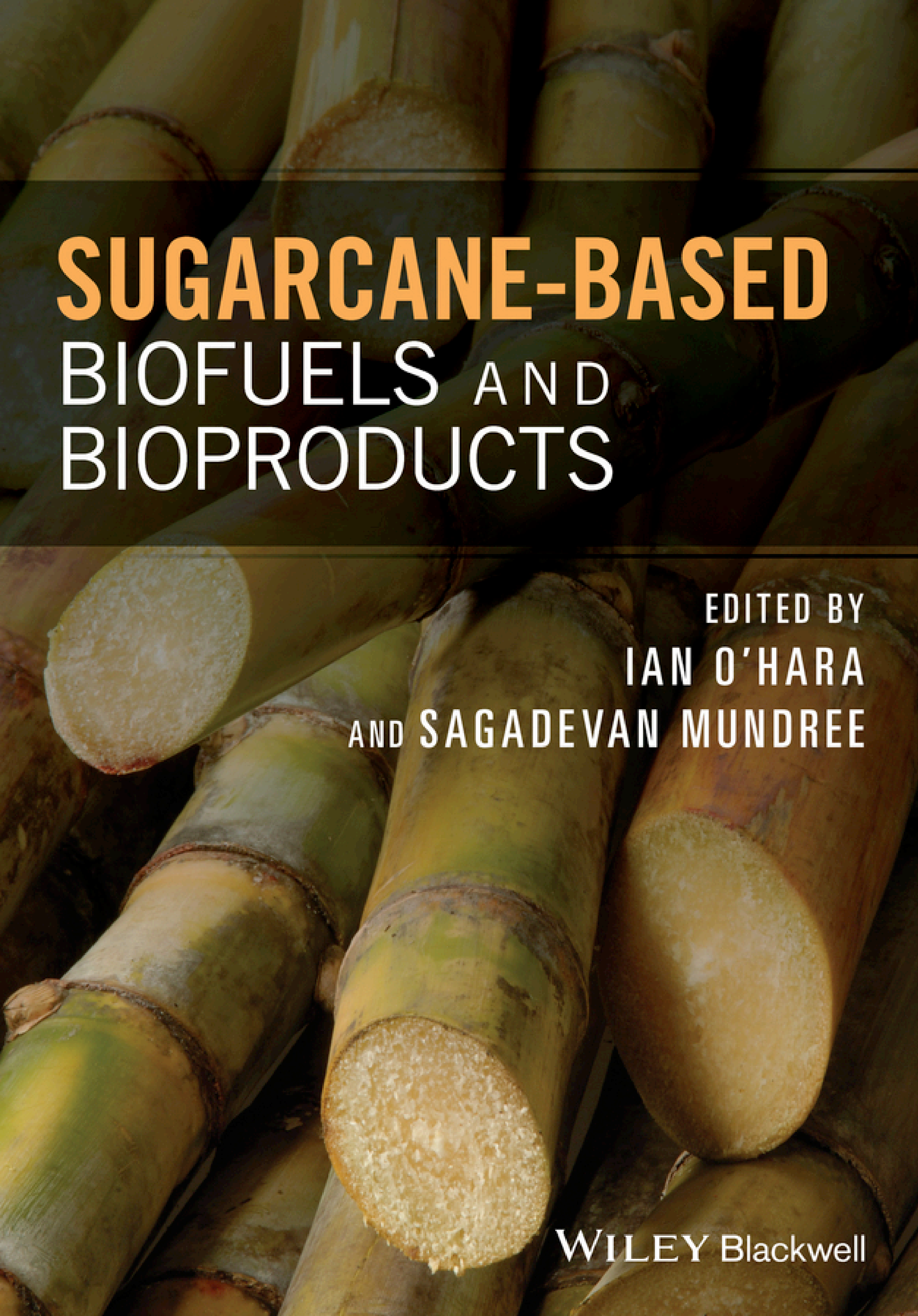

SUGARCANE-BASED BIOFUELS AND BIOPRODUCTS

EDITED BY
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AND SAGADEVAN MUNDREE

WILEY Blackwell

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Preface

As a society we are faced with significant issues. There is an urgent need to address the challenge of climate change while continuing to promote development in the world's poorest countries. From an agricultural perspective, our land, water, energy, and food systems are inextricably linked. New technologies are needed to provide sustainable energy solutions and at the same time enhance food availability and distribution.

Sugarcane is one of the world's most important agricultural crops with a long history of use for the production of food, energy, and coproducts. Growing across many countries in tropical and subtropical regions, sugarcane has a significant global footprint. The high photosynthetic efficiency and high biomass production makes sugarcane an ideal feedstock for both food production and the coproduction of non-fossil-based chemicals, polymers, and energy products.

While the opportunities for the use of sugarcane for ethanol production are well-known, there are many other potential products of similar or higher value that can be produced from the crop. Technology developments, most particularly in the fields of agricultural and industrial biotechnology, are providing new opportunities to diversify the revenue base for sugar producers. Not only does the application of this technology promote economic viability of sugarcane producers and their regional communities, it also helps to address our over-reliance on products from fossil-based resources, and hence contributes to global decarbonization activities. These economic, social, and environmental benefits, however, will only be achieved where technologies are adopted in an appropriate manner.

This book provides a comprehensive overview of current and future opportunities for the production of biofuels and bioproducts from sugarcane. The first section of the book (Chapters 1 and 2) provides an overview of the sugarcane industry and presents the opportunities and challenges in this area. This section also examines the sugarcane crop biotechnology and the opportunities that this field presents in enhancing opportunities for the production of bioproducts. The second section of the book (Chapters 3–12) provides detailed overviews of the current state-of-the-art relating to a variety of biofuel and bioproduct opportunities from sugarcane. These opportunities include more traditional products such as ethanol production, pulp and paper, animal feed products and cogeneration to future opportunities such as the production of fermentable sugars from bagasse and their subsequent conversion into specialty chemical products. The final section of the book addresses aspects relating to sugarcane biofuel and bioproduct sustainability, techno-economics, and whole-of-system process integration.

The editors are very grateful to the many authors who contributed to this book. All of the authors are recognized as leading experts in their fields and provide unique perspectives as a result of their many decades of experience in sugar, biofuels, and bioproducts research. Without their contributions, this book would not have been possible and we appreciate their insights and highly value the contributions that they have made.

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9 July 2015
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PART I

Sugarcane for biofuels and bioproducts

CHAPTER 1

The sugarcane industry, biofuel, and bioproduct perspectives

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1.1 Sugarcane – a global bioindustrial crop

Sugar (or more specifically sucrose) is one of the major food carbohydrate energy sources in the world. It is used as a sweetener, preservative, and colorant in baked and processed foods and beverages and is one of lowest cost energy sources for human metabolism.

On an industrial scale, sucrose is produced from two major crops – sugarcane, grown in tropical and subtropical regions of the world, and sugar beet, grown in more temperate climates. Sugarcane, however, accounts for the vast majority of global sugar production.

For much of the history of sugarcane production, sugar was a scarce and highly valued commodity. Sugarcane processing focused on extracting sucrose as efficiently as possible for the lucrative markets in the United Kingdom and Europe. The potential for the production of alternative products from sugarcane, however, has long been recognized. The key process by-products including bagasse, molasses, mud, and ash have all been investigated as a basis for the production of alternative products (Rao 1997, Taupier and Bugallo 2000).

Sugarcane is believed to have originated in southern Asia, and migrated in several waves following trade routes through the Pacific to Oceania and Hawaii and through India into Europe. Sugarcane was introduced and spread through the Americas following the expansion by British, Spanish, and Portuguese colonies in the 15th and 16th centuries (Barnes 1964).

While various methods of juice extraction and sugar production have been used over centuries to produce sugar, substantial innovations in sugar chemistry and processing technologies throughout the 18th and 19th centuries have formed the basis of modern sugar production methods (Bruhns *et al.* 1998). Dramatic improvements in processing efficiency, sugar quality, and automation and control characterized sugar processing throughout the 20th century.

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While the production of alcoholic liquors from sugarcane juice and molasses has been known since ancient times, the production of rum has been associated with industrial sugar production since the introduction of sugarcane to the Caribbean in the 17th century. More recently, further coproducts started being produced including paper products, cardboard, compressed fiber board, and furfural from bagasse; ethanol, butanol, acetone, and acetates from molasses; and cane wax extracted from filter mud (Barnes 1964).

Perhaps the most significant development in sugarcane coproducts, however, occurred in 1975 when the Brazilian Government established the National Alcohol Program (the ProÁlcool program) in response to high oil prices and increasing costs of oil imports to Brazil. This program established a large domestic demand for ethanol, which resulted in the rapid expansion of the sugarcane industry in Brazil, enhancing technical capability, increasing the scale of factories, and lowering production costs of sugar and ethanol (Bajay *et al.* 2002).

The impact on global sugar and ethanol markets of ProÁlcool was profound, and this impact is still being felt today with Brazil being the undisputed global powerhouse of sugarcane production. The ProÁlcool program demonstrated the viability of sugarcane as a truly industrial crop, not just for food markets but also as a large-scale feedstock for the coproduction of energy products in integrated factories.

The period of the 1980s and 1990s saw sustained periods of low world sugar prices, in part the result of lower crude oil prices and increased Brazilian sugar exports, and increasing electricity prices in many countries. These factors focused the attention of the sugar industry on diversification opportunities and, in particular, the utilization of the surplus energy from bagasse to produce electricity for export into electrical distribution networks.

The past two decades have seen the emergence into the public consciousness of global challenges of climate change and increasing crude oil prices. Both these factors have enhanced human desires to find more renewable feedstocks for fuels, chemicals, and other products currently manufactured from fossil-based resources leading to direct consumer demand for more sustainable consumer products.

At the same time, human achievements and growth in our understanding of biotechnology have resulted in a suite of new tools that allow us to more readily convert renewable feedstocks into everyday products.

Sugarcane is widely acknowledged to be one of the best feedstocks for early-stage and large-scale commercialization of biomass into biofuels and bioproducts. As such, the sugarcane industry, with its abundant agricultural resource, is poised to benefit as a key participant in the growth of biofuel and bioproduct industries throughout the 21st century.

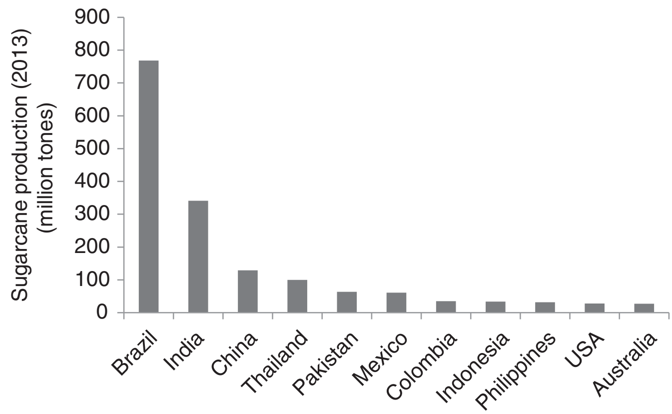

Figure 1.1 Leading sugarcane-producing countries (FAO 2015).

1.2 The global sugarcane industry

In 2013, more than 1.9 billion tons of sugarcane was grown globally at an average yield of 70.9 t/ha dominated by production in Brazil and India. Sugar beet production in 2013 was 247 million tons at an average yield of 56.4 t/ha (FAO 2015). The leading sugarcane-producing countries are shown in Figure 1.1.

Sugarcane is the largest agricultural crop by volume globally and the fifth largest by value with a production value in 2012 of US$103.5 billion (FAO 2015).

The principal use of sugarcane throughout the world is for crystal sugar production for human consumption. In several countries, including Brazil, a sizable portion of the crop is also used for ethanol production from both sugarcane juice and molasses. Many other countries produce lesser quantities of ethanol from sugarcane juice or molasses.

Over the past decade, global sugarcane production has increased by 35%, driven by a doubling in sugarcane production in Brazil (FAO 2015). This increased sugarcane production has resulted in both increased crystal sugar production and increased ethanol production, and has had a significant impact on the world price of raw sugar. Land-use change enabling this global expansion of sugarcane production has both direct and indirect sustainability implications, and the factors relating to these implications are diverse and complex (Martinelli and Filoso 2008, Sparovek *et al.* 2009, Martinelli *et al.* 2010).

1.2.1 Sugarcane

Sugarcane is a C4 monocotyledonous perennial grass grown in tropical and subtropical regions of the world. Modern sugarcane varieties are complex hybrids derived through intensive selective breeding between the species *Saccharum officinarum* and *Saccharum spontaneum* (Cox *et al.* 2000).

Globally, the 1.9 billion tons of sugarcane produced annually is grown on about 26.9 million hectares (FAO 2015) in tropical and subtropical regions. Modern sugarcane varieties are capable of producing more than 55 t/ha/y of biomass (dry weight). The development of high biomass sugarcane (often referred to as energy cane) has the potential to significantly increase the amount of biomass available.

1.2.2 Sugarcane harvesting and transport

Sugarcane harvesting and transport practices vary around the world, principally depending upon the degree of mechanization of the process. Sugarcane may be burnt before harvesting or cut in a green state without burning. The burning of sugarcane is becoming less prevalent with the introduction and enforcement of environmental air quality guidelines and this is increasing the amount of sugarcane leaf material available for coproducts.

In some countries, hand cutting of sugarcane is still widely practiced, although this has been completely replaced by mechanical harvesting in many countries. The transition to mechanized harvesting has often been driven by the difficulty in attracting labor to the very physically demanding work of hand cutting. This transition has not been without significant challenges in ensuring the delivery of both the optimum sugarcane weight and a quality product low in dirt, leaves, and low-sucrose sugarcane tops, which are collectively referred to as extraneous matter.

Traditional sugarcane-harvesting processes cut the stalk around ground level and discard tops and leaf materials. Only the clean stalk (either as a whole stalk or cut into billets) is transported into the factory for the extraction of the juice and production of sugar. Tops and leaf material separated in harvesting (trash) are generally left in the field to decompose, acting as mulch and providing organic matter and nutrient for the soil, or raked and burnt depending upon farming practices.

Some proportion of this leaf material is of value in the agricultural system, improving the soil condition. The remainder of this extraneous matter is potentially available as a feedstock for biomass value-adding processes such as bioethanol production. The impacts of harvesting and transporting extraneous matter on the sugar milling process, and the economics of the industry, are complex and integrated modeling approaches have been developed to analyze these effects (Thorburn *et al.* 2006).

Transport of sugarcane to the factory in a timely manner is important to ensure that little sucrose is lost through degradation processes. Not only is this a requirement to ensure maximum recovery of the sugar product, but a significant presence of one of the key degradation products, dextran, has a major impact on sugar quality. Minimizing the formation of this polysaccharide is crucial to efficient sugar production.

In order to maximize the availability of biomass for cogeneration or coproducts production, some movement has been made toward whole-of-crop harvesting. In this harvesting approach, the entire crop including the field trash may be collected and transported to the mill. Ideally, this trash is separated before processing, as there are significant efficiency, sugar recovery, and sugar quality challenges associated with processing sugarcane trash in a conventional sugar factory.

1.2.3 The raw sugar production process

Sugarcane is processed in factories generally located close to sugarcane farming areas to minimize the cost of sugarcane transportation. The factories are constructed to crush the sugarcane to extract the juice and produce non-food-grade raw sugar as the primary product. Raw sugar from these factories is generally transported to sugar refineries where the sugar is further decolorized and purified to produce the high-quality white "refined" sugar that is used as table sugar and in industrial sugar applications.

Sugarcane factories do not typically operate year round, but only during the period in which sugarcane harvesting is done. This period, which varies throughout the world from around 5 to 9 months, is largely determined by climate and economic factors associated with the period of peak sugar content of the sugarcane.

In the raw sugar production process (Figure 1.2), sugarcane is first shredded to produce a fibrous material and the sugarcane juice extracted from the fiber through a process of milling and/or diffusion. Water is used to assist in washing the sugar from the fiber. The fibrous residue of this process is known as bagasse, and this bagasse is burnt in suspension in bagasse-fired water tube boilers to produce steam. The steam is used to provide energy to drive mill machinery, to produce electricity in turbo-alternators, and to provide heat for the process. The quantity of ash residue from the combustion process, known as boiler ash, varies depending upon the incoming dirt levels of the sugarcane.

The sugarcane juice is heated, limed, and clarified to separate the dirt and other insoluble impurities from the juice. The clean juice, generally known as clarified juice (CJ) or evaporator supply juice (ESJ), is fed into multiple effect vacuum evaporators where the juice is concentrated to around 65–70 brix to produce a concentrated syrup. The syrup is then passed to the panstage where the sugar crystallization occurs in a series of product and recovery sugar strikes.

High-grade (product) sugar from the panstage is centrifuged to produce sugar crystals of the target polarization and the molasses from these centrifugals is recycled to the panstage for further processing. The wet sugar from the centrifugals is passed to the sugar drier that dries the sugar to the target moisture specification, and this product is shipped to a refinery for further decolorization and impurity removal.

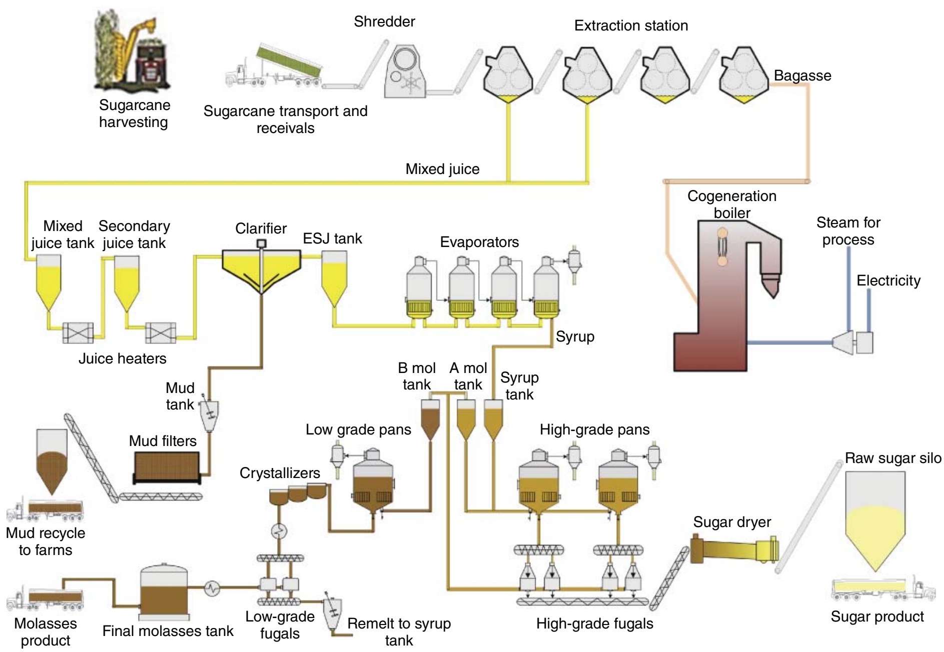

Figure 1.2 Typical schematic of the raw sugar production process.

Low-grade massecuite from the panstage is further processed to recover as much of the remaining sugar as possible from the molasses. This involves a process of cooling crystallization of the low-grade massecuite, followed by centrifugation to separate the recovered sugar from the final molasses. The quantity of final molasses produced depends on the quantity and types of impurities present in the sugarcane but is generally around 3–5% (w/w) of the sugarcane processed.

1.2.4 The refined sugar production process

The process for the conversion of raw sugar to refined sugar (Figure 1.3) is principally designed to achieve decolorization to a desired product specification. A series of processes are used to remove impurities while maximizing the yield of refined sugar. Several processing options exist and the number of decolorization stages required is determined by the purity and color of the initial sugar and the required color standard of the refined sugar product.

In the typical refined sugar process, raw sugar is initially processed through an affination station in which the raw sugar is mixed with affination centrifugal syrup (known as raw wash) and centrifuged to remove impurities contained in the highly colored molasses layer surrounding the sugar crystal. After the affination station, the affined sugar is remelted using water and steam to create melt liquor.

The melt liquor is processed through a primary decolorization stage using either a carbonatation process or a phosphatation clarification process. In carbonatation, the melt liquor is limed to a high pH, and carbon dioxide is bubbled through the liquor in a carbonatation column. The resultant calcium carbonate precipitate that is formed in this process removes impurities, and this precipitate is then filtered from the clarified liquor. In the phosphatation process, the melt liquor undergoes a clarification process with the addition of lime and phosphoric acid. In this case, the calcium phosphate complex adsorbs impurities, and the precipitate is skimmed off the surface of a flotation clarifier.

The clarified liquor then enters the second major decolorization process, and again there are several process options. These options include the use of activated carbon or ion-exchange resins to adsorb impurities from the clarified liquor. Both processes are highly effective at color removal from clarified liquor and the processes generate fine liquor suitable for crystallization.

The final stage of the refinery process is crystallization of the fine liquor to produce refined sugar massecuite, which is then centrifuged to separate the refined sugar crystals from the refined molasses. Several refined sugar strikes can be boiled and the number of product strikes is determined by the color specification of the product sugar. The refined sugar is dried and packaged for transport to retail and industrial customers.

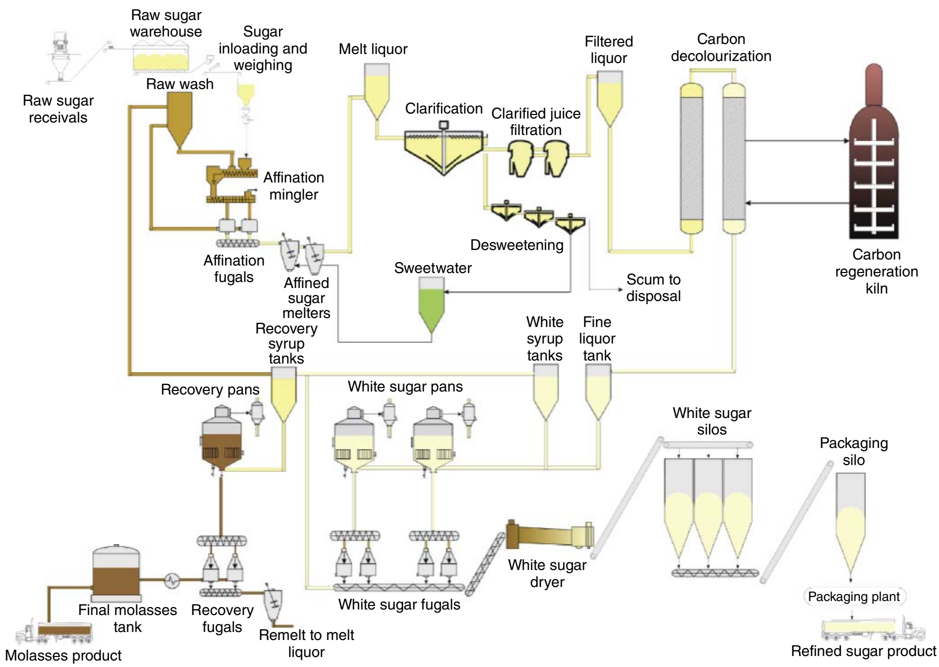

Figure 1.3 Schematic of a typical refined sugar production process showing phosphatation clarification and ion exchange resin decolorization processes.