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*Review*

# A review on bioethanol production from sweet sorghum

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**The consumption of bioethanol as biofule may reduce greenhouse gases, gasoline imports. Also it can be replaced with lead or MTBE (Methyl tert-butyl ether) that are air and underground water pollutants, respectively. Plants are the best choice for meeting the projected bioethanol demands. For this scope, a comparative analysis of the technological options using different feedstocks should be performed. Our research and other studies indicate that sweet sorghum can be used as a feedstock for ethanol production under hot and dry climatic conditions. Because, it has higher tolerance to salt and drought comparing to sugarcane and corn that are currently used for biofuel production in the world. In addition, high carbohydrates content of sweet sorghum stalk are similar to sugarcane but its water and fertilizer requirements are much lower than sugarcane. Also, sugarcane is not a salt tolerant plant. On the other hand, high fermentable sugar content in sweet sorghum stalk makes it to be more suitable for fermentation to ethanol. Therefore, it is suggested to plant sweet sorghum for biofule production in hot and dry countries to solve problems such as increasing the octane of gasoline and to reduce greenhouse gases and gasoline imports.**

**Key words:** Sweet sorghum, carbohydrate, bioethanol, biofuel.

## INTRODUCTION

Each year, fossil energy resource is reducing in the world. Therefore, a substitute should be found. There are many crops available for producing energy such as sweet sorghum which not only produce food (Anglani, 1998 ), but also energy (Reddy et al., 2005), feed (Almodares et al., 1999; Fazaeli et al., 2006) and fiber (Murray et al., 2008a,b). Sorghum can be classified as sweet, grain and forage types (Almodares et al., 2008b). Sweet sorghum like grain sorghum produces grain 3 - 7 t/ha (Almodares and Mostafafi, 2006). But the essence of sweet sorghum is not from its seed, but from its stalk, which contains high sugar content (Almodares et al., 2008c). In general, it can produce stalk 54 - 69 t/ha (Table 1) (Almodares et al., 2008c).

The sugar content in the juice of sweet sorghum varies in different varieties (Almodares et al., 1994a). The Brix range in different varieties of sweet sorghum is 14.32 - 22.85% (Table 2) (Almodares and Sepahi, 1996).

Besides having rapid growth, high sugar accumulation (Almodares and Sepahi, 1996), and biomass production potential (Almodares et al., 1994a), sweet sorghum has wider adaptability (Reddy et al., 2005). Also it is well adapted to sub-tropical and temperate regions of the world and it is water efficient. Sweet sorghum has many good characteristics such as a drought resistance (Tesso et al., 2005), waterlodging tolerance, salinity resistance (Almodares et al., 2007a; Almodares et al., 2008) and with a high yield of biomass etc.

In addition, sweet sorghum is a C4 crop with high photosynthetic efficiency. Thus development of sweet sorghum will play an important role in promoting the development of agricultural production, livestock husbandry (Fazaeli et al., 2006), energy sources (biofule) (Nahvi et al., 1994a, b), refining sugar, paper making etc. Carbohydrates, which are present in sweet sorghum, can be nonstructural such as sugars and starch, or structural such as cellulose, hemicellulose, and pectic substances (Anglani, 1998). The chief sugars present in sorghum kernels are the monosaccharides glucose and fructose,

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**Table 1.** Comparison of sugarcane, sugar beet and sweet sorghum in Iran.

| | **Sugarcane** | **Sugar beet** | **Sweet sorghum** |
|---|---|---|---|
| Crop duration | About 7 months | About 5 - 6 months | About 4 months. |
| Growing season | Only one season | Only one season | One season in temperate and two or three seasons in tropical area. |
| Soil requirement | Grows well in drain soil | Grows well in sandy loam; also tolerates alkalinity | All types of drained soil. |
| Water management | 36000 $m^3$/h | 18000 $m^3$/h | 12000 $m^3$/h |
| Crop management | Requires good management | Greater fertilizer requirement; requires moderate management | Little fertilizer required; less pest and disease complex; easy management. |
| Yield per ha | 70 - 80 tons | 30 - 40 tons | 54 - 69 tons. |
| Sugar content on weight basis | 10 - 12% | 15 - 18% | 7 - 12%. |
| Sugar yield | 7 - 8 tons/ha | 5 - 6 tons/ha | 6 - 8 tons/ha. |
| Ethanol production directly from juice | 3000 - 5000 L/ha | 5000 - 6000 L/ha | 3000 L/ha. |
| Harvesting | Mechanical harvested | Very simple; normally manual | Very simple; both manual and through mechanical harvested. |

the disaccharides sucrose and maltose and the trisaccharide raffinose. According to the kind of sugar in the stalk, it can be divided into saccharin- type sweet sorghum and syrup-type sweet sorghum (Anglani, 1998). Saccharin-type sweet sorghum, which mainly contains sucrose, can be used for refining crystal sugar. Syrup-type sweet sorghum, which mainly contains glucose, can be used for producing syrup. Sugars content in sweet sorghum stalk juice mostly were sucrose and invert sugars which invert sugars are included glucose, fructose, maltose and xylose (Almodares et al., 2008c). Also, they reported that mannose, galactose and arabinose were not detected in sweet sorghum juice. Therefore, it seems that using carbohydrates in the stalk (sucrose and invert sugar) is suitable for ethanol production for biofuel because these carbohydrates are easily converted to ethanol. Although, ethanol can be produced from sweet sorghum grain (Figure 1) but it needs more process for converting it's starch to glucose that later will be converted to ethanol (Jacques et al., 1999).

In addition, the produced baggas after juice extraction can be used for ethanol production (Jacques et al., 1999) or animal feed (Jafarinia et al., 2005). However, presently it is not economically feasible to produce ethanol from sweet sorghum baggas (Drapcho et al., 2008). The aim of this review is to summarize the information available on sorghum carbohydrates for biofule production.

## Sweet sorghum agronomy

Sweet sorghum cultivation and practices are simple and readily adoptable (Almodares et al., 1997b). It is a short – day plant (Almodares et al., 2000; Rezaie et al., 2005), and most varieties require fairly high temperature (Reisi and Almodares, 2008) to make their best growth. The cereals (Tesso et al., 2005) and tolerate a wide range of soil conditions (Almodares et al., 2008e). Sorghum tolerates compacted subsoil and can stand high press wheel pressure at planting. It tolerates a pH range of 5.0 to 8.5 (Smith and Frederiksen, 2000) and some degree of salinity (Almodares et al., 2007a, 2008a, 2008c, 2008), alkalinity and poor drainage (Almodares et al., 2008e). It also will grow on heavy, deep cracking vertisols and light sands (Smith and Frederiksen, 2000). The seed of sweet sorghum should be planted deep enough to give it moisture to germinate and allow its roots to grow down through moist soil into subsoil moisture, ahead of the drying front (Almodares et al., 2008e).

Planting time (Almodares and Mostafafi, 2006) usually start when the air temperature is above 12°C (Almodares et al., 2008e). Late planting reduces the length of the growing season, yield and carbohydrate content (Almodares et al., 1994a). Also, it may cause late and troublesome harvest and may expose the crop to pests and diseases and other hazards which are dominant at the end of the crop season (Almodares et al., 2008e). Balanced fertilization can increase yield (Rego et al., 2003). Nitrogen fertilizer and its application time (Almodares et al., 1996) promotes sucrose content and growth rate in sweet sorghum (Tsialtas and Maslaris, 2005). Application of adequate amounts of K fertilizer increase yield responses than increasing levels of nitrogen fertilizer alone (Pholsen and Sornsungnoen, 2004; Almodares and Mostafafi, 2006; Almodares et al., 2006; Almodares et al., 2008d; Fazaeli et al., 2006) Sweet sorghum is harvested

**Table 2.** Mean comparisons among 36 sweet sorghum cultivars, lines and hybrids regarding stem yield, Brix, Sucrose and purity at university of Isfahan, Iran (Almodares and Sepahi, 1996).

| Genotypes | Stem Yield ($t\ ha^{-1}$) | Brix (%) | Sucrose (%) | Purity (%) |
|---|---|---|---|---|
| **Cultivars** | | | | |
| Roce | 39.14 | 21.96 | 14.39 | 66.71 |
| Vespa | 84.53 | 20.99 | 13.05 | 74.59 |
| Brandes | 77.14 | 18.72 | 8.92 | 46.39 |
| MN1500 | 83.71 | 20.71 | 12.00 | 57.59 |
| E36-1 | 48.00 | 18.26 | 13.41 | 76.02 |
| Soave | 61.57 | 20.73 | 13.46 | 65.00 |
| M81-E | 103.57 | 16.01 | 10.26 | 65.10 |
| Sumac | 44.43 | 21.12 | 12.85 | 60.10 |
| Sofrah | 85.57 | 19.63 | 12.61 | 64.05 |
| SSV-108 | 62.85 | 22.25 | 13.97 | 62.26 |
| SSV-94 | 70.14 | 20.64 | 11.75 | 57.12 |
| SSV-96 | 62.00 | 22.54 | 13.71 | 60.10 |
| Theis | 100.14 | 19.10 | 7.26 | 37.59 |
| Foralco | 97.71 | 20.40 | 12.64 | 60.83 |
| Rio | 95.00 | 22.36 | 16.06 | 71.31 |
| S-35 | 58.43 | 19.78 | 11.58 | 58.75 |
| Turno | 39.86 | 11.16 | 6.00 | 35.86 |
| Satiro | 27.86 | 17.16 | 10.33 | 60.02 |
| Wary | 126.42 | 15.84 | 7.85 | 49.40 |
| **Lines** | | | | |
| IS 686 | 61.43 | 16.54 | 9.00 | 54.39 |
| IS 16054 | 51.85 | 21.07 | 11.73 | 55.83 |
| IS 18154 | 42.14 | 19.04 | 12.71 | 66.71 |
| IS 6962 | 43.00 | 23.01 | 13.61 | 58.85 |
| IS 9639 | 54.00 | 21.77 | 14.31 | 65.23 |
| IS 2325 | 59.57 | 20.70 | 14.28 | 60.18 |
| IS 6973 | 33.43 | 22.85 | 14.21 | 61.88 |
| IS 4546 | 56.43 | 22.03 | 13.05 | 60.12 |
| IS 19273 | 46.28 | 20.29 | 15.04 | 73.69 |
| IS 4354 | 33.86 | 17.66 | 9.80 | 55.28 |
| **Hybrids** | | | | |
| A1 x IS 6973 | 83.28 | 16.46 | 9.53 | 57.17 |
| A13 x IS 1273 | 97.00 | 21.18 | 14.26 | 66.78 |
| A1 x IS 19261 | 88.13 | 18.69 | 11.82 | 63.04 |
| A1 x IS 14446 | 87.13 | 16.51 | 10.51 | 62.89 |
| A45 x IS 14446 | 124.13 | 17.95 | 13.36 | 74.06 |
| A1 x IS 19273 | 128.85 | 17.82 | 13.00 | 73.51 |
| A13 x IS 14446 | 113.56 | 14.32 | 10.73 | 74.40 |

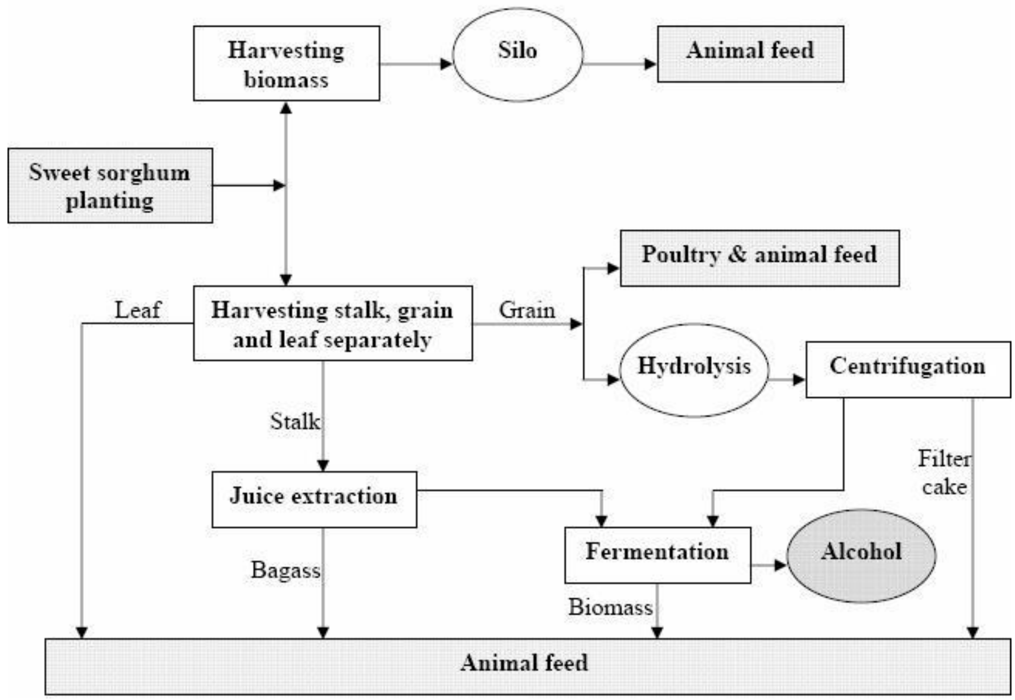


**Figure 1.** Proposed layout for ethanol production and by-product from sweet sorghum.

at milk stage (Ranjbar and Almodares, 2002; Almodares et al., 2007b). Experiment crop can with-stand periods of drought better than mostpotential for sweet sorghum production can be increased through selection and development of adapted cultivars (Almodares and Sepahi, 1996). The aim of agronomy in sweet sorghum is to increase productivity with focus on biofuel and improved feedstock supply duration as follows.

i) Water and fertilizer (macro- and micronutrients) effects and their interaction on sugar, grain and bagasse yield and quality.
ii) Effect of day length, temperature and their interaction, on sugar, grain and bagasse yield and quality (and help identify suitable cultivars for season/location).
iii) Crop rotation experiments to identify the most productive and sustainable cropping systems for different ecosystems.

## Sorghum carbohydrate

The chief nonstructural carbohydrate in grain (Somani et al., 1995) of sweet sorghum is starch while sucrose is the main carbohydrate content in the stalk which is dominant form transported in the plant. Subramanian et al. (1994) have reported that cultivars with white or pale yellow seeds are most suitable for starch production. Both alpha and beta amylases (Reisi and Almodares, 2008) are sugars (Beta et al., 1995). The primary sugars present in grain of sweet sorghum are fructose, glucose, raffinose, sucrose and maltose. In sorghum leaves, sucrose is translocated and transformed into starch during the development of grains (Smith and Frederiksen, 2000).

Grain plus stem of sweet sorghum has been shown to yield more fermentable carbohydrates than other fuel crops (Murray et al., 2008b).

In addition, the grain can be used for production of high fructose syrup (Hosseini et al., 2003) and animal feed (Ebadi et al., 1997; Azarfa et al., 1998) . Therefore, sorghum is an excellent crop for biomass production. The high nonstructural carbohydrate content of its vegetative biomass can be fermented to methane or ethanol (Reddy et al., 2005). Ethanol production by fermentation of sugar solutions obtained from sweet sorghum varies widely among years at different locations, fertility (Almodares et al., 2006, 2008d), moisture, planting/harvest dates (Almodares et al., 1997a; Almodares and Mostafafi, 2006), preclude a strict linear association between number of frost free days (Almodares et al., 2007b). In stems the extent of sucrose accumulation varies among cultivars (Table 2) (Almodares and Sepahi, 1996; Almodares et al., 1997a).

Sorghum nonstructural carbohydrates contents are affected by temperature, time of day (Almodares et al., 2000), maturity (Almodares et al., 1994b), cultivar (Almodares and Sepahi, 1996), culm section, spacing and fertilization (Almodares et al., 2008d). Shading significantly reduces panicle and leaf laminae dry weights of sorghum (Kiniry et al., 1992). Environmental conditions such as water quality (Almodares and Sharif, 2005, 2007) and also growth stage (Almodares et al., 2007c) and maturity is a factor a affecting carbohydrate content (Almodares et al., 1994b). In the sweet sorghum, sucrose, glucose and fructose contents increase after anthesis (Almodares et al., 2008c). In stems, non-structural carbohydrates contents increase after preboot (Almodares et al., 2008c) and reach a maximum level near post anthesis (Almodares et al., 2008c).

Senescence and nonsenescence affect levels of sugar accumulation in the culm of sorghum cultivars (Vietor et al., 1990). The nonsenescent cultivars contain more carbohydrates at all maturity stages than the senescent cultivars. They reported that harvested senescent and nonsenescent sorghum hybrids at three stages of maturity: grain filling, black layer and post-black layer. Plants were shown to be physiologically mature when the black layer formed in the pedicel of kernels at the panicle base. McBee and Miller (1990) reported that closer spacing significantly increased total carbohydrates at the anthesis stage. Sugar production of sweet sorghum was compared with sugarcane and sugar beet and the results showed that sugar production from sweet sorghum is cheaper than both sugar cane and sugar beet (Blas et al., 2000). Therefore, it can be used as a supplementary sugar crop (Kualarni et al., 1995). So, it seems that through cultural prac-tices, breeding and physiological manipulation can increased the carbohydrate contents in sweet sorghum plants and because of sweet sorghum has high amount of sucrose, glucose and fructose which is easily conver-ted to ethanol by microorganism of *Saccharomyces cerevisiae*. Thus, sweet sorghum is a suitable plant for biofuel production.

## The important of ethanol in biofule

One method to reduce air pollution is to oxygenated fuel for vehicles. MTBE (Methyl tert-butyl ether) is a member of a group of chemicals commonly known as fuel oxygenates (Fischer et al., 2005). It is a fuel additive to raise the octane number. But it is very soluble in water and it is a possible human carcinogenic (Belpoggi et al., 1995). Thereby, it should be substituted for other oxygenated substances to increase the octane number of the fuel. Presently, ethanol as an oxygenous biomass fuel is considered as a predominant alternative to MTBE for its biodegradable, low toxicity, persistence and regenerative characteristic (Cassada et al., 2000). The United States gasoline supply is an ethanol blend and the importance of ethanol use is expected to increase as more health issues are related to air quality. Ethanol may be produced from many high energy crops such as sweet sorghum (Figures 1 and 2), corn, wheat, barely, sugar cane, sugar beet, cassava, sweet potato and etc (Drapcho et al., 2008). Like most biofuel crops, sweet sorghum has the potential to reduce carbon emissions. In addition, among the plants, sweet sorghum has the following characteristics (Almodares et al., 2008e):

i) It is an efficient converter of solar energy, as it requires low inputs and yet, a high carbohydrate producer.
ii) As a drought-tolerant crop with multiple uses.
iii) It has a concentration of sugar which normally varies between 12 - 21%, directly fermentable (that is, no starch to convert).
iv) It can be cultivated in temperate, subtropical and tropical climates.
v) All components of the plant have economic value - the grain from sweet sorghum can be used as food or feed, the leaves for forage, the stalk (along with the grain) for fuel, the fiber (cellulose) either as mulch or animal feed and with second generation technologies even for fuel.
vi) Its bagasse, after sugar extraction, has a higher biological value than the bagasse from sugarcane, when used as feed for animals.
vii) Its growing period is shorter (3 - 5 months) than that of sugarcane (10 - 12 months), and the quantity of water required is 1/3 of sugarcane.
viii) In tropical irrigated areas sweet sorghum can be harvested twice each year (by ratooning) and its production can be completely mechanized.
ix) It has some tolerance to salinity.
x) It can produce large quantities of both readily fermentable carbohydrate and fiber per unit land area.

Therefore, based on the above characteristics, it seems that sweet sorghum is the most suitable plant for biofuel production than other crops under hot and dry climatic conditions. In addition, possible use of bagasse as a by-product of sweet sorghum include: burning to provide heat energy, paper or fiber board manufacturing, silage for animal feed or fiber for ethanol production. However, since sweet sorghum is at a relatively early stage of its development, continued research was needed to obtain better genetic material and match local agro-economic conditions. The challenge is to harvest the crop, separate it into juice and fiber and utilize each constituent for year-round production of ethanol.

Sweet sorghum juice is assumed to be converted to ethanol at 85% theoretical, or 54.4 L ethanol per 100 kg fresh stalk yield. Potential ethanol yield from the fiber is more difficult to predict (Rains et al., 1993). The emerging enzymatic hydrolysis technology has not been proven on a commercial scale (Taherzadeh and Karimi, 2008) . One ton of corn grain produces 387 L of 182 proof alcohol while the same amount of sorghum grain produces 372 L (Smith and Frederiksen, 2000). Sorghum is used extensively for alcohol production (Kundiyana, 1996; Bulawayo et al., 1996; Smith and Frederiksen, 2000; Gnansounou et al., 2005), where it

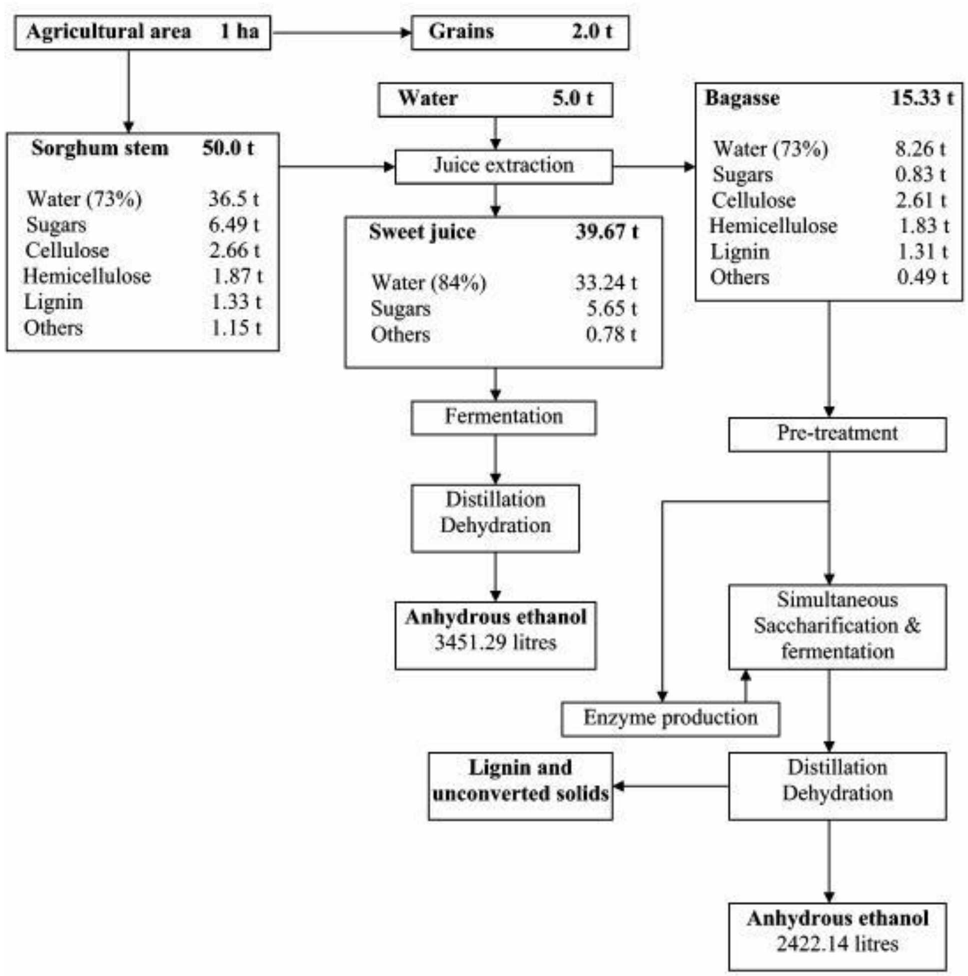


**Figure 2.** Mass balance of sweet sorghum juice extraction and ethanol production (Prasad et al., 2007).

is significantly lower in price than corn or wheat (Smith and Frederiksen, 2000). The commercial technology required to ferment sweet sorghum biomass into alcohol has been reported in china (Gnansounou et al., 2005). One ton of sweet sorghum stalks has the potential to yield 74 L of 200- proof alcohol (Smith and Frederiksen, 2000). Therefore, it seems that because ethanol can be produced from both stalk and grain of sweet sorghum (Figure 1), so it is the most suitable crop for ethanol production using for biofuel comparing to other crops such as corn or sugarcane.

## Sweet sorghum stalk processing for ethanol production

### Juice extraction

Juice is extracted by series of mills (Almodares et al., 2008e). The juice coming out of milling section is first screened, sterilized by heating up to 100°C and then clarified (Quintero et al., 2008). The muddy juice is then sent to rotary vacuum filter and the filtrate juice is sent to evaporation section for concentration (syrup to ethanol). The juice can also be directly sent to fermentation section (Figure 1) (juice to ethanol). Depending on the scheme selected the juice can be concentrated using evaporators to attend various brix. In case of juice to ethanol (no syrup), it is advisable to partially increase the concentration of juice to 16 - 18 brix. The syrup which needs storage for using during off season needs to concentrate to minimum 65 brix (normally 85 brix).

### Fermentation

Fermentation is a multidisciplinary process based on the chemistry, biochemistry and microbiology of the raw materials. Juice or syrup is converted into ethanol by the yeast *Saccharomyces cerevisiae*. Sugar is converted to ethanol, carbon dioxide and yeast biomass as well as much smaller quantities of minor end products such as glycerol, fusel oils, aldehydes and ketones

(Jacques et al., 1999).

## Distillation and dehydration

In the distillation section, alcohol from fermented mash is concentrated up to 95% v/v. This is further concentrated to produce ethanol with 99.6% v/v (minimum) concentration. The treatment of vinasse generated in the distillation section can be done using following option:

Concentration of part of vinasse to 20 to 25% solids followed by composting using press mud available and concentration of rest of the vinasse to 55% solids and use as liquid fertilizer.

Since Iran has dry and hot climatic conditions (Almodares, 2000) therefore sweet sorghum has emerged as a leading candidate for liquid sugar (Almodares and Sepahi, 1997) and biofuel production (Nahvi et al., 1994a) with minimum inputs (Almodares and Sepahi, 1997).

## Processing ethanol production from sweet sorghum grain

The ethanol production processing from sweet sorghum grain (Figure 1) is similar to corn and it can be described according to Quintero et al. (2008). After washing, crushing and milling the sweet sorghum grains, the starchy material is gelatinized, liquefied and saccharified using -amylase and glucoamylase enzymes to produce glucose. Fermentation, distillation and dehydration processing of grain sorghum are similar to the sweet sorghum stalk. However, the by-products of grain is not similar to the stalk because DDGS (dried distillers grains with solubles) as a co-product of the ethanol production process from grain is a high nutrient feed valued which is used by the livestock industry.

## Conclusion

It is clear that fuel ethanol from sweet sorghum is the best choice to be implement under hot and dry climatic conditions regarding both economic and environmental considerations. Because, sweet sorghum has higher tolerance to drought (Tesso et al., 2005), water logging and salt (Almodares et al., 2008, 2008a), alkali and aluminum soils; It may be harvested 3 - 4 months after planting (Table 1) and planted 1 - 2 times a year (in tropical areas); Its energy output / fossil energy input is higher than sugarcane, sugar beet, corn, wheat and etc… specially in temperate areas; It is more water use efficient (1/3 of water used by sugarcane at equal sugar production); Its production can be completely mechanized and Its bagasse has higher nutritional value than the bagasse from sugarcane, when used for animal feeding.

Also, by implementing agricultural practices such as adequate water and fertilizers, suitable cultivars or hybrids, crop rotation, pest management and etc… can increase productivity with focus on biofuel production (Reddy et al., 2005). In addition, sweet sorghum has high amount of sucrose (Almodares and Sepahi, 1996) and invert sugar (Almodares et al., 2008c) which are easily converted to ethanol (Jacques et al., 1999; Prasad et al., 2007). Therefore, it seems that sweet sorghum is the most suitable crop for biofuel production in arid regions of the world. This awareness should push government of the countries with such climatic conditions to promote the development of projects for fuel ethanol production from sweet sorghum.

However, social aspects (including environmental concerns) should play a more significant role in the selection of the most suitable feedstocks for the alcohol industry. In this way, financial indicators would not be necessarily the decisive factors when new large-impact projects for biofuels production are studied and implemented in developing countries.

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