Sugar (sucrose, C$_{12}$H$_{22}$O$_{11}$) is a disaccharide of glucose and fructose, manufactured from either sugarcane (Saccharum spp.) or sugar beet (Beta vulgaris). In 2005-06, the world sugar production was 152.08 million tons (ISMA, 2007). The manufacturing process is believed to have originated in India in 3000 BC (Hunsigi, 2001); subsequently, the Persians developed the chemical process for solidifying and refining sugar in the sixth or seventh century (Mitchell, 2004). Sugar was introduced into Europe from the Caribbean islands in the early sixteenth century and was considered a precious commodity. Subsequently, the sugar industry began developing in various European colonies such as Java and America, and sugar was exported to Europe. The high demand coupled with the high cost of shipment led to the development of the sugar beet based industry in Europe. Presently, around three quarters of the world sugar production is from sugarcane. The use of sugar beet is mainly confined to Europe, Japan and the U.S.A., whereas the industry in countries such as Brazil, India, Thailand, Australia and South Africa depends mainly on sugarcane.

Sugar is marketed primarily as raw sugar, refined (or white) sugar and plantation white (or mill white) sugar. In western hemisphere countries such as Brazil, U.S.A. and Canada, sugar mills manufacture raw sugar that is then refined in separate refineries. In contrast, countries like Indonesia, Taiwan and South Africa mainly produce plantation white sugar. Brazil and India are the world's major sugar producers accounting for nearly one-third of the total production (FAS, 2006). There are over 400 sugar mills in India, most of which are concentrated in the states of Uttar Pradesh and Maharashtra (Figure 1.1). These mills predominantly manufacture plantation white sugar. The total production for 2006-2007 was 25 million tons (Indian Sugar, 2007).

In general, cane sugar manufacture involves four major steps viz. juice extraction, clarification, concentration and crystallization (Figure 1.2). Freshly extracted sugarcane juice is dark-green in color, acidic (pH 4.7-5.6) and turbid. The juice clarification process, designed to remove both soluble and insoluble non-sugar impurities universally employs lime and heat as the clarifying agent. Boiling the limed juice coagulates the non-sugar impurities and also captures the suspended solids and fine particles. The precipitate (“mud”) is separated from
the clear juice by sedimentation and is subsequently subjected to vacuum filtration to extract the entrapped juice.

Clarified juice is typically brownish in colour, is at neutral pH and contains lower amounts of non-sugar constituents like waxes, gums and suspended solids. This is concentrated in multiple effect evaporators to produce syrup with over 60% solids content. The syrup is further treated with phosphoric acid and lime, and aerated with the addition of flocculent. The treated syrup is then subjected to crystallization to obtain sucrose crystals that are washed, dried and packaged.
The raw sugar so produced varies in colour from light yellow to deep mahogany red. It typically has small grain size and irregular crystal shape and is subsequently processed in a sugar refinery. The key steps in refining are as follows.

- **Affination:** This involves washing the raw sugar to remove the molasses layer adhering to the sugar crystal, followed by dissolving the washed raw sugar in water to produce affination syrup.

- **Clarification:** The affination syrup is clarified either by pressure filtration or chemical defecation. The latter is the preferred option and involves either...
phosphatation using phosphoric acid and lime as the clarifying agent, or carbonation involving addition of lime followed by bubbling carbon dioxide.

- **Decolorization:** This consists of adsorption of colorants using adsorbents like bone char, activated carbon or resins.

- **Crystallization:** The decolorized syrup is evaporated and then crystallized to yield refined sugar.

In plantation white sugar manufacture, direct consumption white sugar is produced by sulfitation or carbonation of limed juice in the clarification step. This is followed by additional syrup clarification with sulfur dioxide prior to crystallization. A comparison of the standard properties of raw, refined (white) and plantation white cane sugar is presented in Table 1.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Raw sugar</th>
<th>Plantation white sugar</th>
<th>White sugar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color (ICUMSA units)</td>
<td>NA</td>
<td>≤150</td>
<td>≤60</td>
</tr>
<tr>
<td>Sulfur dioxide (ppm)</td>
<td>≤20</td>
<td>≤70</td>
<td>≤15</td>
</tr>
<tr>
<td>Conductivity ash (%m/m)</td>
<td>NA</td>
<td>≤0.1</td>
<td>≤0.04</td>
</tr>
<tr>
<td>Polarization value (°Z)</td>
<td>NA</td>
<td>≥99.5</td>
<td>≥99.7</td>
</tr>
</tbody>
</table>

The quality of refined sugar is the best in terms of low color and higher sucrose content and purity; however, refining is a multi-step process and is energy intensive. Plantation white sugar manufacture is relatively simpler in terms of the fewer steps involved but is limited by the inferior product quality in terms of higher color and higher sulfur dioxide content (up to 70 ppm).

Since India mainly produces double sulfitation sugar, its export potential is restricted due to the undesirable sulfur dioxide content. Though sulfitation is used for bleaching the juice, color removal is temporary and color reverts back with time. Thus the quality declines during storage. Further, bulk consumers of sugar like soft drink manufacturers require low sulfur content (Coca-Cola Specifications) (Chou, 1993). Moreover, almost 70% of the world trade takes place in raw sugar and the balance is almost completely white sugar (Jain,
Because of the huge stocks, India is seeking to diversify its production so that the product is suited for export (Godshall, 2004). In this context, there are two options available to Indian sugar factories:

- Follow the conventional raw sugar-refining route or
- Develop an alternative approach for the direct production of refined quality sugar.

Pressure-driven membrane systems like microfiltration (MF) and ultrafiltration (UF) have replaced the conventional clarification/purification process in various applications (Daufin et al., 2001). The resulting benefits include reduced processing time and product loss thereby improving yield, product quality and minimizing waste generation. Since the late 80s, MF / UF for clarification of wine, beer, vinegar as well as various fruit juices like apple, pear etc. have been commercially established (Van der Horst and Hanemaaijer, 1990; Jönsson and Trägårdh, 1990).

Membrane filtration of sugarcane juice was initiated in the early 70s (Madsen, 1973). In the last decade, several laboratory and field trials have been conducted and it has been demonstrated that sugarcane juice can be effectively clarified/purified by MF/UF (Willet, 1997; Saska et al., 1999; Balakrishnan et al., 2000). Figure 1.3 depicts the key steps of the two conventional manufacturing schemes and a modified process employing UF. Incorporating an UF step in the sugar manufacturing process leads to the following advantages.

- Compared to conventional clarification, UF results in better non-sugars removal. This increases the juice purity and reduces the sucrose loss in molasses; moreover, lower boiling times and higher crystal growth rates are obtained (Chou et al., 2002). These combined benefits result in superior product quality, higher yield and overall increase in mill capacity.
- Juice UF results in lower calcium content in the permeate (Ghosh et al., 2000). This contributes to controlling the scaling in the evaporators thereby reducing the cleaning frequency and duration.
- Refined grade sugar can be produced directly from ultrafiltered juice (Chou et al., 2002). Compared to refining, UF is less energy intensive; thus
membrane filtration can add to the process economy without compromising the product quality.

In spite of these advantages, application of UF using polymeric membranes for sugarcane juice clarification is seriously limited because of membrane fouling. Fouling is a vital design and operational concern since it can significantly alter the flux and separation characteristics leading to deterioration in performance and shortening of membrane life. This translates into larger membrane area requirement as well as more frequent cleaning and membrane replacement ultimately resulting in loss of productivity and unfavorable process economics. Consequently, there is a need to understand and mitigate membrane fouling in sugarcane juice UF for the process to become economically viable. So far, there has been no attempt to systematically characterize the key juice components causing polymeric membrane fouling and thus develop a possible strategy to minimize their impact.
Figure 1.3 Comparison of sugar manufacturing processes