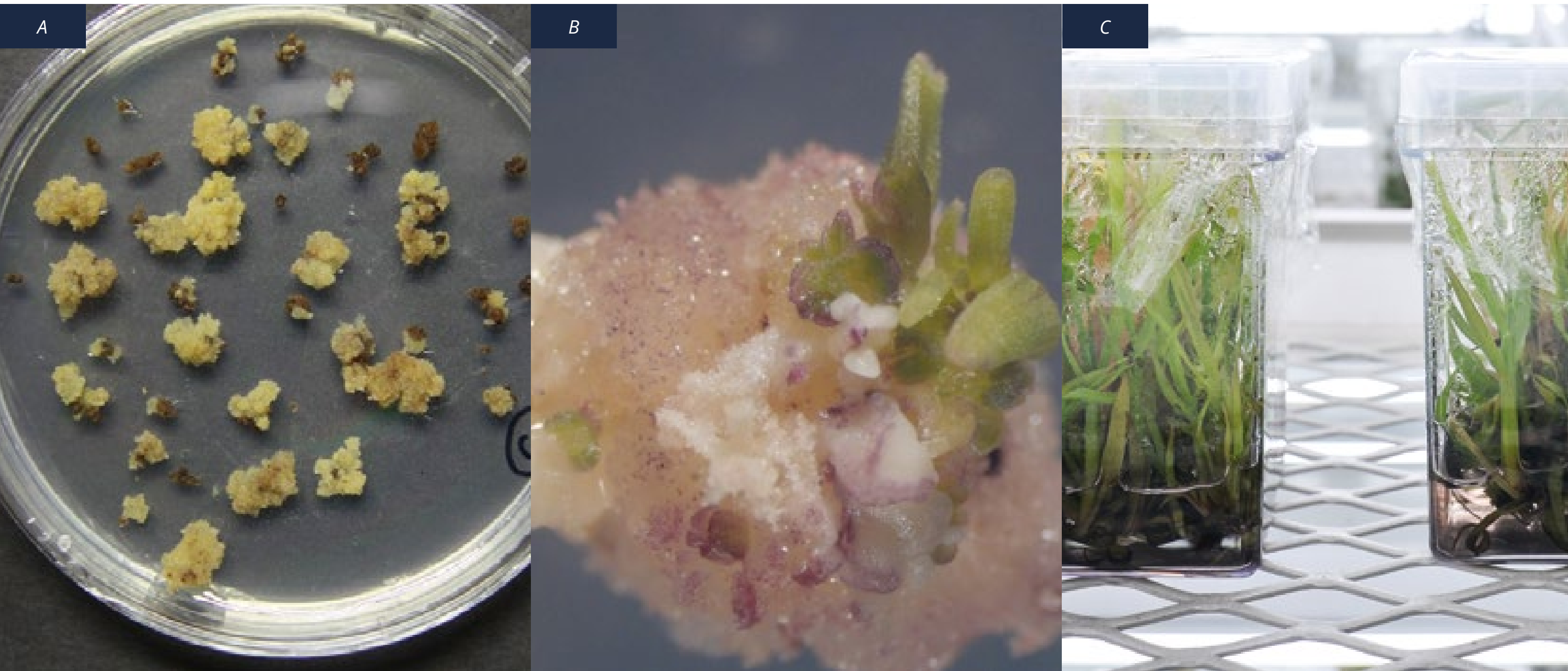
Moreover, progress has been made with the use of so called Single Nucleotide Polymorphisms (SNP) markers, which are distributed at high density across the genome. For complex genomes such as that of sugarcane, these markers can allow estimation of the number of allelic copies and the ploidy level of genomes.[110] More recently, so called Diversity Array Technology (DArT) markers were integrated into the largest markers collection for sugarcane.[111] All these markers will be a valuable resource in facilitating and unraveling the complex genome structure of sugarcane.

Despite sugarcane's economic importance and significant efforts made by several international research groups, a reference genome is still unavailable today. The hybrid nature of the crop, the high degree of ploidy and the high proportion of repetitive DNA sequences (see Chapter 1) make sequencing the sugarcane genome a big challenge. Nevertheless, in recent years, considerable progress has been made in understanding the sugarcane genome. Several sugarcane projects are ongoing around the world, among them the Sugarcane Genome Sequencing Initiative led by an international research group from Australia, Brazil, China, France, South Africa, and the USA. To date, only the chloroplast genome of sugarcane has been completely sequenced.[112] A reference genome (or genomes) for this crop would dramatically accelerate genetic and genomic research and breeding programs, as it would facilitate gene expression studies and interactions on a genome-wide scale.

The GM route for the improvement of sugarcane

Sugarcane can be genetically modified (GM) by using either *Agrobacterium tumefaciens* or particle bombardment (biolistics) techniques (for more information on these two techniques, see VIB Facts Series issue 'Bananas, the green gold of the South').[113] Although these techniques have been successfully employed [114, 115], genetic modification of sugarcane is hindered by low efficiencies, inactivation of the gene of interest, somaclonal variations (which is a genetic variability seen in plants that are recovered from *in vitro* tissue cultures) and difficulties in backcrossing (for more information on backcrossing, see VIB Facts Series issue 'From plant to crop: the past, present and future of plant breeding') (Figure 7.1).[106] These problems prompted other research groups to develop a sugarcane transformation method without the necessity to recover plants from *in vitro* tissue culture: an *in planta* transformation system using axillary buds instead of tissue cultures as the target for genetic modification.[116]

Figure 7.1: In vitro *regeneration of sugarcane. (A) Callus induction on selective medium (source: Stefaan Werbrouck, personal collection); (B) shoot regeneration from somatic embryos (source: Stefaan Werbrouck, personal collection); (C) shoot elongation (source: SASRI South African Sugarcane Research Institute, 2017 collection).*



This alternative method allows the bypassing of the *in vitro* regeneration of GM plants and thus avoids somaclonal variation. In addition, the *in planta* transformation method can produce GM plants in a relatively short time and with limited cost and manpower.[116]

On June 2017, Brazil has approved the commercial cultivation of a GM sugarcane developed by the Brazilian company Centro de Tecnologia Canavieira.[117] Bt sugarcane, the first GM sugarcane approved for cultivation in the world, is resistant to damage caused by sugarcane borer (*Diatraea saccharalis*), the main pest of sugarcane in Brazil. The soil bacterium *Bacillus thuringiensis* (usually abbreviated to 'Bt') produces proteins (Cry1Ac and Cry2Ab, for instance), which are only toxic to some moth and butterfly caterpillars and/or larvae of beetles and mosquitoes. They are harmless to other insects and animals, including humans. Once ingested by the sugarcane borer, the Cry proteins bind to specific receptors on the lining of the caterpillar's gut, where they create holes and quickly cause death (for more information on the Bt gene, see VIB Facts Series issue 'Bt cotton in India').[118] In May 2013, Indonesia's Biosafety Commission for GM Products issued food and environmental safety certificates for a GM, drought-tolerant sugarcane.[119] In 2016, the Biosafety Commission issued guidelines on feed safety that has to be undertaken before granting approval for commercial release. Once feed approval is obtained, commercial cultivation of this drought-tolerant sugarcane can be expected in the near future.[120]

Table 7.1 provides an overview of the global pipeline of GM sugarcane in 2014 [121] and in 2017 [117]. The pipeline distribution focuses on the following development stages (developed by [121]): commercial cultivation (events that are currently cultivated and commercialized in at least one country worldwide), pre-commercial stage (GM events that are authorized for cultivation in at least one country worldwide but not yet marketed – commercialization only

Table 7.1: *GM sugarcane events in the market and at the pre-commercial, regulatory and advanced, early R&D in 2014[a] (source: based on the data of [121]) and in 2017[b] (source [117]).*

Stage	Trait description	Developer	Country
Commercial cultivation[b]	Insect resistance	Centro de Tecnologia Canavieira	Brazil
Pre-commercial[a]	Drought stress tolerance	PT Perkebunan Nusantara XI	Indonesia
Regulatory[a]	Herbicide tolerance	PT Perkebunan Nusantara XI	Indonesia
Advanced R&D[a]	Herbicide tolerance	Sugar Research Australia Ltd	Australia
	Insect resistance	Sugarcane Breeding Institute	India
	Herbicide tolerance + Insect resistance	Monsanto	US
Early R&D[a]	Increased yield (nitrogen)	South African Sugarcane Research Institute and Arcadia Biosciences	South Africa
	Drought stress tolerance	Embrapa: Brazilian Agricultural Research Corporation	Brazil
	Sugar metabolism	Bayer CropScience and Centro de Tecnologia Canavieira	Brazil
	Increased yield	BASF and Centro de Tecnologia Canavieira	Brazil

depends on the developer's decision), regulatory stage (GM events that are under assessment for authorization in at least one country worldwide - and are likely to reach the market in the short term: 2-3 years), advanced R&D stage (GM events not yet in the regulatory process but at late stages of development – large-scale multi-location field trials, generation of data for the authorization dossier – and likely to reach the market in the medium term: 7-8 years), and early R&D stage (GM events for which a proof of concept has been obtained).

Towards a sustainable sugarcane industry in Sub-Saharan Africa

The development of high sugar and biomass-yielding sugarcane will contribute to improving the value and sustainability of the sugarcane industry worldwide, and particularly in Sub-Saharan Africa. An uninterrupted supply of quality sugarcane should be able to meet the increasing demand for sugarcane-derived products and to improve the value of sugarcane industry.

Sugarcane yield relies on crop varieties (genotypes), biotic and abiotic growth environments and management practices. The unknown impact of climate change also presents challenges for the growth and development of sugarcane in the future. Candidate genes of interest for sugarcane improvement have been selected using the large quantity of gene expression data accumulated for this crop.[122, 123, 124] Several traits related to sustainable high-yield sugarcane production have been introduced by genetic modification, including herbicide tolerance, disease and pest resistance, and cold and drought tolerance (Figure 7.2). Sugarcane's tolerance to drought is an important trait for Africa especially, where cultivation expands into water-limited regions. Other agronomic traits of interest include ratooning, flowering, and nutrient use efficiency. The output traits of interest to sugarcane industry include those related to enhanced sugar content, high-value sugars, fiber quality, industrial enzymes, aromatics, and biopolymers (waxes, bioplastics) (Figure 7.2). Targets tackled so far include genes associated with biomass synthesis pathway, modification of the cell wall polysaccharide content, lignin content, lignin modification, flowering inhibition, and production of bioplastics and biopharmaceuticals.

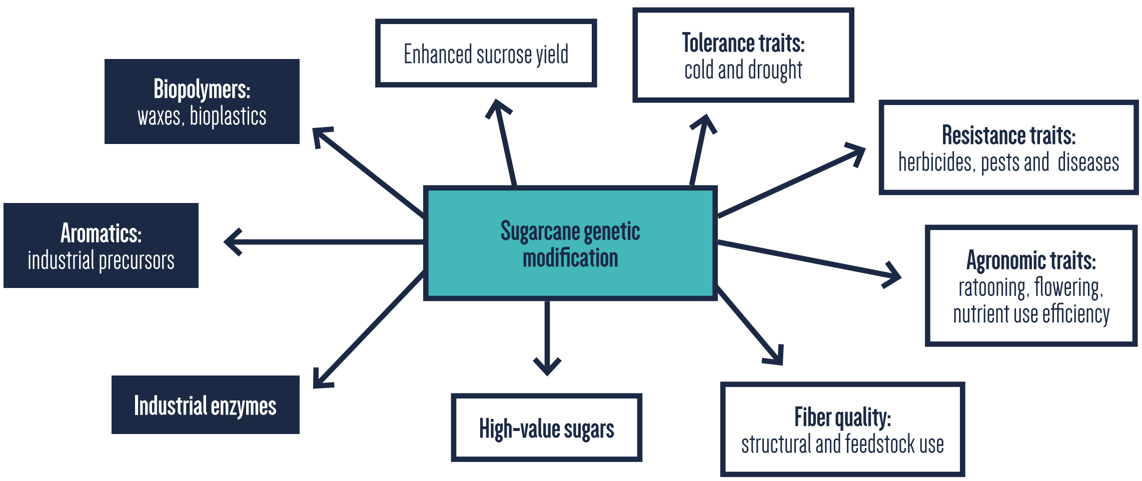
The competitiveness of biofuels over other options relies on biotechnology to improve the biomass yield and the feedstock composition for biofuels. Besides the input traits required to sustainably produce biomass in large quantities at high yields, biotechnology aims at modifying the carbohydrates of the cell walls, which are crucial for protecting cells. Plant cell walls have evolved to be recalcitrant to degradation, as walls contribute extensively to the strength and structural integrity of the entire plant. A major hurdle to producing second-generation bioethanol from the cell walls of sugarcane is the high proportion of lignocellulose residues, material left after the extraction of the juice for which sugarcane is grown. Here, the presence of lignin in the cell wall exacerbates biomass recalcitrance to enzymatic hydrolysis. Enzymatic hydrolysis is the decomposition/conversion of cellulose into fermentable sugars by the addition of specific enzymes along with a reaction with water (see Figure 7.3). Thus, lignin should be removed before further processing. Sugarcane lignin content can be reduced by downregulating some of the key genes encoding enzymes of the lignin biosynthesis pathway. Field trials with GM sugarcane lines displaying suppression (80–90%) of these genes presented a reduction of lignin (6–12%), which improved the efficiency of sugar conversion with about 28–32%. [126, 127] Moreover, lignin biosynthesis is regulated by the action of different transcription factors, which are proteins that control the rate of transcription of genetic information from DNA to messenger RNA. The transcription factor MYB42 downregulates multiple genes within the lignin biosynthetic pathway. Recently, sugarcane plants genetically modified with MYB42 showed a significant decrease in total lignin content of 8–21%. These plants also showed increased glucose release from the bagasse by enzymatic hydrolysis with no reduction to juice sugar levels.[128]

Some remarkable strategies for second-generation bioethanol are the production of GM sugarcane plants with a favorable ratio of cellulose to non-cellulose content, or with *in planta* enzymes that can digest the biomass or degrade the lignin prior to its conversion to ethanol. *In planta* enzymes can lead to production of fermentable sugars. The approach is to design ways to induce production of endogenous enzymes – called hydrolases – at the end of the sugarcane crop growth cycle, at which time the tissues would be pre-treated biologically. Current research in this area involves identification and characterization of hydrolytic enzymes that can break down sugarcane cell wall polysaccharides into fermentable sugars (Figure 7.3).[129]

Sugarcane biotechnology research in Africa is limited to South Africa

The South African Sugarcane Research Institute (SASRI), the University of Stellenbosch and the National Innovation Centre for Plant Biotechnology (PlantBio) are currently active in GM sugarcane research. SASRI has worked on the improvement of sugarcane by genetic engineering for the last 18 years. Early research projects concerned tolerance to herbicides (glyphosate and glufosinate ammonium), resistance to the lepidopteran stalk borer *Eldana*

Figure 7.2: *Applications of genetic modification for sugarcane improvement. Traits shown in dark boxes at left are most likely to be engineered in cultivars grown for non-food purposes. Traits in white boxes are likely to be compatible with cultivars grown for both food and by-product supply (source: based on the data of [125]).*

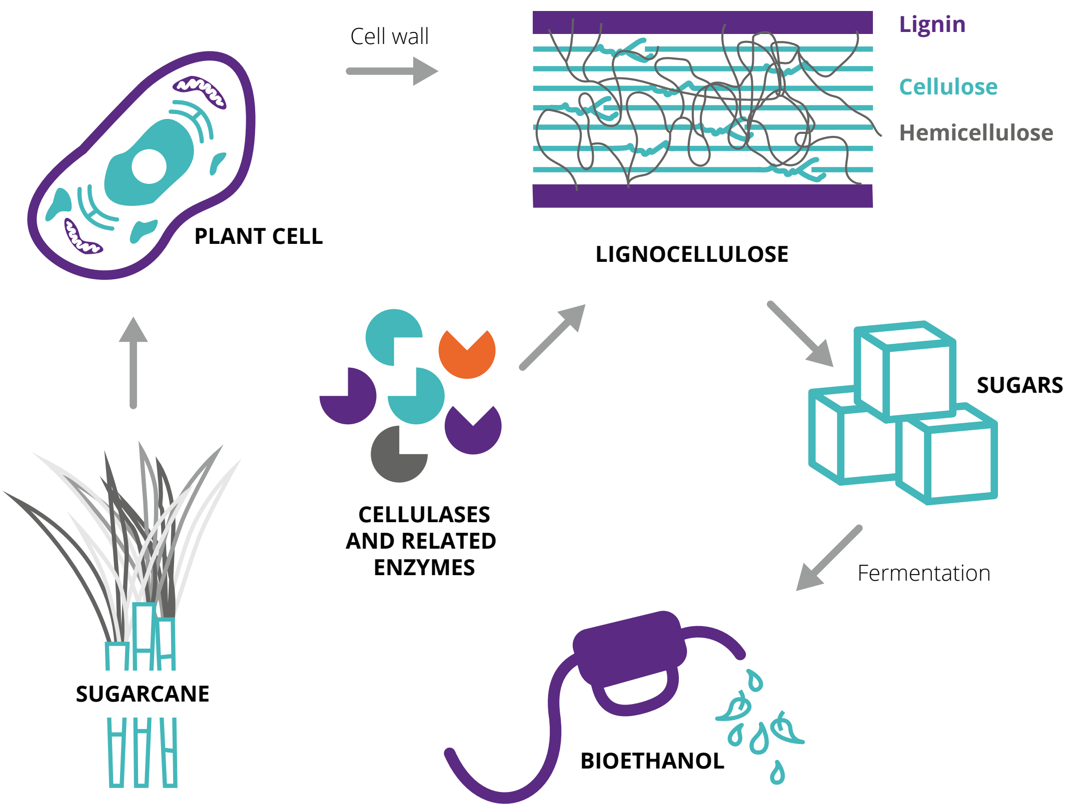


saccharina, resistance to the sugarcane mosaic virus as well as perturbations of enzymes involved in sugar metabolism.[131] Sugarcanes containing these traits have been evaluated in confined field trials at SASRI.[132] Current projects include drought tolerance and nitrogen use efficiency in collaboration with the Institute for Plant Biotechnology at the University of Stellenbosch.[133]

Presently, the major focus on biofuels in South Africa and in other large sugar-producing African nations is on conventional sugarcane. Several large-scale projects involving the Central Energy Fund and the Industrial Development Corporation were earmarked across South Africa for the cultivation of sugarcane for ethanol. The South African Sugarcane Research Institute produced 'N' varieties via conventional breeding, which are grown in much of Sub-Saharan Africa (Table 7.2). Some of them are also used for genetic modification, as they respond favorably to *in vitro* culture.

In August 2009, a Brazilian-South African partnership was formed between the Brazilian Development Bank and the Industrial Development Corporation. The agreement covers technology sharing, strategy formulation and the joint financing of capital projects in South Africa. According to the African Centre for Biosafety [134], should GM sugarcane become commercially feasible, the switch to GM ingredients in the

Figure 7.3: *Plant cell walls are the most abundant renewable resource. Cellulose is the most abundant polysaccharide in plant cell walls and is a potential source of bioethanol (source: based on the data of [130]).*



production of bioethanol would be based more on commercial incentives than worries over biosafety or biodiversity.

Substantial institutional and regional strategic reforms and international collaboration are required to leverage science and technology in Sub-Saharan Africa and close the gap between the regional and international sugarcane biotechnology research communities.

Table 7.2: *List of African countries the South African Sugarcane Research Institute (SASRI) has agreements with to use the 'N' varieties within their own breeding programs (source: South African Sugarcane Research Institute, personal communication).*

Country	Type of agreement	Description
Zimbabwe	Sugarcane Fuzz Agreement	Sugarcane seed (unselected populations)
Angola	Variety Evaluation Agreement	Varieties being evaluated for suitability to growing conditions. Not in commercial production yet
Burundi	Variety Evaluation Agreement	
Cameroon	Variety Evaluation Agreement	
Chad	Variety Evaluation Agreement	
Congo	Variety Evaluation Agreement	
Gabon	Variety Evaluation Agreement	
Ghana	Variety Evaluation Agreement	
Ivory Coast	Variety Evaluation Agreement	
Kenya	Variety Evaluation Agreement	
Nigeria	Variety Evaluation Agreement	
Senegal	Variety Evaluation Agreement	
Sierra Leone	Variety Evaluation Agreement	
Sudan	Variety Evaluation Agreement	
Tanzania	Variety Evaluation Agreement	
Uganda	Variety Evaluation Agreement	
Zambia	Variety Evaluation Agreement	
Mauritius	Variety Exchange Agreement	For breeding purposes only
Congo	Variety License Agreement	SASRI varieties being considered for commercial production. Some companies are still in the process of bulking up their seedcane material. Other companies are paying levies (based on tons of sugar produced or tons of cane produced) for the commercial production of SASRI varieties.
Ghana	Variety License Agreement	
Kenya	Variety License Agreement	
Malawi	Variety License Agreement	
Mozambique	Variety License Agreement	
Nigeria	Variety License Agreement	
Swaziland	Variety License Agreement	
Tanzania	Variety License Agreement	
Zambia	Variety License Agreement	
Zanzibar	Variety License Agreement	
Zimbabwe	Variety License Agreement	

8 Conclusions

Given the natural endowment of Sub-Saharan Africa, development of a viable sugarcane industry could potentially assist many countries of the region in solving some of their pressing needs. Sugarcane has the potential to contribute to a more dynamic and competitive economy in Sub-Saharan Africa. Sugarcane is grown under a wide variety of management regimes in Sub-Saharan Africa, ranging from large commercial plantations to smallholder farms, and it is being cut by hand or harvested mechanically. Sugarcane offers high socio-economic sustainability with respect to job creation due to the high-labor requirements on the agricultural side. Smallholder farmers in particular can reap benefits of sugarcane cultivation in terms of food and energy security. In order to thrive, smallholders need access to the basics: (i) land and inputs (water, fertilizers, quality sugarcane varieties), (ii) technology, (iii) good management practices, (iv) functioning markets (requiring adequate infrastructure and market information), and (v) affordable credit.

Sugarcane industry can cause small but deep environmental, economic and social footprints. The experience to date in Sub-Saharan Africa suggests that these impacts can be either positive or negative depending on the environment, the production model and, perhaps most importantly, the quality of management. Well-managed sugarcane industries offer the opportunity to increase soil health and thus improve carbon sequestration and water management. Certification schemes for sugarcane sustainability and better practices are experiencing rapid uptake, providing an opportunity to realize the positive potential of sugarcane industry.

Environmental sustainability of sugarcane production can also be improved through better knowledge of the genetics and physiology of the plant. The deployment of new technologies, including modern plant biotechnology, will be critical for achieving sustainable high-yield sugarcane production. Molecular genetics and genomics will play important roles in sugarcane breeding programs. GM technology approaches can significantly and rapidly improve plant characteristics, considerably reducing the breeding time. As genetic modification of sugarcane becomes more efficient and additional molecular tools become available, the sugarcane industry will soon reach greater potential to provide food, feed, energy and high-value products.

Future advances will require synergy across several fields of research, including traditional breeding, genetics, physiology and biotechnology, but also good agronomic practices. The goal is to tap into the enormous potential of the crop in term of chemicals, bioproducts and energy production. The transformation of conventional sugar factories into sugarcane processing complexes for multiple products, especially electricity and ethanol, will help to sustain the long-term viability of the industry.

9 References

1. Da Costa, M.L.M., Amorim, L.L.B., Onofre, A.V.C., De Melo L.J.O.T., De Oliveira, M.B.M., de Carvalho, R., Benko-Iseppon A. M. (2011). Assessment of genetic diversity in contrasting sugarcane varieties using inter-simple sequence repeat (ISSR) markers. *American Journal of Plant Sciences 2: 425-432.*
2. Cheavegatti-Gianotto, A., Couto de Abreu, H. M., Arruda, P., Bespalhok Filho, J. C., Burnquist, W. L., Creste, S., et al (2011). Sugarcane (Saccharum X officinarum): A reference study for the regulation of genetically modified cultivars in Brazil. *Tropical Plant Biol*. 4: 62–89.
3. Ramdoyal, K., Dookun-Saumtally, A., Badaloo, G. H. (2012). Sugar cane physiology, breeding and biotechnology. In: *Bioenergy for Sustainable Development and International Competitiveness. The Role of Sugar Cane in Africa,* Johnson F. X. and Seebaluck V. (eds.), 19-47.
4. OECD (2013). Consensus document on the biology of sugarcane (*Saccharum* spp.). *Series on Harmonisation of Regulatory Oversight in Biotechnology*, No. 56. OECD Environment, Health and Safety Publications.
5. Mitchell, H. J. (2011). Regulation of genetically modified (GM) sugarcane in Australia. *Proc Aust Soc Sugar Cane Technol* 33: 1-8.
6. Rae, A. L., Martinelli, A. P., Dornelas, M. C. (2014). Anatomy and morphology. In *Sugarcane: Physiology, Biochemistry, and Functional Biology*, Moore P.H. and Botha F.C. (eds.), Wiley Blackwell, 19-34.
7. Ambrosano, E. J., Azcón, R., Cantarella, H., Ambrosano, G.M.B., Schammass, E. A., Muraoka, T., Ocheuze, P. C. *et al*. (2010). Crop rotation biomass and arbuscular mycorrhizal fungi effects on sugarcane yield. *Sci. Agric. (Piracicaba, Braz.)*, 67(6): 692-701.
8. Davis, S. C., LeBauer, D. S., Long, S. P. (2014). Light to liquid fuel: theoretical and realized energy conversion efficiency of plants using Crassulacean Acid Metabolism (CAM) in arid conditions. *Journal of Experimental Botany* 65(13): 3471–3478.
9. Van der Weijde, T., Kamei, C. L. A., Torres, A. F., Vermerris, W., Dolstra, O., Visser, R. G. F., Trindade, L. M. (2013). The potential of C4 grasses for cellulosic biofuel production. *Frontiers in Plant Science* 4: 107.
10. James, G.L. (2004). An introduction to sugarcane. *Sugarcane*, Second Edition, Blackwell Science Ltd: 1-19.
11. Dillon, S.L., Shapter, F.M., Robert, H.J., Cordeiro, G., Izquierdo, L., Lee, S.L. (2007). Domestication to crop improvement: genetic resources for sorghum and saccharum (Andropogoneae). *Ann Bot* 5: 975–989.
12. Paterson, AH, Moore, PH, Tew, TL (2013). The gene pool of Saccharum species and their improvement. In: *Genomics of the Saccharinae. Plant genetics and genomics: crops and models*, vol 11. Paterson, A.H. (ed): 43-71.
13. Moore, P. H., Paterson, A. H., Tew, T. (2014). Sugarcane: the crop, the plant, and domestication. In *Sugarcane: Physiology, Biochemistry, and Functional Biology*, Moore P.H. and Botha F.C. (eds.), Wiley Blackwell, 1-17.
14. Hoang, N.V., Furtado, A., Botha, F.C., Simmons, B.A., Henry, R.J. (2015). Potential for genetic improvement of sugarcane as a source of biomass for biofuels. *Frontiers in bioengineering and biotechnology* 3(182): 1-15.
15. Bhowmik, S.S.D., Brinin, A.K., Williams, B., Mundree, S.G. (2016). Sugarcane biotechnology: tapping unlimited potential. In: *Sugarcane-based Biofuels and Bioproducts*, I.M. O'Hara and S.G. Mundree (eds.), Wiley Blackwell: 23-48.
16. Gonçalves, M.C., Pinto, L.R., Souza, S.C., Landell, M.G.A. (2012). Virus diseases of sugarcane. A constant challenge to sugarcane breeding in Brazil. *Functional plant science and biotechnology* 6(2): 108-116.
17. Rott, P., Sood, S., Comstock, J. C., Gilbert, R. A., Sandhu, H. S. (2014). Sugarcane ratoon stunting. *U.S. Department of Agriculture, UF/IFAS Extension Service, University of Florida*: 3 p.
18. Magarey, R. C., Bull, J. I., Sheahan, T., Denney, D. (2010). Yield losses caused by sugarcane smut in several crops in Queensland. *Proc Aust Soc Sugar Cane Technol* 32: 347-354.
19. Sharma, R., Tamta, S. (2015). A review on red rot: the 'cancer' of sugarcane. *J Plant Pathol Microbiol* S1: 003. doi:10.4172/2157-7471.S1-003.
20. Verheye, W. (2010). Growth and production of sugarcane. In *Soils, plant growth and crop production Volume II,* Verheye W. (Ed.), Encyclopedia of Life Support Systems, 208-241.
21. Tyler, G. (2008). The African sugar industry - A frustrated success story. *Background paper prepared for the Competitive Commercial Agriculture in Africa* (CCAA) study, World Bank, Washington, DC.
22. Cumo, C. (2016). Plants and people: origin and development of human – plant science relationships. CRC Press, Taylor and Francis Group, Boca Raton, Florida, International Standard Book Number-13: 978-1-4987-0709-1.
23. Whipps H. (2008). How sugar changed the world. https://www.livescience.com/4949-sugar-changed-world.html.
24. FAOSTAT (2017). Available at http://www.fao.org/faostat/en/#data.
25. McKay, B., Sauer, S., Richardson, B., Herre, R. (2016). The political economy of sugarcane flexing: initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies* 43(1): 195-223.
26. Hess, T.M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Monteagudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A., Marin, F. (2016). A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change* 39: 181-194.
27. Knox, J.W., Rodríguez Díaz, J.A., Nixon, D.J., Mkhwanazi, M. (2010). Climate change impacts on water use and productivity of sugarcane in Swaziland. *Agric*. Syst. 103 (2): 63–72.
28. Kusangaya, S., Warburton, M.L., Archer Van Garderen, E., Jewitt, G.P.W. (2014). Impacts of climate change on water resources in Southern Africa: a review. *Phys. Chem. Earth Parts* A/B/C 67–69: 47–54.
29. Levin, J., Stevenson, M. (2012). The 2050 criteria: Guide to responsible investment in agricultural, forest, and seafood commodities. *WWF Report, Sept.*
30. United Nations Environment Programme UNEP (2009). Towards sustainable production and use of resources: assessing biofuels. Report.

31. Ben-Iwo, J., Manovic, V., Longhurst, P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. *Renewable and Sustainable Energy Reviews* 63: 172-192.
32. OECD (2008). Biofuels support policies: an economic assessment. *Organisation for Economic Cooperation and Development* (OECD). Paris.
33. Seabra, J. E. A., Macedo, I. C., Chum, H. L., Faroni, C. E., Sarto, C. A. (2011). Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioprod. Bioref*. 5: 519-532.
34. United Nations Conference on Trade and Development UNCTAD (2016). Second-generation biofuel markets: state-of-play, trade and developing country perspectives. Report UNCTAD/DITC/TED/2015/8.
35. Renzaho, A. M. N., Kamara, J. K., Toole M. (2017). Biofuel production and its impact on food security in low and middle income countries: Implications for the post-2015 sustainable development goals. *Renewable and Sustainable Energy Reviews* 78: 503-516.
36. Schaffnit-Chatterjee, C. (2014). Agricultural value chains in Sub-Saharan Africa - from a development challenge to a business opportunity. *Deutsche Bank Research*, 1-28.
37. Amigun, B., Musango, J. K., Stafford, W. (2011). Biofuels and sustainability in Africa. *Renewable and Sustainable Energy Reviews* 15: 1360–1372.
38. International Renewable Energy Agency (IRENA) (2013). The Path to Sustainable Growth. *Africa's Renewable Future*: 1-32.
39. Sekoai, P. T., Yoro, K. O. (2016). Biofuel development initiatives in Sub-Saharan Africa: opportunities and challenges. *Climate* 4(33): 1-13.
40. McHenry, M. P., Doepel, D., de Boer, K. (2014). Rural African renewable fuels and fridges: cassava waste for bioethanol, with stillage mixed with manure for biogas digestion for application with dual-fuel absorption refrigeration. *Biofuels, Bioprod. Bioref*. 8: 103–113.
41. Pacini, H., Batidzirai, B. (2012). The development of biofuel capacities: strengthening the position of African countries through increased energy security. In: *Bioenergy for Sustainable Development and International Competitiveness: The Role of Sugarcane in Africa*, Johnson F. and Seebaluck V. (eds.) Routledge, New York: 331-349.
42. Saboori, B., Sapri, M., binBaba, M (2014). Economic growth, energy consumption and CO2 emissions in OECD (Organization for Economic Co-operation and Development)'s transport sector: a fully modified bi-directional relationship approach. *Energy* 66: 150-161.
43. Terry, A., Ryder, M. (2007). Improving food security in Swaziland: the transition from subsistence to communally managed cash cropping. *Natural Resources Forum* 31: 263–272.
44. Balogun, B. O. (2015). Potentials for sustainable commercial biofuels production in Nigeria. *STECH International Journal of Science and Technology* 4(2): 25-41.
45. Gómez-Merino, F.C., Trejo-Téllez, L.I. Sentíes-Herrera, H.E. (2014). Sugarcane as a novel biofactory: potentialities and challenges. In: *Biosystems Engineering. Biofactories for Food Production in the Century XXI*, Guevara-Gonzalez R. and Torres-Pacheco I. (eds.), Springer International Publishing: 129-149.
46. Thorburn, P.J., Biggs, J.S., Attard, S.J., Kemei, J. (2011). Environmental impacts of irrigated sugarcane production: nitrogen lost through runoff and leaching. *Agric. Ecosyst. Environ*. 144 (1): 1–12.
47. Signor, D., Cerri, C.E.P., Conant, R. (2013). N_2O emissions due to nitrogen fertilizer applications in two regions of sugarcane cultivation in Brazil. *Environ. Res. Lett*. 8 (1): 1-9.
48. La Scala, N., Bolonhezi, D., Pereira, G.T. (2006). Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. *Soil Tillage Res*. 91 (1): 244–248.
49. Anaya, C.A., Huber-Sannwald, E. (2015). Long-term soil organic carbon and nitrogen dynamics after conversion of tropical forest to traditional sugarcane agriculture in East Mexico. *Soil Tillage Res*. 147: 20–29.
50. Watson, H.K. (2011). Potential to expand sustainable bioenergy from sugarcane in southern Africa. *Energy Policy* 39 (10): 5746–5750.
51. Watson, H., Purchase, B. (2012). Land suitability and crop handling. In *Bioenergy for Sustainable Development and International Competitiveness. The Role of Sugarcane in Africa*, Johnson F. and Seebaluck V. (eds.) Routledge, New York: 66-96.
52. Hess, T., Aldaya, M., Fawell, J., Franceschini, H., Ober, E., Schaub, R., Schulze-Aurich, J. (2014). Understanding the impact of crop and food production on the water environment—using sugar as a model. *J. Sci. Food Agric*. 94 (1): 2–8.
53. Filoso, S., do Carmo, J. B., Mardegan, S. F., Machado Lins, S. R., Figueiredo Gomes, T., Martinelli, L. A. (2015). Reassessing the environmental impacts of sugarcane ethanol production in Brazil to help meet sustainability goals. *Renewable and Sustainable Energy Reviews* 52: 1847–1856.
54. Kushwaha, J.P. (2013). A review on sugar industry wastewater: sources, treatment technologies, and reuse. *Desalination and water treatment* 53(2): 1-10.
55. Mapako, M., Farioli, F. Diaz-Chavez, R.A. (2012). Sustainability assessment of energy production from sugar cane resources. In: *Bioenergy for Sustainable Development and International Competitiveness. The Role of Sugar Cane in Africa*, Johnson F. and Seebaluck V. (eds.), Routledge, New York: 255-283.
56. Lautze, J., Giordano, M. (2007). Demanding supply management and supplying demand management transboundary waters in Sub-Saharan Africa. *The J. Environ. Dev*. 16 (3): 290–306.
57. Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C., Mahé, G. (2009). Rainfall and water resources variability in Sub-Saharan Africa during the twentieth century. J. *Hydrometeorol*. 10 (1): 41–59.
58. World Bank (2008). http://econ.worldbank.org.
59. FAO (2004). Crop suitability assessment. Accessed at www.fao.org/ag/agl/agll/cropsuit.asp.
60. Kgathi, D.L., Mazonde, I., Murray-Hudson, M. (2012). Water implications of biofuel development in semi-arid Sub-Saharan Africa: case studies of four countries. In: *Bioenergy for Sustainable Development in Africa*, Janssen R. and Rutz D. (eds.), Springer, Dordrecht: 261–279.
61. Van der Zaag, P., Juizo, D., Vilanculos, A., Bolding, A., Uiterweer, N.P. (2010). Does the Limpopo River Basin have sufficient water for massive irrigation development in the plains of Mozambique? *Phys. Chem. Earth Parts A/B/C* 35 (13): 832–837.
62. Armas, E.D., de Monteiro, R.T.R., Amâncio, A.V., Correa, R.M.L., Guercio, M.A. (2005). Uso de agrotóxicos em cana-de-açúcar na bacia do Rio Corumbataí e o risco de poluição hídrica. *Química* Nova 28 (6): 975–982.

63. Meyer, J.H., Van Antwerpen, R. (2001). Soil degradation as a factor in yield decline in the South African sugar industry. *Proc. Int. Soc. Sugar Cane Technol*. 24: 8–15.
64. Trivelin, P.C.O., Franco, H.C.J., Otto, R., Ferreira, D.A., Vitti, A.C., Fortes, C., Faroni, C.E., Oliveira, E.C.A., Cantarella, H. (2013). Impact of sugarcane trash on fertilizer requirements for São Paulo. *Brazil. Sci. Agric*. 70: 345–352.
65. Mardamootoo, T., Ng Kee Kwong, K.F., Du Preez, C.C. (2010). History of phosphorus fertiliser usage and its impact on the agronomic phosphorus status of sugarcane soils in Mauritius. *Sugar Technol*. 12 (2): 91–97.
66. Lecler, N.L. Tweddle, P.B. (2010). Double profits with a controlled traffic zero-till irrigation farming system? *Proc. S. Afr. Sugarcane Technol. Assoc.* 83: 46–62.
67. De Figueiredo, E.B., Panosso, A.R., Romano, R., La Scala Jr., N. (2010). Greenhouse gas emission associated with sugar production in southern Brazil. *Carbon Balance and Management* 5: 3.
68. Woods, J., Tipper, R., Brown, G., Diaz-Chavez, R., Lovell, J., de Groot, P. (2006). Evaluating the sustainability of co-firing in the UK. DTI (ed.).
69. South African Sugar Association SASA (2014). South African Sugar Directory 2013/2014, 1-51.
70. Richardson-Ngwenya, P., Richardson, B. (2014). Aid for trade and African agriculture: the bittersweet case of Swazi sugar. *Review African Political Economy* 41 (140): 201–215.
71. Watson, H.K., Garland, G.G., Purchase, B., Dercas, N., Griffee, P., Johnson, F.X. (2008). Bioenergy for Sustainable Development and Global Competitiveness: the case of Sugar Cane in Southern Africa, T hematic Report 1-Agriculture. Cane Resources Network for Southern Africa.
72. Arbex, M.A., Pereira, L.A.A., Carvalho-Oliveira, R., do Nascimento Saldiva, P.H., Braga, A.L.F. (2014). The effect of air pollution on pneumonia-related emergency department visits in a region of extensive sugar cane plantations: a 30-month time-series study. *J. Epidemiol. Community Health* 68 (7): 669–674.
73. Ribeiro, H. (2008). Sugar cane burning in Brazil: respiratory health effects. *Revista de Saúde Pública* 42 (2): 370–376.
74. Dusfour, I., Achee, N.L., Briceno, I., King, R., Grieco, J.P. (2010). Comparative data on the insecticide resistance of *Anopheles albimanus* in relation to agricultural practices in northern Belize. *J. Pest Sci.* 83 (1): 41–46.
75. Richardson, B. (2010). Big sugar in southern Africa: rural development and the perverted potential of sugar/ethanol exports. *J. Peasant Stud.* 37 (4): 917–938.
76. Zhao, D., Li, Y. R. (2015). Climate change and sugarcane production: Potential impact and mitigation strategies. *International Journal of Agronomy*, 1-10.
77. Junaidu, M., Ngaski, A. A., Abdullahi, B. S. (2017). Prospect of Sub-Saharan African agriculture amid climate change: a review of relevant literatures. *International Journal of Sustainability Management and Information Technologies* 3(3): 20-27.
78. Singels, A., Jones, M., Marin, F., Ruane, A.C., Thorburn, P. (2014). Predicting climate change impacts on sugarcane production at sites in Australia: Brazil and South Africa using the Canegro model. *Sugar Technol*. 16(4): 347-355.
79. Marin, F. R., Ribeiro, R. V., Marchiori, P. E. R. (2014). How can crop modeling and plant physiology help to understand the plant responses to climate change? A case study with sugarcane. *Theoretical and Experimental Plant Physiology* 26(1): 49.
80. Everingham, Y. L., Inman-Bamber, N. G., Sexton, J., Stokes, C. (2015). A dual ensemble agroclimate modelling procedure to assess climate change impacts on sugarcane production in Australia. *Agricultural Sciences* 6(8): 870.
81. Stokes, C. J., Inman-Bamber, N. G., Everingham, Y. L., Sexton J. (2016). Measuring and modelling CO_2 effects on sugarcane. *Environmental Modelling and Software* 78: 68.
82. IPCC, 2014. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 151.
83. Chandiposha, M. (2013). Potential impact of climate change in sugarcane and mitigation strategies in Zimbabwe. *African Journal of Agricultural Research* 8: 2814-2818.
84. Deressa, T., Hassan, R., Poonyth, D. (2005). Measuring the impact of climate change on south African agriculture: the case of sugarcane growing regions. *Agrekon* 44(4): 524-542.
85. Da Silva, P. P., Soares, L., da Costa, J. G., et al. (2012). Path analysis for selection of drought tolerant sugarcane genotypes through physiological components. *Industrial crops and products* 37(1): 11-19.
86. De Silva, A. L. C., De Costa, W. A. J. M. (2012). Growth and radiation use efficiency of sugarcane under irrigated and rainfed conditions in Sri Lanka. *Sugar Tech*. 14(3): 247-254.
87. Zhao, D., Glaz, B., Comstock, J. C. (2014). Physiological and growth responses of sugarcane genotypes to nitrogen rate on a sand soil. *Journal of Agronomy and Crop Science* 200(4): 290-301.
88. Matthieson L. (2007). Climate change and the Australian Sugarcane Industry: impacts, adaptation and R&D opportunities. SRDC Technical Report, Sugar Research and Development, Brisbane, Australia.
89. Everingham, Y. L., Muchow, R. C., Stone, R. C., Inman-Bamber, N. G., Singels, A., Bezuidenhout, C. N. (2002). Enhanced risk management and decision-making capability across the sugarcane industry value chain based on seasonal climate forecasts. *Agricultural Systems* 74(3): 459-477.
90. Leite, J. G., Leal. M.R., Nogueira, L.A., Cortez, L.A., Dale, B.E., da Maia, R.C., Adjorlolo, C., 2016. Sugarcane: a way out of energy poverty. *Biofuels, Bioproducts and Biorefining*. 10: 393–408.
91. European Commission, 2016. Frequently Asked Questions 'The abolition of EU sugar production quotas'. https://ec.europa.eu/agriculture/sugar_en.
92. World Bank (2016). Available at http://data.worldbank.org/
93. Aro, E.-M. (2016). From first-generation biofuels to advanced solar biofuels. *Ambio* 45(1): 24-31.
94. Environmental Protection Agency of the United States (EPA) (2010). EPA reaffirms sugarcane biofuel is advanced renewable fuel with 61% less emissions than gasoline. *News*: https://www.epa.gov/renewable-fuel-standard-program.
95. Leal, M.R.L.V. (2012). Ethanol production from cane resources. In: *Bioenergy for Sustainable Development and International Competitiveness. The Role of Sugar Cane in Africa*, Johnson F. and Seebaluck V. (eds.) Routledge, New York: 126-157.

96. Thaler, K. (2013). Brazil, biofuels, and food security in Mozambique. In: *Agricultural development and food security in Africa. The impact of Chinese, Indian and Brazilian investment*s, Modi R. and Cheru F. (eds.), Zed Books, London, New York: 145-158.
97. Lynd, L. R., Sow, M., Chimphango, A. F., Cortez, L. A., Brito Cruz, C. H., Elmissiry, M., Laser, M., Mayaki, I. A., Moraes, M. M., Nogueira, L. A., Wolfaardt, G. M., Woods, J., van Zyl, W. H. (2015). Bioenergy and African transformation. *Biotechnology for Biofuels* 8: 1-18.
98. Losordo, Z., McBride, J., Rooyen, J.V., Wenger, K., Willies, D., Froehlich, A., Macedo, I., Lynd, L. (2016). Cost competitive second‐generation ethanol production from hemicellulose in a Brazilian sugarcane biorefinery. *Biofuels, Bioproducts and Biorefining* 10(5): 589-602.
99. Almedia, C. (2007). Sugarcane ethanol: Brazil's biofuel success. *SciDev.Net*, http://www.scidev.net/global/policy/feature/sugarcane-ethanol-brazils-biofuel-success.html.
100. Deepchand, K., Rao, P.M. (2012). Other co-product options from cane resources. In: *Bioenergy for Sustainable Development and International Competitiveness. The Role of Sugar Cane in Africa*, Johnson F. and Seebaluck V. (eds.) Routledge, New York: 158-180.
101. Eggleston, G., Lima, I. (2015). Sustainability issues and opportunities in the sugar and sugar-bioproduct industries. *Sustainability* 7(9): 12209-12235.
102. Tremblay, J.-F. (2015). Sustainability yields sweet success. *Chem. Eng. News* 93 (22): 18–19.
103. Barros, G.O.F., Ballen, M.A.T., Woodard, S.L., Wilken, L.R., White, S.G., Damaj M.B., Mirkov T.E., Nikolov, Z.L. (2013). Recovery of bovine lysozyme from transgenic sugarcane stalks: extraction, membrane filtration, and purification. *Bioprocess and Biosystems Engineering* 36(10): 1407-1416.
104. Henrique-Silva, F. Soares-Costa, A. (2012). Production of a His-tagged canecystatin in transgenic sugarcane. *Methods Mol Biol*. 847: 437-450.
105. Bremer, G. (1961). Problems in breeding and cytology of sugar cane. *Euphytica* 3: 59-78.
106. VIB Facts Series (2016). From plant to crop: the past, present and future of plant breeding.
107. D'Hont, A., Rao, P.S., Feldmann, P., Grivet, L., Islam-Faridi, N., Taylor, P., Glaszmann, J.C. (1995). Identification and characterization of sugarcane intergeneric hybrids, *Saccharum officinarum X Erianthus arundinaceus, with molecular marker and DNA in situ hybridization. Theor. Appl. Genet*. 91: 320-326.
108. Hoang, N. V., Furtado, A., Mason, P. J., Marquardt, A., Kasirajan, L., Thirugnanasambandam, P. P., Botha, F. C., Henry R. J. (2017). A survey of the complex transcriptome from the highly polyploid sugarcane genome using full-length isoform sequencing and de novo assembly from short read sequencing. *BMC Genomics* 18(395): 1-22.
109. Racedo, J., Gutiérrez, L., Perera, M.F., Ostengo, S., Pardo, E.M., Cuenya, M.I., Welin, B., Castagnaro, A.P. (2016). Genome-wide association mapping of quantitative traits in a breeding population of sugarcane. *BMC Plant Biology* 16: 142.
110. Hall, D., Tegstrom,C., Ingvarsson,P.K. (2010).Using association mapping to dissect the genetic basis of complex traits in plants. *Brief.Funct.Genomics* 9: 157–165.
111. Aitken, K.S., McNeil, M.D., Hermann, S., Bundock, P.C., Kilian, A., Heller-Uszynska, K., et al. (2014). A comprehensive genetic map of sugarcane that provides enhanced map coverage and integrates high-throughput diversity array technology (DArT) markers. *BMC Genomics* 15: 152.
112. Asano, T., Tsudzuki, T., Takahashi, S., Shimada, H., Kadowaki, K.I. (2004). Complete nucleotide sequence of the sugarcane (*Saccharum officinarum*) chloroplast genome: a comparative analysis of four monocot chloroplast genomes. *DNA research* 11(2): 93-99.
113. VIB Facts Series (2016). Bananas, the green gold of the South.
114. Khamrit, R., Jaisil, P., Bunnag, S. (2012). Callus induction, regeneration and transformation of sugarcane (Saccharum officinarum L.) with chitinase gene using particle bombardment. *Afr J Biotechno*l 11(24):6612–6618.
115. Joyce, P., Hermann, S., O'Connell, A., Dinh, Q., Shumbe, L., Lakshmanan, P. (2014). Field performance of transgenic sugarcane produced using agrobacterium and biolistics methods. *Plant Biotech J* 12:411–424.
116. Mayavan, S., Subramanyam, K., Jaganath, B., Sathish, D., Manickavasagam, M., Ganapathi, A. (2015). Agrobacterium-mediated in planta genetic transformation of sugarcane setts. *Plant cell reports* 34(10): 1835-1848.
117. ISAAA (2017). Brazil approves GM sugarcane for commercial use. http://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=15510. Accessed 14.06.2017.
118. VIB Facts Series (2013). Bt cotton in India – A success story for the environment and local welfare.
119. James, C. (2015). Global Status of Commercialized Biotech/GM Crops: 2015. *ISAAA Brief No*. 51. ISAAA: Ithaca, NY.
120. South Asia Biotechnology Centre (2017). Personal communication.
121. Parisi, C., Tillie, P., Rodriguez-Cerezo, E. (2016). The global pipeline of GM crops out to 2020. *Nature Biotechnology* 34(1): 31-36.
122. Rocha, F. R., Papini-Terzi, F. S., Nishiyama, M. Y., Vencio, R. Z. *et al*. (2007). Signal transduction-related responses to phytohormones and environmental challenges in sugarcane. *BMC Genomics*, 8: 71.
123. Papini-Terzi, F. S., Rocha, F. R., Vencio, R. Z., Felix, J. M. *et al*. (2009). Sugarcane genes associated with sugar content. *BMC Genomics*, 10: 120.
124. Waclawovsky, A. J., Sato, P. M., Lembke, C. G., Moore, P. H., Souza, G. M. (2010). Sugarcane for bioenergy production: an assessment of yield and regulation of sugar content. *Plant Biotechnol J* 8: 263-276.
125. Birch, R.G. (2014). Sugarcane Biotechnology: Axenic Culture, Gene Transfer, and Transgene Expression. *In Sugarcane: Physiology, Biochemistry, and Functional Biology*, Moore P.H. and Botha F.C. (eds.), Wiley Blackwell, 645-681.
126. Jung, J.H., Vermerris, W., Gallo, M., Fedenko, J.R., Erickson, J.E., Altpeter, F. (2013). RNA interference suppression of lignin biosynthesis increases fermentable sugar yields for biofuel production from field-grown sugarcane. *Plant Biotech J* 11: 709–716.
127. Bewg, W. P., Poovaiah, C., Lan, W., Ralph, J., Coleman, H. D. (2016). RNAi downregulation of three key lignin genes in sugarcane improves glucose release without reduction in sugar production. *Biotechnol Biofuels* 9(270): 1-13.
128. Poovaiah, C.R., Bewg, W.P., Lan, W., Ralph, J., Coleman, H.D. (2016). Sugarcane transgenics expressing MYB transcription factors show improved glucose release. *Biotechnology for Biofuels* 9(143): 1-18.

129. De Souza, A.P., Grandis, A., Leite, D.C., Buckeridge, M.S. (2014). Sugarcane as a bioenergy source: history, performance, and perspectives for second-generation bioethanol. *BioEnergy Research* 7(1): 24-35.
130. Phitsuwan, P., Laohakunjit, N., Kerdchoechuen, O., Kyu K. L., Ratanakhanokchai, K. (2013). Present and potential applications of cellulases in agriculture, biotechnology, and bioenergy. *Folia Microbiol* 58: 163–176.
131. Snyman, S.J., Meyer, G.M. (2012). Improvement of sugarcane in South Africa using genetic engineering: requirements for potential commercialization. *Proc. S. Afr. Sug. Technol. Ass.* 85: 96 – 101.
132. Meyer, G. M., Snyman, S. J. (2013). Progress in research on genetically modified sugarcane in South Africa and associated regulatory requirements. Proc. 2nd Genetically Modified Organisms in Horticulture Symposium, Veale M.A. (Ed.), *Acta Hort*. 974: 43-50.
133. Snyman, S. J., Hajari, E., Watt M. P. Lu, Y., Kridl, J. C. (2015). Improved nitrogen use efficiency in transgenic sugarcane: phenotypic assessment in a pot trial under low nitrogen conditions. *Plant Cell Rep*. 34:667–669.
134. African Centre for Biosafety ACB (2010). GM sugarcane: a long way from commercialisation? ACB Briefing Paper N° 15.

IPBO (International Plant Biotechnology Outreach), which forms part of the VIB, was set up in 2000 by Prof. Em. Marc Van Montagu and Ghent University. IPBO's mission is to promote knowledge and technology transfer in the area of plant biotechnology to developing countries, with a focus on a green and sustainable agriculture and agro-industry. To accomplish this mission, IPBO focuses on communication, training in plant breeding, green biotechnology and related biosafety, and fosters networking and project development to implement cooperation between developing countries and Flanders. For more information, visit: www.ipbo.vib-ugent.be

Basic research in life sciences is **VIB**'s raison d'être. VIB is an independent research institute where some 1,500 top scientists from Belgium and abroad conduct pioneering basic research. As such, they are pushing the boundaries of what we know about molecular mechanisms and how they rule living organisms such as human beings, animals, plants and microorganisms. Based on a close partnership with five Flemish universities – Ghent University, KU Leuven, University of Antwerp, Vrije Universiteit Brussel and Hasselt University – and supported by a solid funding program, VIB unites the expertise of all its collaborators and research groups in a single institute. The VIB-UGent Center for Plant Systems Biology wants to gain insight into how plants grow and respond to the environment. Scientists study how leaves and roots are formed, which micro-organisms live on and around the plant and which substances the plant makes. This knowledge can lead to sustainable innovations in agriculture and food.

After more than twenty years of uninterrupted growth, **Ghent University** is now one of the most important institutions of higher education and research in the Low Countries. Ghent University yearly attracts over 41,000 students, with a foreign student population of over 2,200 EU and non-EU citizens. Ghent University offers a broad range of study programs in all academic and scientific fields. With a view to cooperation in research and community service, numerous research groups, centers and institutes have been founded over the years. For more information, visit: www.UGent.be.

The International Industrial Biotechnology Network (**IIBN**) was established in 2010 as a joint initiative of UNIDO, the Flemish Government (EWI) and IPBO. IIBN serves as a catalyst for advancing sustainable applications of agricultural and industrial biotechnology in developing and emerging economies in cooperation with Flanders and other international partners. IIBN is being developed along three tracks: (1) engage in advocacy to raise awareness for the development potential of agricultural biotechnology by providing science-based information and case studies; (2) establish a formal network of like-minded institutions and organizations, and (3) foster R&D cooperation and capacity building in biosciences that addresses the needs of developing and emerging economies, in cooperation with stakeholders in Flanders and beyond.

The department of Economy, Science and Innovation (**EWI Department**) of the Flemish Government prepares, monitors and evaluates policy in the economy, science and innovation policy area. The aim is to develop Flanders into one of the most advanced and prosperous regions of the world. Their driving forces are the promotion of (1) excellence in scientific research, (2) an attractive and sustainable business strategy and (3) a creative, innovative and entrepreneurial society.

The United Nations Industrial Development Organization (**UNIDO)** aims to eradicate poverty through inclusive and sustainable industrial development (ISID). UNIDO advocates that ISID is the key driver for the successful integration of the economic, social and environmental dimensions, required to fully realize sustainable development for the benefit of future generations.

IPBO

Technologiepark 3, 9052 Ghent, Belgium

Tel: + 32 9 264 87 27 - ipbo@vib-ugent.be - www.ipbo.vib-ugent.be

R.E. Silvia Travella and Dulce de Oliveira (IPBO/VIB) D/2017/12.267/8