Muhammad Tahir Khan
Imtiaz Ahmed Khan *Editors*

Sugarcane Biofuels

Status, Potential, and Prospects of the Sweet Crop to Fuel the World

Springer

Sugarcane Biofuels

Muhammad Tahir Khan • Imtiaz Ahmed Khan
Editors

Sugarcane Biofuels

Status, Potential, and Prospects of the Sweet Crop to Fuel the World

Springer

Editors
Muhammad Tahir Khan
Sugarcane Biotechnology Group
Nuclear Institute of Agriculture
Tandojam, Pakistan

Imtiaz Ahmed Khan
Sugarcane Biotechnology Group
Nuclear Institute of Agriculture
Tandojam, Pakistan

ISBN 978-3-030-18596-1 ISBN 978-3-030-18597-8 (eBook)
https://doi.org/10.1007/978-3-030-18597-8

© Springer Nature Switzerland AG 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Sugarcane is the world's largest crop with respect to total production and is cultivated in a wide range of tropical and subtropical climate. It is grown in more than a hundred countries of the world, mainly as a source of sugar. Nevertheless, sugarcane has recently been endorsed as a source of biofuel and bioenergy also, as its sucrose production can be diverted to ethanol production through first-generation route and its biomass can be utilized for engendering second-generation biofuels as well as bioenergy.

Ever-increasing energy demands of the world, diminishing reserves of fossil-based fuel resources, environmental pollution, and consequential economic disquiet have induced huge interests into renewable, sustainable, and environment-friendly sources of energy, such as sugarcane. Since the success of *ProAlcool* program in Brazil, one of the major questions in sugarcane and bioenergy research has been whether the same could be replicated in other cane-growing countries as well. This is the question which intrigued us to compile this book. Sugarcane exhibits all the major characteristics of a promising bioenergy crop including high biomass yield, C4 photosynthetic system, perennial nature, and ratooning ability. Apart from Brazil, Thailand and Colombia are also significantly exploiting this energy source. However, other sugarcane producers including India, China, Pakistan, Mexico, Australia, Indonesia, and the United States could also augment the contribution of this incredible crop toward their fuel and energy sector.

This book analyzes the significance, applications, achievements, and future avenues of biofuels and bioenergy production from sugarcane in top cane-growing countries around the globe. Moreover, we also evaluate the barriers and areas of improvement for targeting efficient, sustainable, and cost-effective biofuels from sugarcane to meet the world's energy needs and combat climate change. Despite economic and environmental benefits, there are challenges both common and unique to each of the cane producers. The agroclimatic conditions, land resources, water availability, planting conditions, and capacity of the sugar industry vary from country to country. There is a considerable knowledge gap on these issues which have been analyzed in this book in order to understand the role sugarcane can play as an energy resource.

The book has been divided into three major sections. Part I summarizes various possible routes of energy extraction from cane. Part II deals with the current status and future prospects of sugarcane's role in bioenergy production in major cane-growing countries, while Part III covers the industrial and technological aspects, sustainability issues, and future avenues of energy engenderment from sugarcane. Recent developments in energy cane, transgenics and genome editing, second-generation bioethanol, and biorefinery concept have also been presented as such advances will play a preponderant role in energy independence of various countries in the future, without impacting the food security.

We are extremely thankful to all the contributors for sharing their erudition and for bearing with us during the rigorous editing and review process. We also want to thank the authors for enduring editorial suggestions to produce this venture. Moreover, we acknowledge the support received from friends and our family members to make this happen. Finally, we also wish to express our gratitude to Springer International Publishers for cooperation and feedback during the editing of this book.

Tandojam, Pakistan

Muhammad Tahir Khan
Imtiaz Ahmed Khan

Contents

Part I Sugarcane as a Bioenergy Crop

Part II Sugarcane Biofuels Production in the World

Part III Industrial and Technological Aspects of the Sugarcane Bioenergy Production Process

Part I
Sugarcane as a Bioenergy Crop

Chapter 1
Sugarcane as a Bioenergy Source

Ghulam Raza, Kazim Ali, Muhammad Aamir Hassan, Mudassar Ashraf, Muhammad Tahir Khan, and Imtiaz Ahmed Khan

1.1 World's Resources of Energy

There are two types of energy resources for the world's needs: primary and secondary. Primary sources are the main reservoirs from where the energy generates. These can be converted into secondary resources which can further be used as input for a system. Such energy resources could be renewable (consonants) and non-renewable (non-consonants) (Bokor 2016). Major types of non-renewable energy resources are coal, hydrocarbons (petroleum and natural gases), and nuclear (Fig. 1.1). Such resources have played important role to meet the world's energy requirements. Eighty-four percent of the global consumption is being fulfilled through such resources; therefore, they are depleting continuously at a rapid pace. It has been forecasted that fossil fuel reservoirs will not extend beyond half of this century given the increasing rate of their use (Carvalho-Netto et al. 2014). These sources also have various adverse effects on the environment and climate, and ultimately long-term implications on the globe. Climatic outcomes of the fossil fuels include global warming, smog, air pollution, and increase in atmospheric CO_2 (Bokor 2016).

In recent years, there has been a special research focus on exploration of alternative energy that could minimize or replace the fossil fuel usage (Waclawovsky et al. 2010). The most attractive alternate options are renewable energy resources such as solar, wind, hydropower, wave/tidal, geothermal, and bioenergy, as described in Fig. 1.1 (Bokor 2016). Among these renewable energy resources, bioenergy can be

G. Raza (✉) · M. A. Hassan · M. Ashraf
National Institute for Biotechnology and Genetic Engineering (NIBGE), Faisalabad, Pakistan

K. Ali
National Agricultural Research Center (NARC), Islamabad, Pakistan

M. T. Khan · I. A. Khan
Nuclear Institute of Agriculture (NIA), Tandojam, Pakistan

M. T. Khan, I. A. Khan (eds.), *Sugarcane Biofuels*,
https://doi.org/10.1007/978-3-030-18597-8_1

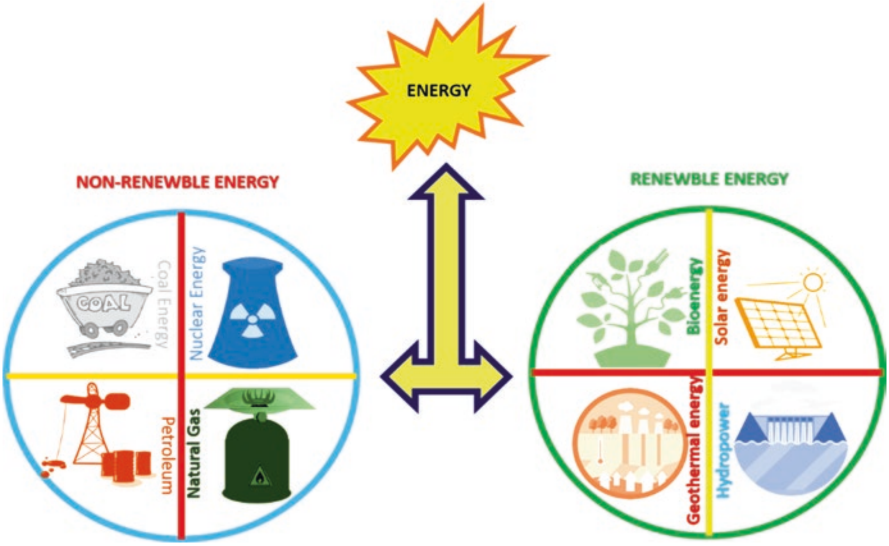

Fig. 1.1 Different sources of energy

produced from many available feedstocks to satisfy our increasing energy demands. Ample bioenergy production in a country can play significant role for secure, sustainable, and economically sound future by providing clean energy domestically, reducing oil imports, and creating jobs.

1.2 Bioenergy

Bioenergy is the energy produced from biological material (including plants, animals, and their by-products), called biomass. Bioenergy can be utilized to generate heat, electricity, and transportation fuels. In 2015, 10% of the total global energy consumption and 1.4% of global power generation were shared by bioenergy (International Renewable Energy Agency [IRENA] 2017). Globally, North America contributes maximum toward biofuel production (~50%) followed by South America and Europe, while contribution from other regions is very small. Apart from reducing dependency on fossils-based resources, utilization of bioenergy would also decrease the negative effects on environment by limiting the release of greenhouse gases (GHG). Considering socioeconomic and environmental benefits of renewable sources of energy, several countries are mandating the share of bioenergy in their national energy matrix.

Till now, many crops have been identified and others are being explored for marketable energy farming, for instance, corn, soybean, willow, and switch grass in the USA; rapeseed, wheat, sugar beet, and willow in Europe; palm oil and miscanthus in Southeast Asia; sorghum and cassava in China; and hemp in India (Cho 2018;

Davis et al. 2013). In broad spectrum, features of the most ideal bioenergy crop would be high dry matter production per unit area, small input costs, simple digestion, and low level of contaminants in the produce (McKendry 2002). Among various bioenergy options, sugarcane is one of the most efficient energy crops as it converts sunlight energy into stored chemical energy with huge efficiency. Sugarcane has C4 photosynthetic system which results in enormous biomass production per unit area (Tew and Cobill 2008; Furtado et al. 2014). It exceptionally fulfills all the basic requirements to serve as a potential energy source including excellent yields, low inputs for growth, less competition against food crops, and good processing efficiencies.

1.3 Economic Importance of Sugarcane in the World

Sugarcane is mainly a crop of tropical and subtropical regions, and it is being cultivated since pre-historic period. Being a source of 70% of world's sugar production, it is a very important cash crop for cane-growing countries. Sugarcane has a wide range of adaptability and is grown in more than 100 countries. Worldwide, it is grown on an area of 26.8 million ha, and its total production is ~1.9 billion tons with a fresh cane yield of 70.9 tons ha^{-1} (Hoang et al. 2015; FAOSTAT 2016). Gross production value of sugarcane is US$92.2 billion for the globe (FAOSTAT 2016). Sugarcane is source of a number of industrial products and by-products, which have transformed the local and international trade in many countries. Its production has played significant and dominant role in changing the economic and fiscal position of sugarcane-farming countries. From its domestication to date, sugarcane has remained an important crop and a role player for the betterment of socioeconomic status of growing regions.

1.4 Sugarcane: As an Agricultural Commodity

Sugarcane (*Saccharum officinarum* L.) is a perennial grass, classified as tribe *Andropogoneae*, family *Poaceae*, genus *Saccharum*, and species *officinarum* (Hodkinson et al. 2002). Commercial sugarcane is the cross of *Saccharum officinarum* with wild *Saccharum* spp., i.e., *S. spontaneum*, *S. robustum*, *S. barberi*, *S. sinense*, and *S. edule* (Talukdar et al. 2017). Previously commercial sugarcane was designated as *Saccharum officinarum*; however, *Saccharum* sp. hybrid has been adopted as the prioritized term to refer to commercial sugarcane (Tai and Miller 2001). Due to high pollen sterility, viable seed production is scarce, and therefore, it is grown through vegetative cuttings. Because of its vegetative mode of cultivation, sugarcane is among the plants which require great human intervention (Allsopp et al. 2000).

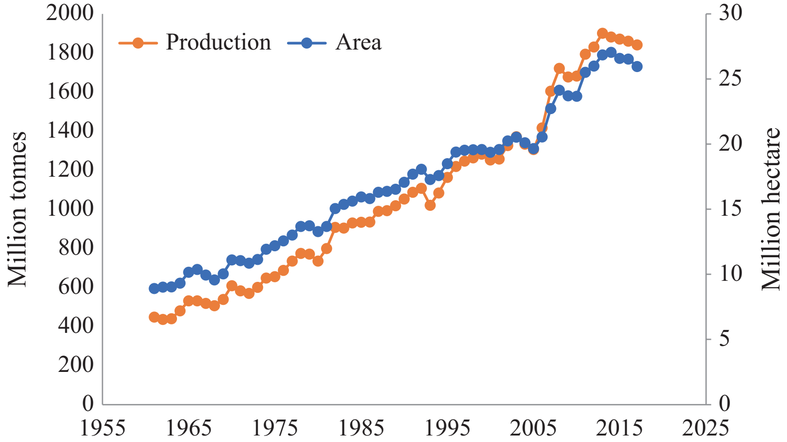

Fig. 1.2 Sugarcane area and production around the world over time (FAOSTAT 2017)

Sugarcane was identified as a cash crop in early ages of its farming (Price 1963). Being a crop of tropical region, it was mainly grown in the southern states of Americas initially and then spread to the USA (Hawaii, Louisiana, Florida, and Puerto Rico). Afterward, its production has continuously increased over time (Fig. 1.2) (FAOSTAT 2017; Ham et al. 2000; Hammond 1999; Price 1963, 1965). The primary use of sugarcane is to produce sucrose sugar; moreover, carbohydrates of sugarcane are employed as a preservative as well as bonbon agent for foods and in the manufacture of confectionary items and alcohol (Aoki et al. 2006; Wu and Birch 2007). Miller and Tai (1992) reported that more than 70% of the world's sugar demand is fulfilled through sugarcane, ranking it as the chief source of sugar supply to the world.

1.4.1 Origins and Distribution

Sugarcane is a C4 monocotyledonous plant. Cultivated sugarcane is an interspecific hybrid primarily evolved through crosses between *Saccharum officinarum* L. and *S. spontaneum* L. (Allen et al. 1997; Jeswiet 1929).

Saccharum officinarum produces high sucrose content; therefore, it is named as "noble cane." Nevertheless, it has poor attributes of tolerance against biotic and abiotic stresses. *S. officinarum* is premised as an outcome of introgression between *S. spontaneum*, *Erianthus arundinaceus*, and *Miscanthus sinensis* (Daniels and Roach 1987; Sreenivasan et al. 1987). Polynesia is contemplated to be the center of origin of *S. officinarum*. The species was later transported to Southeast Asia, Papua New Guinea, and Irian Jaya (Indonesia) in the late 1800s (Daniels and Roach 1987). Sugarcane is now grown in a wide range of altitudes covering more than 100

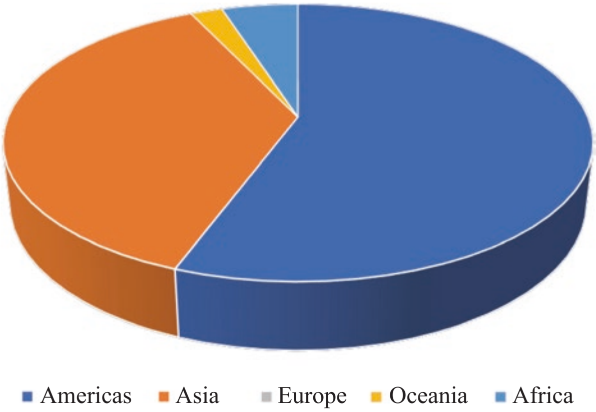

Fig. 1.3 Worldwide share of sugarcane production by different cane-growing regions (FAOSTAT 2017)

countries of tropics and temperate regions from latitude 80S to 40N (Fig. 1.3) (Daniels and Roach 1987; Tai and Miller 2001).

Sugarcane is a mainly cultivated for disaccharide sugar. Sugar production starts with juice extraction by crushing cane at the mills. The juice is then clarified at high temperature in the presence of lime [$Ca(OH)_2$], which forms complexes with phosphorus in the juice and precipitates as calcium phosphate, and allowed to settle down taking other impurities with it. Flocculants (substances added to solutions to produce woolly looking masses of particles which assist in settling down suspensions) are added to speed up this process (Mackintosh 2000).

1.4.2 Modern Commercial Hybrids

Breeding for sugarcane improvement has mainly emphasized on the sugar contents; however, now sugarcane is being recognized as an excellent source of fuel energy as well (Besse et al. 1997; Sreenivasan et al. 1987). Improvement in sucrose percentage along with maintaining tolerance against biotic and abiotic stresses has been achieved through a number of back-crosses to several different cultivars of *S. officinarum* (Bull and Glasziou 1979). Approximately 80% of the chromosomes in these commercial hybrid cultivars are derived from *S. officinarum* and 10% are from *S. spontaneum*, with remainder being chromosomes from the two species produced by the natural process of synapsis during meiosis (D'Hont et al. 1996).

D'Hont et al. (1996) and Sreenivasan et al. (1987) elaborated that for accumulation of more *S. officinarum* genome in genotypes, interspecific hybridization between *S. officinarum* and *S. spontaneum* resulted in triploid chromosome number ($2n + n = 100$ to 130). Commercial sugarcane spreads vegetatively; hence, it is highly heterozygous in nature (Kimbeng et al. 2001). Pollen sterility and uneven distribution of chromosomes during anaphase stage restrict selfing in sugarcane; therefore, pure lines do not exist (Milligan et al. 1990). Uneven chromosome pairing of sugarcane also results in aneuploidy and euploidy during chromosomal transmission (Tai and Miller 2001).

1.5 Sugarcane as a Bioenergy Crop: Advantages over Other Options

Industrial revolution of the seventeenth and eighteenth centuries resulted in escalation in petroleum prices. Consequently, high demands of fuels and the aims of curtailing petroleum usage pushed fuel industries to look for feasible substitutes including biofuels. Moreover, advances in fermentation technology and improvement in process efficiencies enhanced prospects for using crops for biofuels production.

Sugarcane, as a feedstock, has potential to become a major bioenergy source as it has highest yield per unit area among the agricultural commodities, thus offering possibility of excellent energy balance than other bioenergy options (Waclawovsky et al. 2010). As a C4 plant, sugarcane yields higher biomass than maize, miscanthus, and switch grass (Heaton et al. 2008). Its per hectare yield is also far greater than that of sugar beet, thus surpassing all other options in this context. High-yielding biofuel feedstocks are preferred as they offer less competition for the land to be used for food crops otherwise (Peskett et al. 2007).

Sugarcane and energy cane have good potential for cultivation on non-fertile agricultural lands as well (Waclawovsky et al. 2010). Furthermore, first-generation sugarcane bioethanol engenderment does not need expensive pretreatment steps, which are the major monetary barriers in case of other crops. Additionally, sugarcane already has a well-set milling industry established in many cane-growing countries of the world, most of which are developing nations—in urgent need of alternative energy sources.

Sugarcane industry is not only limited to sugar, ethanol, and bioelectricity production, but numerous other products can also be manufactured using the same feedstock hinting toward sustainability and cost-effectiveness of this industry, as biorefinery concept of sugarcane is rapidly evolving (Fig. 1.4). Moreover, the potential of sugarcane for its energy parameters has been widely unexplored yet, thus offering more likelihood of breakthroughs for any breeding program targeting the same. Even more, sugarcane feedstock can excellently deal with the food vs. fuel issues when its second-generation processing is matured, as second-generation route will be providing additional incentives in the form ethanol which won’t offer any competition against sugar engenderment (Khan et al. 2017a). Hence, sugarcane is one of the most suitable options for bioenergy production.

Fig. 1.4 Different products and by-products from sugarcane

1.6 Deriving Biofuels and Bioenergy from Sugarcane: History, Status, Approaches, and Potential

Sugarcane's fibrous stalks are rich in sucrose, which is accumulated in its internodes. Sugarcane industry and distilleries extract this sugar and subject it to fermentation to generate ethanol (Talukdar et al. 2017). Cane-derived ethanol is being used as a first-generation biofuel predominately in Brazil, where half of the total crop is used to produce ethanol (Pessoa et al., 2005). Worldwide, sugarcane is source of 21 million m^3 ethanol (Renewable Energy Policy Network for the 21st Century 2016). Average sugarcane varieties yield 85–100 kg sugar and 35–45 kg molasses (as by-product) from 1 ton of cane biomass, whereas 22–25% ethanol recovery is obtained from molasses through fermentation (Sukumaran et al. 2017). About 80% of the world's molasses is used for alcohol production through biochemical process, whereas the remaining finds applications as animal feed. Bagasse, the other major by-product of sugarcane processing, is mainly used as a source of bioelectricity and also for paper, board, and xylitol production purposes (Wolf 2012).

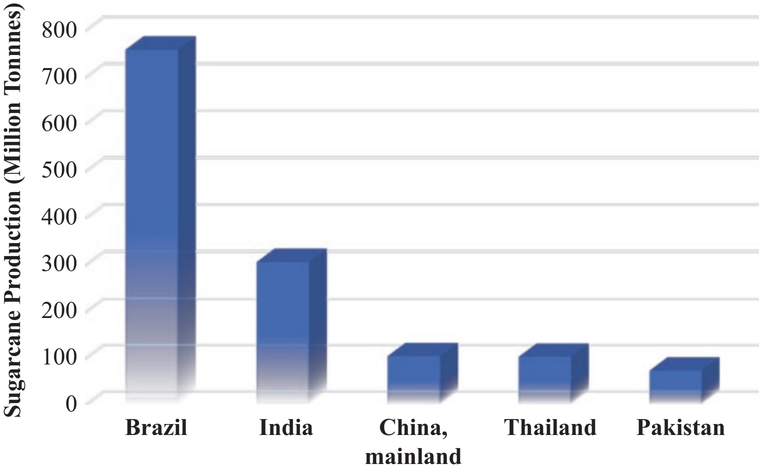

Fig. 1.5 Sugarcane production in top five cane-growing countries of the world

Sugarcane is being extensively used for biofuels production in Brazil, while the crop has significant unexplored potential for other cane-growing countries as well (Fig. 1.5). It has emerged as an excellent source of biofuels since the 1930s, when Brazil launched a policy requiring industrial-scale production of ethanol as an automobile fuel (Alagoas 2000). Brazil regularized the sugarcane production under the umbrella of the Institute of Sugar and Alcohol (Instituto do Açúcar e do Álcool). In 1973, first oil crisis drove the Brazilian administration to launch the *ProAlcool* program for realizing the possibilities of commercial and large-scale biofuel production from sugarcane. Through this program, the country launched a number of bioethanol units in existing sugarcane industry. The primary purpose was to generate ethanol for blending with gasoline in different ratios, for using as a biofuel in automobiles. In parallel, the automobile industry focused on modification of car engines, and the cars having ability to use bioethanol as fuel were introduced. After 2003, flex-fuel cars were developed in Brazil. Engines of these cars were modified to either completely replace gasoline or use a mixture of bioethanol and gasoline in any certain ratio. Presently, in Brazil, it is mandatory for gasoline business to mix at least 22% bioethanol.

Brazil also ranks at top globally in terms of efficiency of its biofuel sector. During 1980–1998, sugarcane culm yields improved from 73 to 90 tons ha^{-1} $year^{-1}$, sugar extraction efficiency increased from 90% to 96%, and fermentation output enhanced from 84% to 90.7%, whereas sugar conversion also reached 90%. During 2017–2018, Brazil produced 511 million tons of sugarcane and 26.7 billion liters of bioethanol (FAOSTAT 2016; STATISTA 2017). Xavier (2007) evaluated that ethanol produced from sugarcane accounts only 1% of the existing land in Brazil, and the current increase in sugarcane production for biofuels is not bulky enough to enlighten the shift of small farmers into deforested zones. Although efficiency of sugarcane crop and its processing industry is quite up to the mark, still, there is a gap for improvement of sugarcane productivity and industrial processing.

Sugarcane ethanol and biomass, an ample carbon-neutral renewable energy resource, offers a promising prospect as an alternative of non-renewable fuels (Lynd et al. 2008). Apart from vehicle fuels, Ragauskas et al. (2006) proposed that the combination of bioenergy crops and establishment of bioenergy industries would help in sustainable power production that may lead to a new industrial paradigm. This road map incited the launching of a number of biomass energy centers in different countries across the world.

Presently, first-generation bioethanol is being produced from sugarcane, which involves sucrose concentration and extraction from juice, followed by fermentation and distillation. This ethanol fraction corresponds to only a third of the cane energy, and the other plant residues correspond to the remaining two thirds. So, by utilizing bagasse, straw, trash, and tops, the other portion (66%) of sugarcane biomass, production of bioenergy from this crop can be enhanced. It has been predicted using simulation studies that reasonable outcomes could be achieved from sugarcane biomass for ethanol production through biochemical and/or thermochemical conversion methods (de Souza et al. 2014).

In the past, sugarcane research has been focused on the development of new sugarcane cultivars which could have high sucrose contents to generate more sugar and first-generation bioethanol. However, recently, focus has also been shifted to high-fiber/high-biomass “energy cane” varieties for the production of second-generation bioethanol (Landell and Bressiani 2008; Knoll et al. 2013). This type of cane varieties is endowed with two distinguishing agronomic traits, viz., high tillering capacity and excellent ratooning ability. Such cultivars are further classified into two types: Type I contains sugar >13% and has fiber content >17%, while Type II energy cane is exclusively developed for higher biomass and contains low sugar (<5%) and high fiber (>30%) (Tew and Cobill 2008). Energy cane also contains marginally higher lignin than the conventional type (Knoll et al. 2013). Moreover, total biomass and fiber contents of energy cane are also significantly higher, i.e., 138% and 235% more than the conventional cultivars, respectively (Matsuoka et al. 2012). Such cane type easily meets all the requirements of a renewable biomass resource (Matsuoka and Stolf 2012).

Based on sugar and fiber contents, energy cane has been grouped as a potential energy source (Matsuoka et al. 2014). Cultivation of energy cane varieties is expected to increase as the advanced methods to convert lignocellulosic biomass into bioethanol become available (Carvalho-Netto et al. 2014). Sugarcane growers may use marginal and less fertile land to produce lignocellulosic biomass by cultivating energy cane in the areas where conventional sugarcane cultivation is not feasible (Sandhu and Gilbert 2014). Recently, Matsuoka et al. (2014) reported that private breeding companies have developed both Type I and Type II energy canes in Brazil, which were proposed for expansion beyond tropical and subtropical areas due to their wide range of adaptability and tolerance to low temperature (Knoll et al. 2013; Van Antwerpen et al. 2013).

Sugarcane cell wall is the most important factor dictating the efficiency of second-generation cane biofuels production. On the basis of structure, chemical composition, and biosynthesis, the cell wall is divided into two types: (1) primary cell wall (PCW) and (2) secondary cell wall (SCW) (Carpita 1996). PCW is formed by the deposition of complex carbohydrates mainly cellulose, hemicellulose, and pectin (Cosgrove 2005). Cellulose and hemicellulose work as the bones of plants and are supported further by lignin and phenolic cross-linkages (Carpita 1996). Sugarcane SCW is made up of 50% cellulose, 25% lignin, and 25% hemicellulose (Loureiro et al. 2011). Production of second-generation bioethanol from plant biomass is not only linked with cellulose content, but also depends upon the cell wall quality. Buckeridge et al. (2010) obtained 40% increase in sugarcane-based bioethanol production by exploiting the potential energy in sugarcane cell wall. In this perspective, de Souza et al. (2014) indicated that distribution of carbon between non-structural carbohydrates (sucrose, glucose, fructose, and starch) and structural carbohydrates (cellulose, hemicelluloses, and pectin) is very important to determine an optimal balance between bioethanol-producing processes of first and second generations. The stability between structural (cell wall) and non-structural polysaccharides (typically consisting of sucrose and starch) varies among the feedstocks.

Significant variations exist in starch and sucrose contents of the cell wall among different crops and even within species and cultivars. It is an established fact that breeding for higher sucrose contents is strongly associated with the decline in cellulose content. Carbon distribution between non-structural and structural carbohydrates is generally controlled through the variations in metabolism of nucleotide sugars. However, the process involved in the completion of plant cells' fluxes between ADP and UDP-glucose is unclear (de Souza et al. 2014). The complex cell wall structure and biosynthetic processes of the cell wall polysaccharides indicate that it is not easy to take on the methods which could help in changing cell wall composition without affecting other biological systems or pathways (Pauly and Keegstra 2010). Yet, it has been discovered that sugarcane cell wall is composed of remarkably high magnitude of mixed-linkage β-glucan, which increases the possibility for improvement of sugarcane for higher bioenergy production (de Souza et al. 2013).

In 2013, detailed analysis of sugarcane cell wall was done using various techniques. Glycomic profiling was employed to determine the monosaccharide composition of sugarcane cell wall, while structural analysis of oligosaccharides was examined by hydrolysis with endo-glucanases and separation by liquid chromatography (de Souza et al. 2013). As mentioned earlier, major components of lignocellulosic substrate include cellulose (40–50%), hemicellulose (25–35%), and lignin (15–20%). Cellulose is a polymer of glucose and hemicellulose (consisting of xylose and arabinose), whereas lignin is a complex poly-aromatic compound. In sugarcane, cellulose contents of 43– 49% were found in dry biomass and energy cane varieties (Sanjuan et al. 2001; Kim and Day 2011), while in wood and forage grass, the contents are about 45% and 30%, respectively (Theander and Westerlund 1993; Smook 1992). Development of efficient cell wall digestion approaches is expected to enhance fuel and energy yields of sugarcane by manifolds.

1.7 Sugarcane Improvement for Bioenergy

There have been strenuous research efforts for genetic improvement of sugarcane (Hoang et al. 2015). In countries having mandated ethanol blends already, sugarcane crop has gained vital importance as a fuel source. However, its expansion as a bioenergy system has been slow due to less understanding of its physiological aspects of photosynthesis and intricate source-sink relationships. Two routes of fuel production are being exploited: the first one involves the conversion of sugar or molasses into ethanol, while the second one considers biomass conversion into ethanol—for ultimate blending with gasoline. It is anticipated that, in recent future, sugarcane will be extensively grown as a fuel feedstock also, rather than as a sugar crop only (de Souza et al. 2014).

To generate more ethanol per unit area of sugarcane, it is necessary to improve sugarcane varieties to produce higher sucrose and biomass. Development of elite of sugarcane varieties is an extremely arduous task when compared to other crops' breeding, mainly due to its complex genome and hindrance in viable fuzz production. Improvement of sugarcane varieties through biotechnological tools is a feasible option, but it has yielded limited success yet. Targeting bioethanol-related traits through integrated conventional and biotechnological approaches will enhance the viability and suitability of sugarcane for biofuel and bioenergy production.

There is huge unexplored potential in sugarcane regarding its energy parameters, as earlier cane-breeding efforts have only focused on sugar yields. Thus, sugarcane breeding offers greater chances of success for any breeding program prioritizing biomass instead of sugar potential since a plateau is supposed to have been reached regarding sugar parameters (Khan et al. 2017a). Energy cane varieties, recently introduced, are an example of the dramatic improvement of sugarcane for biomass production which can find applications as a source of second-generation ethanol.

1.8 Possibilities of Enhancing the Potential of Sugarcane for Biofuels and Bioenergy Production

Industrial and molecular approaches are anticipated to play substantial role in improving the process efficiencies and making the sugarcane bioenergy production process even promising. Various energy-related traits can be introduced/manipulated in sugarcane crop for the same purpose.

One of the major problems in the production of second-generation bioethanol from plant cell walls, as in sugarcane, is the presence of large amounts of pentoses in cell wall polysaccharides. With advancements in biotechnology and genetic engineering, now it has become possible to identify and discover the candidate genes which may be used successfully for developing structural and architectural changes in the cell wall. Sugarcane's cell wall engineering is one of most promising options to make the second-generation bioethanol production economical, reducing the need of expensive pretreatment steps.

In many studies, modification in cell wall properties has been successfully accomplished and evaluated in the field with encouraging results. Jung et al. (2013) reported that caffeic acid *O*-methyltransferase (*COMT*) can be lowered in transgenic sugarcane plants using RNAi, which resulted in transcript reduction by 80–91%. A total lignin content reduction of 6–12% was observed in different genetically modified sugarcane lines. The lignin reduction improved 19–23% saccharification efficiency with non-significant effect on biomass yield and other useful agronomic characters. It was also recorded that biomass from transgenic sugarcane lines having modified cell wall characteristics required almost one third of the hydrolysis time and three- to fourfold less amount of enzymes to release an equal or greater amount of fermentable sugar than the wild-type plants (Jung et al. 2013).

The enzymes involved in lignin synthesis such as Cinnamyl Alcohol Dehydrogenase (CAD) have also been manipulated to change the cell wall composition. Moreover, transgenic sugarcane lines have been seen to produce higher sucrose and fiber contents in immature internodes by down regulating pyrophosphate (fructose 6-phosphate 1-phosphotransferase) (Groenewald and Botha 2008; van der Merwe et al. 2010).

A reduction in lignocellulosic recalcitrance of biomass to carry out saccharification through modification of lignin biosynthesis is expected to greatly benefit the economic competitiveness of sugarcane as a biofuel feedstock (Jung et al. 2013; Kandel et al. 2018). However, 100% saccharification efficiency has not been achieved till date. Hence, cell wall characteristics render some constraints for the hydrolysis which need to be tackled to make the second-generation cane biofuel more cost-effective and profitable.

Moreover, for success of 2G bioethanol production, along with cell wall modulations, numerous other approaches can also be considered. Regarding industrial conversion, identification and characterization of efficient hydrolytic enzymes may speed up the conversion of sugarcane cell wall polysaccharides into fermentable sugars. The cell wall organization and the complexity of cross-linked domains do not permit cellulases alone to release all of the fermentable sugars present in the sugarcane cell wall. Ultimately, for complete digestion of cell walls, large amounts of enzymes are required. Extra proficient hydrolysis could only be attained by using efficient and improved hydrolases.

In recent past, in-planta enzymes are being targeted to introduce the cane varieties self-producing the enzymes needed for cell wall digestion. Such endogenous hydrolases are supposed to be induced at the crop maturity. In this way, the hydrolytic activity of in-planta activated enzymes will loosen the cell wall, making it vulnerable toward disassembly and release of fermentable sugars in industrial processing. Hence, developments in sugarcane research can play a huge role in its future as a bioenergy source. Through genetic manipulation and industrial improvements, sugarcane will have an even greater role to play as a promising feedstock for bioenergy engenderment.

1.9 Challenges and Future Prospects

To fulfill the increasing demands of fuel and energy, in context of growing population, depleting fossil fuel resources, and climate change mitigation, it is important to explore alternative energy resources. Biological sources can play a paramount role in satisfying the world’s energy needs; however, this must not compromise the food production—one of the major arguments against bioenergy crops. Sugarcane, being a huge biomass and sucrose producer, is an excellent bioenergy crop grown in many countries around the world. Nevertheless, using this crop only for energy production through conventional approaches will give rise to food vs. fuel issues; therefore, only wise expansion should be adopted to make the shift feasible and sustainable.

Various routes of extracting fuels and energy can be exploited in case of sugarcane. In order to deal with the sustainability and food security issues, enhancing crop production in a country and diverting only excess sucrose toward ethanol production is one solution, whereas use of only lignocellulosic materials of this huge biomass producer is the other one. Additionally, production of energy cane only on marginal barren lands also provides an answer to the question of sustainability of cane bioenergy production (Khan et al. 2017b). However, to make use of lignocellulosic biomass of sugarcane rather than molasses, pretreatment technologies need to be improved and made cost-effective. In spite of current limitations, with the advances in crop improvement and processing technology, it is anticipated that sugarcane will become an even popular and economical source of energy because of its exceptional characteristics (Yuan et al. 2008).

To date, Brazil is the only country which is utilizing the appropriate potential of sugarcane crop as a biofuel resource. There are many other sugarcane growing countries, where this crop is being solely employed for sugar production and it is not finding applications for the other use(s). Having unique industrial and agronomic advantages over any other crop energy source, sugarcane provides excellent opportunities to harvest its energy potential for meeting the fuel and energy needs of the long list of cane-growing countries.

Hence, in the future, sugarcane produce will be used as feedstock for bioenergy purposes as well in many countries of the world rather than as sugar crop only (de Souza et al. 2014). Nevertheless, apart from agronomic and industrial perspectives, such role of sugarcane would also face policy challenges, as being a multi-stakeholders’ industry, adopting any new model in a particular country would need government support through apposite policies. Suitable policies are necessary to facilitate the small-scale cane growers, launch mandatory ethanol blends, and introduce compatible car engines. Proper planning is also needed for developing sustainable cane industry having minimal economic risks and impact on food security and biodiversity.

1.10 Conclusion

Sugarcane is largest agricultural commodity with respect to total production. Its high photosynthetic efficiency, and tillering and ratooning ability make this crop extremely attractive to be used as an energy crop. Sugarcane's excess sucrose can be diverted to bioethanol production through first-generation approaches, while its bagasse, trash, and leaves can all be subjected to second-generation ethanol and bioelectricity production. Very recently, newly developed energy cane varieties are also being exploited for production of second-generation biofuel. Sugarcane has a wide range of adaptability and is being grown in a number of countries. However, its potential as an energy crop has not been explored extensively to date. Adoption of sugarcane as an energy crop can offer huge economic incentives to many of the cane-growing countries around the world and can help the world mitigate GHG emissions to combat climate change.

References

Alagoas UUSG (2000) Em 1927, o Primeiro grande empreendimento brasileiro em álcool combustivel. Boletim Enfoque 7

Allen CJ, Mackay MJ, Aylward JH, Campbell JA (1997) New technologies for sugar milling and by-product modification. In: Keating BA, Wilson JR (eds) Intensive sugarcane production: meeting the challenges beyond 2000. CAB International, Wallingford, pp 267–285

Allsopp P, Samson P, Chandler K (2000) Pest management. In: Hogarth M, Allsopp P (eds) Manual of cane growing. Bureau of Sugar Experimental Stations, Indooroopilly, pp 291–337

Aoki N, Scofield GN, Wang XD, Offler CE, Patrick JW, Furbank RT (2006) Pathway of sugar transport in germinating wheat seeds. Plant Physiol 141:1255–1263

Besse P, McIntyre CL, Berding N (1997) Characterisation of Erianthus sect Ripidium and Saccharumgermplasm (Andropogoneae-Saccharinae) using RFLP markers. Euphytica 93:283–292

Bokor L (2016) Energy resources and energetic challenges for the United Kingdom in the shadow of Brexit. Energy 4(1):854–897

Buckeridge M, Dos Santos W, De Souza A (2010) Routes for cellulosic ethanol in Brazil. In: LAB C (ed) Sugarcane bio-ethanol. R&D for productivity and sustainability. Edgard Blucher, São Paulo, pp 365–380

Bull TA, Glasziou KT (1979) Sugarcane. In: Lovett JV, Lazenby A (eds) Australian field crops. Angus and Robertson Publishers, Sydney, pp 95–113

Carpita NC (1996) Structure and biogenesis of the cell walls of grasses. Annu Rev Plant Biol 47(1):445–476

Carvalho-Netto OV, Bressiani JA, Soriano HL, Fiori CS, Santos JM, Barbosa GV, Xavier MA, Landell MG, Pereira GA (2014) The potential of the energy cane as the main biomass crop for the cellulosic industry. Chem Biol Technol Agric 1(1):20. https://doi.org/10.1186/s40538-014-0020-2

Cho R (2018) Is biomass really renewable? Earth Institute, Columbia University

Cosgrove DJ (2005) Growth of the plant cell wall. Nat Rev Mol Cell Biol 6(11):850

D'Hont A, Grivet L, Feldmann P, Rao S, Berding N, Glaszmann JC (1996) Characterisation of the double genome structure of modern sugarcane cultivars (Saccharum spp.) by molecular cytogenetics. Mol Gen Genet 250:405–413

Daniels J, Roach BT (1987) Taxonomy and evolution. In: Heinz DJ (ed) Sugarcane improvement through breading, vol 11. Elsevier, Amsterdam, pp 7–84

Davis SC, Boddey RM, Alves BJ, Cowie AL, George BH, Ogle SM, Smith P, van Noordwijk M, van Wijk MT (2013) Management swing potential for bioenergy crops. GCB Bioenergy 5(6):623–638

de Souza AP, Leite DC, Pattathil S, Hahn MG, Buckeridge MS (2013) Composition and structure of sugarcane cell wall polysaccharides: implications for second-generation bioethanol production. Bioenergy Res 6(2):564–579

de Souza AP, Grandis A, Leite DC, Buckeridge MS (2014) Sugarcane as a bioenergy source: history, performance, and perspectives for second-generation bioethanol. Bioenergy Res 7(1):24–35

FAOSTAT (2016) Crops. Food and Agriculture Organization of United Nations. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 24 Nov 2018

FAOSTAT (2017) Crops. Food and Agriculture Organization of United Nations. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 24 Nov 2018

Furtado A, Lupoi JS, Hoang NV, Healey A, Singh S, Simmons BA, Henry RJ (2014) Modifying plants for biofuel and biomaterial production. Plant Biotechnol J 12(9):1246–1258

Groenewald J-H, Botha FC (2008) Down-regulation of pyrophosphate: fructose 6-phosphate 1-phosphotransferase (PFP) activity in sugarcane enhances sucrose accumulation in immature internodes. Transgenic Res 17(1):85–92

Ham G, McGuire P, Kingston G (2000) Irrigation of sugarcane. In: Hogarth M, Allsopp P (eds) Manual of cane growing. Bureau of Sugar Experiment Stations, Indooroopilly, pp 369–377

Hammond BW (1999) *Saccharum spontaneum* (Gramineae) in Panama: the physiology and ecology of invasion. J Sust For 8(3–4):23–38. https://doi.org/10.1300/J091v08n03_03

Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of Miscanthus. Glob Chang Biol 14(9):2000–2014

Hoang NV, Furtado A, Botha FC, Simmons BA, Henry RJ (2015) Potential for genetic improvement of sugarcane as a source of biomass for biofuels. Front Bioeng Biotechnol 3:182

Hodkinson TR, Chase MW, Lledó DM, Salamin N, Renvoize SA (2002) Phylogenetics of Miscanthus, Saccharum and related genera (Saccharinae, Andropogoneae, Poaceae) based on DNA sequences from ITS nuclear ribosomal DNA and plastid trnL intron and trnL-F intergenic spacers. J Plant Res 115(5):381–392

International Renewable Energy Agency (2017) Bioenegy. http://www.irena.org/bioenergy. Accessed 24 Nov 2018

Jeswiet J (1929) The development of selection and breeding of the sugarcane in Java. Proceedings of the 3rd congress of the International Society of Sugar Cane Technologists, Soerabaia, pp 44–57

Jung JH, Vermerris W, Gallo M, Fedenko JR, Erickson JE, Altpeter F (2013) RNA interference suppression of lignin biosynthesis increases fermentable sugar yields for biofuel production from field-grown sugarcane. Plant Biotechnol J 11(6):709–716. https://doi.org/10.1111/pbi.12061

Kandel R, Yang X, Song J, Wang J (2018) Potentials, challenges, and genetic and genomic resources for sugarcane biomass improvement. Front Plant Sci 9:151. https://doi.org/10.3389/fpls.2018.00151

Khan MT, Seema N, Khan IA, Yasmine S (2017a) Applications and potential of sugarcane as an energy crop. In: Gorawala P, Mandhatri S (eds) Agricultural research updates, vol 16. Nova Science Publishers, New York, pp 1–24

Khan MT, Seema N, Khan IA, Yasmine S (2017b) The green fuels: evaluation, perspectives, and potential of sugarcane as an energy source. Environ Res J 10(4):381–396

Kim M, Day DF (2011) Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills. J Ind Microbiol Biotechnol 38(7):803–807

Kimbeng CA, McRae TA, Cox M (2001) Optimizing early generation selection in sugarcane breeding. Proc Int Soc Sugarcane Technologists 24:488–494

Knoll JE, Anderson WF, Richard EP Jr, Doran-Peterson J, Baldwin B, Hale AL, Viator RP (2013) Harvest date effects on biomass quality and ethanol yield of new energycane (Saccharum hyb.) genotypes in the Southeast USA. Biomass Bioenergy 56:147–156

Landell MA, Bressiani JA (2008) Melhoramento genético, caracterização e manejo varietal. Cana-de-açúcar Campinas. Instituto Agronômico:101–155

Loureiro ME, Barbosa MH, Lopes FJ, Silvério FO (2011) Sugarcane breeding and selection for more efficient biomass conversion in cellulosic ethanol. In: Buckeridge MS, Goldman GH (eds) Routes to cellulosic ethanol. Springer, New York, pp 199–239

Lynd LR, Laser MS, Bransby D, Dale BE, Davison B, Hamilton R, Himmel M, Keller M, McMillan JD, Sheehan J (2008) How biotech can transform biofuels. Nat Biotechnol 26(2):169

Mackintosh D (2000) Sugar milling. In: Hogarth M, Allsopp P (eds) Manual of cane growing. Bureau of Sugar Experiment Stations, Indooroopilly, pp 369–377

Matsuoka S, Stolf R (2012) Sugarcane tillering and ratooning: key factors for a profitable cropping. In: Joao FG, Kaue DC (eds) Sugarcane: production, cultivation and uses. Nova Science Publishers, New York, pp 137–157

Matsuoka S, Bressiani J, Maccheroni W, Fouto I, Santos F, Borém A (2012) Sugarcane bioenergy. In: Santos F, Borém A, Caldas C (eds) Sugarcane: bioenergy, sugar and ethanol-technology and prospects (Viçosa: Suprema) MAPA/ACS, pp 471–500

Matsuoka S, Kennedy AJ, EGDd S, Tomazela AL, Rubio LCS (2014) Energy cane: its concept, development, characteristics, and prospects. Adv Bot 2014: Article ID 597275

McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresour Technol 83(1):37–46

Miller JD, Tai PYP (1992) Use of plant introduction in sugarcane cultivar development. In: Shands HL, Weisner LE (eds) Use of plant introduction in cultivar development Part 2. Special Publication, Crop Science Society of America, Madison, pp 137–149

Milligan SB, Gravios KA, Bischoff KP, Martin FA (1990) Crop effects on broad-sense heritabilities and genetic variances of sugarcane yield components. Crop Sci 30(2):344–349

Pauly M, Keegstra K (2010) Plant cell wall polymers as precursors for biofuels. Curr Opin Plant Biol 13(3):304–311

Peskett L, Rachel S, Chris S (2007) Biofuels, agriculture and poverty reduction. Overseas Development Institute, UK Department for International Development (DfID), London. https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/3441.pdf. Accessed 30 Apr 2019

Pessoa-Jr A, Roberto IC, Menossi M, Santos RRd, Filho SO, Penna TCVJAB (2005) Perspectives on bioenergy and biotechnology in Brazil. Appl Biochem Biotechnol 121(1-3):59–70. https://doi.org/10.1385/abab:121:1-3:0059

Price S (1963) Cytogenetics of modern sugarcane. Econ Bot 17:97–106. https://doi.org/10.1007/BF02985359

Price S (1965) Cytology of *Saccharum robustum* and related sympatric species and natural hybrids. United States Department of Agriculture: Agricultural Research Service Technical Bulletin 1337:47

Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, Frederick WJ, Hallett JP, Leak DJ, Liotta CL (2006) The path forward for biofuels and biomaterials. Science 311(5760):484–489

Renewable Energy Policy Network for the 21st Century (2016) Global status report. REN21 secretariat, Paris

Sandhu H, Gilbert R (2014) Production of biofuel crops in Florida: sugarcane/energy cane. The Institute of Food and Agricultural Sciences (IFAS), University of Florida, Gainesville. http://edis.ifas.ufl.edu/pdffiles/AG/AG30300.pdf. Accessed 15 Nov 2018

Sanjuan R, Anzaldo J, Vargas J, Turrado J, Patt R (2001) Morphological and chemical composition of pith and fibers from Mexican sugarcane bagasse. Holz als Roh-und Werkstoff 59(6):447–450

Smook G (1992) Handbook for pulp and paper technologists. TAPPI Press, Peachtree Corners

Sreenivasan TV, Ahloowalia BS, Heinz DJ (1987) Cytogenetics. In: Heinz DJ (ed) Sugarcane improvement through breeding. Elsevier, Amsterdam, pp 211–253

STATISTA (2017) Fuel ethanol production worldwide in 2017, by country. https://www.statista.com/statistics/281606/ethanol-production-in-selected-countries/. Accessed 24 Nov 2018

Sukumaran RK, Mathew AK, Kumar MK, Abraham A, Chistopher M, Sankar M (2017) First-and second-generation ethanol in India: a comprehensive overview on feedstock availability, composition, and potential conversion yields. In: Chandel AK, Sukumaran RK (eds) Sustainable biofuels development in India. Springer International Publishing, Switzerland. pp 223–246

Tai PYP, Miller JD (2001) A core collection for *Saccharum spontaneum* L. from the world collection of sugarcane. Crop Sci 41:879–885

Talukdar D, Verma DK, Malik K, Mohapatra B, Yulianto R (2017) Sugarcane as a potential biofuel crop. In: Mohan C (ed) Sugarcane biotechnology: challenges and prospects. Springer International Publishing, Cham, pp 123–137. https://doi.org/10.1007/978-3-319-58946-6_9

Tew TL, Cobill RM (2008) Genetic improvement of sugarcane (Saccharum spp.) as an energy crop. In: Vermerris W (ed) Genetic improvement of bioenergy crops. Springer, New York, pp 273–294

Theander O, Westerlund E (1993) Quantitative analysis of cell wall components. In: Jung HG, Buxton DR, Hatfield RD, Ralph J (eds) Forage cell wall structure and digestibility. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, pp 83–104

Van Antwerpen R, Berry S, Van Antwerpen T, Smithers J, Joshi S, Van Der Laan M (2013) Sugarcane as an energy crop: its role in biomass economy. In: Singh BP (ed) Biofuel crop sustainability. Wiley, Hoboken, pp 53–108

van der Merwe MJ, Groenewald J-H, Stitt M, Kossmann J, Botha FC (2010) Downregulation of pyrophosphate: D-fructose-6-phosphate 1-phosphotransferase activity in sugarcane culms enhances sucrose accumulation due to elevated hexose-phosphate levels. Planta 231(3):595–608

Waclawovsky AJ, Sato PM, Lembke CG, Moore PH, Souza GM (2010) Sugarcane for bioenergy production: an assessment of yield and regulation of sucrose content. Plant Biotechnol J 8(3):263–276

Wolf D (2012) Adjusting expectations of scale based on limitations of supply: a review of the case for a forest bioenergy strategy that prioritizes decentralization, efficiency, and integration. Dissertation, University of Toronto

Wu L, Birch RG (2007) Doubled sugar content in sugarcane plants modified to produce a sucrose isomer. Plant Biotechnol J 5:109–117

Xavier MR (2007) The Brazilian sugarcane ethanol experience. Competitive Enterprise Institute, Washington, DC200714p. http://www.cei.org. Accessed 25 Apr 2019

Yuan JS, Tiller KH, Al-Ahmad H, Stewart NR, Stewart CN Jr (2008) Plants to power: bioenergy to fuel the future. Trends Plant Sci 13(8):421–429

Chapter 2
Biofuel Production from Sugarcane: Various Routes of Harvesting Energy from the Crop

**Adônis Moreira, Larissa Alexandra Cardoso Moraes,
Gisele Silva de Aquino, and Reges Heinrichs**

2.1 Introduction

Global energy supply comes mainly from fossil fuels (oil, natural gas, and coal), which contribute by more than 82% to help the world meet its energy needs (Ho et al. 2014). Fossil fuels are a polluting form of energy source in terms of greenhouse gas (GHG) emissions; 56.6% of all GHG emissions come from burning oil, natural gas, and coal (Intergovernmental Panel on Climate Change [IPCC] 2011). GHG emissions lead to anthropocentric global warming—the main contributor toward climate change (Brazilian Sugarcane Industry Association [UNICA] 2018).

Thus, growing global demand for food, energy, and water is putting pressure on the sustainability of the "planetary boundaries," necessitating actions for sustainable production across all sectors (Rockström et al. 2009). Considering that 60% of the oil use is for transportation sector (Silva 2009), the alternative and renewable fuel production became essential. Bioethanol has become an excellent option for its efficiency, energy balance, and cost, causing several countries to compete in its production and turning the world's attention to this source of energy.

Bioethanol can be produced from several types of feedstocks, which are classified into three categories: (i) sucrose-containing feedstocks, such as sugarcane (*Saccharum* spp.), beets (*Beta vulgaris*), sucrose sorghum (*Sorghum* spp.), and

---

A. Moreira (✉) · L. A. C. Moraes
Department of Plant Physiology and Soil Science, Embrapa Soja,
Londrina, Paraná State, Brazil
e-mail: adonis.moreira@embrapa.br

G. S. de Aquino
Department of Crop Science, Londrina State University, Londrina, Paraná, Brazil

R. Heinrichs
Department of Soil and Plant Nutrition, São Paulo State University,
Dracena, São Paulo State, Brazil

M. T. Khan, I. A. Khan (eds.), *Sugarcane Biofuels*,
https://doi.org/10.1007/978-3-030-18597-8_2

fruits; (ii) starch materials such as maize (*Zea mays*), sorghum (*Sorghum* spp.), wheat (*Triticum* spp.), rice (*Oryza sativa*), potato (*Solanum tuberosum*), manioc (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and barley (*Hordeum vulgare*); and (iii) lignin-cellulose materials, i.e., wood, straw, and grass (Balat 2010; Leite and Leal 2007; Solomon and Bailis 2014). Bioethanol can be developed in a sustainable way and will contribute to promoting the use of renewable sources.

For a certain production line in a mill, comparison of feedstocks includes several factors such as biomass chemical composition, availability and soil usage practices of the area, energetic balance, logistics' costs, as well as the feedstock's direct economic value (Aquino et al. 2018). Through analysis of these factors influencing bioethanol production at mills, it is noted that the feedstock availability is the main determinant since it can vary from season to season and depends largely on geographical location of the corporation (Aquino et al. 2017; Balat 2010; Fageria et al. 2013; Solomon and Bailis 2014).

Sugarcane is not only an excellent source of bioethanol from sucrose fermentation, but it also has huge biomass potential to provide lignocellulosic material for biofuel engenderment (Henrichs et al. 2017). Conversion of lignocellulosic material or biomass in to fermented sugars for bioethanol production is considered a promising alternative to increase the biofuel production in order to attend the global energy demands. Bioethanol obtained from sucrose of the sugarcane (*Saccharum officinarum* L.) is called "first-generation." Whereas, the production of lignocellulosic bioethanol from the plant cell wall is defined as "second-generation." Moreover, studies to obtain third- and fourth-generation bioethanol from other sources are also underway (Buckeridge et al. 2010; Carvalho et al. 2013).

Lignocellulosic biomass is considered as the future feedstock for bioethanol production because of its socioeconomic benefits and huge availability (Cardona et al. 2010). Apart from sugarcane, lignocellulosic biomass can be collected from various sources which include (i) harvest residues (corn straw), (ii) hardwood (alpine poplar, *Populus tremula*), (iii) conifer wood (pine tree, *Pinus* spp.), (iv) cellulose residues (recycled paper sludge, newspapers, etc.), (v) herbaceous biomass (alfalfa, *Medicago sativa*, reed stick (*Phalaris arundinacea*), etc.), and (vi) municipal solid residues (Cardona et al. 2010; Chemmés et al. 2013).

Bagasse and sugarcane straw have been the most widely used feedstocks for second-generation (2G) bioethanol. Bagasse is a leftover lignin-cellulose residue obtained after the sugarcane milling process that produces the cane broth. Sugar and bioethanol production generate huge amounts of bagasse as by-product, which then is employed for energy generation for the boilers and for the national grid. Brazil alone milled more than 635 million tons of sugarcane in the 2017/2018, generating up to 285 million tons of residues as bagasse and straw (Companhia Nacional de Abastecimento [CONAB] 2018). Around 66.6% of the total energy that can be produced by sugarcane is available as residues. These substrates can be used for cogeneration or to yield bioethanol and other products. Silva (2009) analyzed the energy contained in basic sugarcane composition and compared it against gasoline, reporting that sugarcane has great potential in terms of its energy contents (Fig. 2.1).

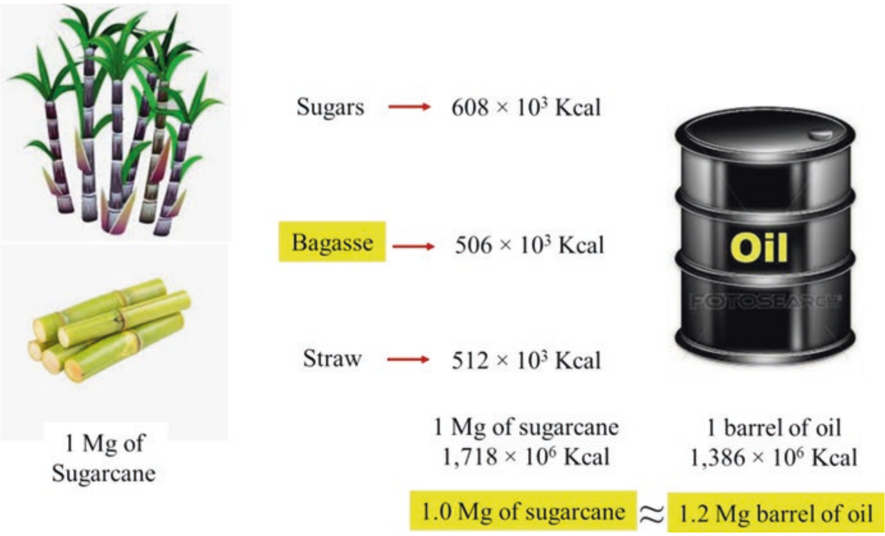

Fig. 2.1 Comparison of energy contents of sugarcane against gasoline. (Adapted from Silva 2009)

2.2 Sucrose for Bioethanol Production (First-Generation Cane Biofuels)

In order to reduce the dependence on fossil fuels and to mitigate the climate change, many countries are adopting mandatory blends of biofuels, expanding the prospects for consolidation of a global market for renewable energy sources. At the beginning of 2014, the number of countries using mandates for biofuel blending was estimated to be around 35 (Dias et al. 2015; UNICA 2018). With an increasing number of countries adopting biofuels, world is anticipated to benefit from the consequent stability in fuel bioethanol and gasoline prices, as well as environmental benefits due to reduction of greenhouse gas emissions (GGE). Moreover, such efforts are also expected to contribute toward energy security of many of the countries. These factors have already resulted in significant adoption of biofuels in Americas. Moreover, European Union's program called Directive on Renewable Energy (DRE) has also proposed that 10% of all energy consumed in the 28 countries should be from clean sources by 2020 (Dias et al. 2015; UNICA 2018).

In South America, with addition of 25% bioethanol to gasoline, Brazil is in vanguard in terms of relative consumption, being the country with the largest substitution of gasoline for bioethanol in the world. Paraguay ranks next, with 24% mixing. Chile and Argentina, more modest, add 5% of biofuel to their fossil fuel. In sum, 13 Latin countries already use or are in an advanced process to establish the biofuel blends—as is the case of Uruguay. With nine provinces using the 10% bioethanol blend, China leads the mandates on Asian continent. China also aims to increase the blend to 15% by 2020. Philippines is targeting 10%, while India and Vietnam aim mixing 5% (Table 2.1) (UNICA 2018).