Chapter 12

Utilizing co-products of the sweet sorghum-based biofuel industry as livestock feed in decentralized systems

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ABSTRACT

Sweet sorghum-based decentralized crushing and syrup-making units are a major component of sweet sorghum value chains in India. Apart from the main product, syrup, there are several co-products, including grain, bagasse, vinasse, steam, foam and froth. This chapter looks at the state of the art in utilization of these products in livestock feed, as well as exploring emerging opportunities. If the policy framework of the country supports decentralized models, this co-products utilization not only improves economic viability but also has environmental benefits by way of reduced greenhouse gas (GHG) emissions, which are yet to be quantified.

INTRODUCTION TO THE SWEET SORGHUM VALUE CHAIN

Renewable energies are critical contributors to the energy supply portfolio as they contribute to global energy security, reduce dependency on fossil fuels and provide opportunities for reducing emissions of greenhouse gases (GHG), and are expected to play major roles in energy strategies of nations to mitigate adverse global climatic change (Reddy *et al*., 2008; Srinivasa Rao *et al*., 2009). The price volatility of global crude oil is more unprecedented and unpredictable than ever before, as seen during the last decade. Hence many policy-makers consider renewable indigenous sources of energy, like biofuels, would be a viable option for energy security. Since biofuels can be produced from diverse crops, each country is adopting a strategy that exploits the comparative advantages it holds with respect to such crops. For example, sugar cane and maize are the main feedstocks for ethanol in Brazil and US respectively, while rapeseed in Europe and palm oil in Malaysia are the main feedstocks for biodiesel. In India, sugar cane, sweet sorghum and tropical sugarbeet are the major bio-ethanol feedstocks, while biodiesel is produced on a limited scale from *Jatropha* (Srinivasa Rao *et al*., 2010). More than 95 percent of the bio-ethanol in India is produced from molasses, a co-product of the sugar industry, by over 1500 distilleries spread across the country (Aradhey, 2010). As sugarbeet is being grown only on an experimental scale in India the co-products are not available to explore, while *Jatropha* oilcake contains toxins and antinutrient factors such as phorbol esters, trypsin inhibitors, lectins and phytates, and hence is not suitable for animal feed (Reddy *et al*., 2008). However, the detoxified *Jatropha* cake, i.e. *Jatropha* meal, can be used as feed. There are currently two models of operation in sweet sorghum value chains, namely a Centralized model and a Decentralized model. This chapter primarily discusses the co-products of sweet sorghum in a decentralized model of the sweet sorghum value chain.

SWEET SORGHUM AS BIO-ETHANOL FEEDSTOCK

Sorghum (*Sorghum bicolor* (L) Moench) is one of the most important food, feed and fodder crops in arid and semi-arid regions of the world. Globally, it was cultivated on about 39.96 million hectares in 2009, with Africa and India accounting for about 80 percent of the global acreage (FAOSTAT data). Although sorghum is best known as a dual-purpose grain and fodder crop, the sweet-stalked sorghums, referred to as sweet sorghums, are similar to the grain sorghums, but possess sweet juice in their stalk tissues, and are traditionally used as livestock fodder due to their ability to form excellent silage; the stalk juice is extracted and fermented and distilled to produce ethanol (Table 1). Thereafter the juice, grain and bagasse (the fibrous residue that remains after juice extraction) can be used to produce food, fodder, ethanol and cogeneration. The ability of sweet sorghum to adapt to drought; to saline and alkaline soils; and to waterlogging has been proven by its wide prevalence in various regions of the world. The

MAIN MESSAGES

- **Sweet sorghum is a climate change-ready crop owing to its resource use efficiency and wide adaptability, in addition to apart biotic and abiotic stress tolerance.**
- **In poor soils with limited inputs, sweet sorghum-based agro-enterprises offer both food for humans and fodder (bagasse) for their livestock, forming a resilient mixed crop-livestock system.**
- **The sweet sorghum value chain offers immense opportunities to the marginal farmers of the semi-arid tropics as sweet sorghum offers food, feed, fodder and fuel.**
- **The centralized and decentralized systems complement each other, and benefits percolate down to the associated farming communities.**
- **The socio-economic, environmental and ecological benefits from sweet sorghum production and processing can be large, and need to be quantified from a systems perspective.**
- **To benefit from all the above on a large scale in farmers' fields, well structured, sustained, supportive policies and R&D programmes with inclusive market-oriented approaches are required at both national and international levels.**

TABLE 1
Favourable traits of sweet sorghum cultivation as biofuel feedstock compared with popular biofuel feedstocks such as sugar cane, maize and sugarbeet

As crop	As ethanol source	As Bagasse	As raw material for industrial products
• Short duration (3–4 months) • C_4 dryland crop • Good tolerance of biotic and abiotic constraints • Meets fodder and food needs • Non-invasive species • Low soil N_2O and CO_2 emission • Seed propagated	• Amenable to eco-friendly processing • Less sulphur in ethanol • High octane rating • Automobile friendly (up to 25% of ethanol-petrol mixture without engine modification)	• High biological value • Rich in micronutrients • Use as feed, for power co-generation or bio-compost • Good for silage making	• Cost-effective source of pulp for paper making • Dry ice, acetic acid, fusel oil and methane can be produced from the co-products of fermentation • Butanol, lactic acid, acetic acid and beverages can be manufactured.

Notes: For further details see Srinivasa Rao *et al*., 2009). N_2O = nitrous oxide; CO_2 = carbon dioxide.
Sources: Reddy *et al*., 2005; Srinivasa Rao *et al*., 2009, 2010.

per-day ethanol productivity of sweet sorghum is higher than sugar cane (Srinivasa Rao *et al*., 2010, 2011), as well as having a shorter growing period (four months) and a low water requirement of 8000 m^3/ha (over two crops annually) that is only 25 percent of that required for sugar cane, which has a 12–16-month growing season and needs 36 000 m^3 water/ha. It translates to sugar cane needing 900 m^3 water for producing 1 tonne of dry matter (DM) while sorghum requires only 200 m^3 water, based on productivity of sugar cane at 40 t/ha and sorghum at 20 t/ha.

Sweet sorghum's lower cost of cultivation compared with sugar cane and sugarbeet, and farmer familiarity with cultivation of sorghum, aid in greater adoption of sweet sorghum.

Mixed crop-livestock systems are the dominant form of agricultural production in dryland Africa and Asia. Integrating crops and livestock on the same farm helps small-scale farmers to diversify their sources of income and employment. Livestock act as a storehouse of capital and an insurance against crop production risks, and thus provide a coping mechanism against livelihood shocks as well as a vital source of dietary protein. Development of the livestock sector provides new livelihood opportunities for women, who otherwise often lack access to and control over land-based means of production. For the majority of small-scale farmers, crop residues from dual-purpose crops constitute 40–60 percent of total dry matter intake in their animal feed rations. The rest is made up from other sources.

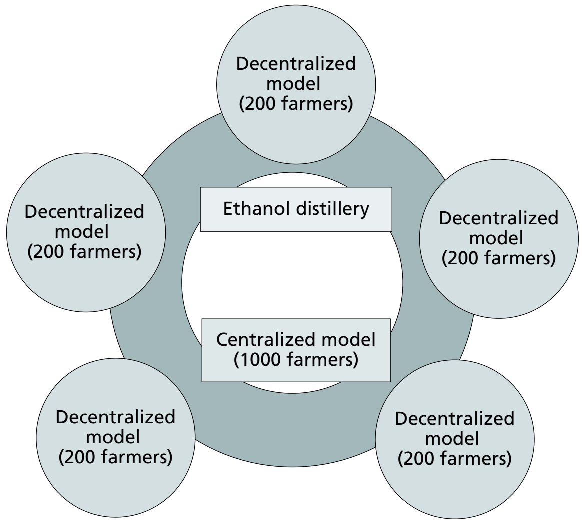
Sweet sorghum supply chain

Sweet sorghum feedstock supply chains have primarily two models of operation (Figures 1 and 2). These are considered below.

The centralized model

The sweet stalk is directly supplied to the plant from the farmers' fields, and the juice is extracted and fermented to ethanol and allied co-products. Its operational area is generally limited to a 40–50 km radius around the plant owing to high transportation costs involved in bulky raw

FIGURE 1
Linkage between centralized model and decentralized models of the sweet sorghum supply chain

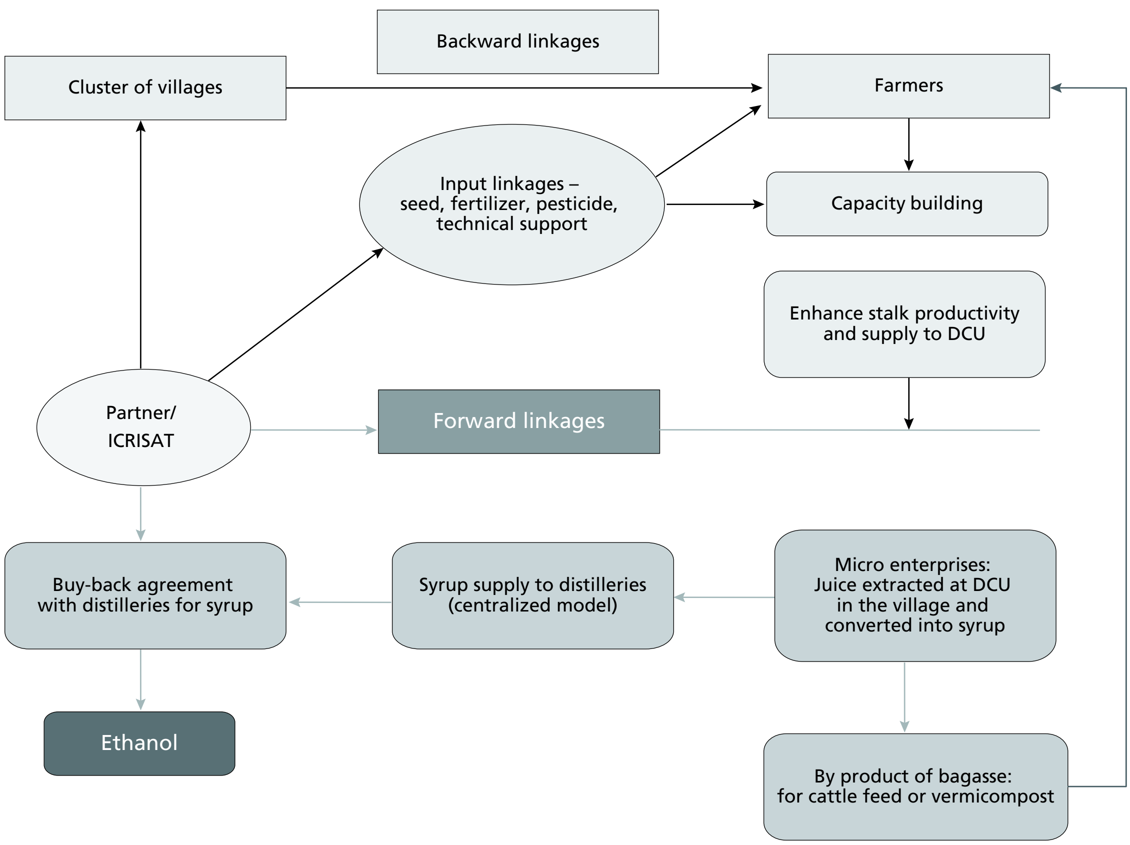


material supply. Examples of such centralized plants include Rusni Distilleries Ltd, Sangareddy, Medak District, Andhra Pradesh, India; Tata Chemicals Ltd, Nanded, Maharashtra, India; and ZTE Ltd, Inner Mongolia, China.

The decentralized model

Figure 1 illustrates the overlap of the two models, showing linkages of hundreds of farmers to decentralized crushing units (DCU), while thousands connect to a central distillery. The finer details reflect productivity, capacity utilization and other factors. In simple terms a DCU comprises the crusher and boiling unit, and essentially crushes the stalks to extract juice. The extracted juice is either concentrated to syrup or fermented *in situ* to alcohol. The forward and backward linkages of DCU are illustrated in Figure 2. Sweet sorghum is a seasonal crop that in India can be cultivated in three seasons a year (rainy, post-rainy and summer) to supply raw material for 3 to 4 months annually for ethanol production (Kumar *et al*., 2010). The grain and sugar yields are best in the rainy and summer seasons, whereas in the post-rainy season the grain yield is high, but with less stalk and sugar yield. A commercial ethanol distillery requires

FIGURE 2
Decentralized model. A village enterprise to crush stalks and produce syrup, linked with a centralized unit to produce ethanol from syrup



feedstock year round – for at least 10 months annually – for economical operation. However, in regions with short harvest windows, smaller acreages or with low plantation densities, a typical centralized model with a 30 kilolitres per day (KLPD) processing plant dedicated to sweet sorghum ethanol production could operate only seasonally, requiring a high capital investment that might not be cost effective. In areas with low plantation densities, the transportation costs associated with supplying the plant with sweet sorghum feedstock become prohibitive. Transportation costs are a significant cost factor in all sweet sorghum models studied, with costs ranging from US$ 34 to US$ 107 per tonne of fermentable carbohydrates (Bennett and Anex, 2009). Larger plant sizes may not benefit from traditional economies of scale because of the increased transportation costs associated with longer travel distances. Due to these limitations, alternative processing options have been investigated. In view of the need for regular supply of feedstock to the distillery, it is widely believed that DCUs help in sustainability of the supply chain. The juice obtained after crushing the stalks is boiled in pans to produce concentrated syrup (~60 percent Brix) (Photo 1), which is supplied to a distillery for ethanol production (Reddy *et al*., 2009).

Alternatively, extracted juice can also be fermented *in situ*, resulting in a fermentation mash containing 6–10 percent ethanol. Studies have shown that non-sterile fermentation in the field is possible, with very good ethanol conversion efficiencies, as demonstrated by a research group at the University of Oklahoma, USA (Kundiyana *et al*., 2006). As an alternative to fermentation of the sweet sorghum liquids, several groups have investigated the solid-phase fermentation of sweet sorghum for production of ethanol as it (i) has greater ethanol production per unit volume of the fermenter, (ii) has reduced fermentation capacity requirement, (iii) has no nutrient supplementation requirement, (iv) has lower production costs, (v) leaves smaller volumes of stillage for disposal, and (vi) needs less energy for distillation (Gibbons, Westby and Dobbs, 1986). In these systems, shredded sweet sorghum is injected into a solid-phase fermenter, inoculated with yeast, and mixed during fermentation. Fermenters have been of varied sizes and configurations, including rotary drums and screw augers (Gibbons, Westby and Dobbs, 1986). Solid-phase fermentations typically result in higher ethanol yield than fermentation of the juice alone (78 percent of theoretical ethanol yield in solid state versus 75 percent in juice fermentation) (Bryan, Monroe and Caussanel, 1985), but may have higher capital costs and lower throughput. Other variations to the system have included operating in a semi-continuous rather than batch mode, and application of immobilized yeast in the system, both of which improved system performance.

Potential advantages of small-scale, decentralized ethanol processing are:

- Promotes biodiversity by using more diverse feedstock.
- Enhances food security and food system resilience by ensuring that geographically diverse farms have access to locally-produced renewable fuel for food production.
- Promotes resource cycling by keeping nutritious co-products of ethanol production close to their farm source, where they can be returned to farms for feed or fertilizer.

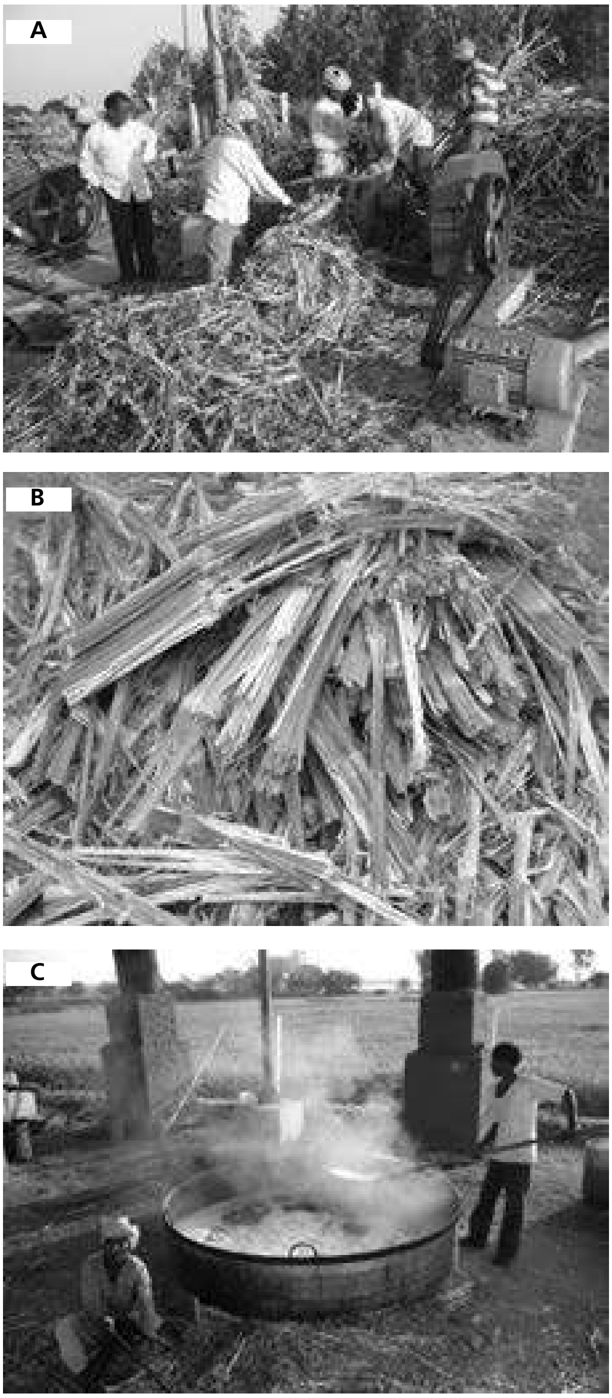


Photo 1
Decentralized sweet sorghum crushing unit. A. Crushing. B. Bagasse. C. Boiling the juice to produce syrup

- Produces feedstock on small farms, which tend to use land more efficiently than large farms.
- Co-products remain with the farmers.
- Reduces farm input needs through promotion of regionally-appropriate, low-input feedstock crops.
- Promotes equitable distribution and greater retention of wealth by rural communities.

CO-PRODUCTS

The processing options discussed above focus on the liquid carbohydrate portion of the sweet sorghum, but do not address the use of grain, the solid bagasse and steam that are generated during the pressing process, or the waste vinasse that is generated during the dewatering process. An ideal system will utilize as many crop components as possible to create a closed-loop system (Worley, Vaughan and Cundiff, 1992).

Grain

Currently the stalk from rainfed sweet sorghum grown in the rainy season is the source of raw material for the decentralized units in India. The grain is considered a co-product here as sweet sorghum is basically grown for production of ethanol by fermenting extracted juice from the sugary stalks. Mould-affected grain can be used as raw material for ethanol production, while mould-free grain can be used for human consumption. The primary product in DCU is syrup, which can be used either in ethanol production or in the food and pharmaceutical industries.

Grain from the rainy season crop is mostly mould-affected due to rains during grain development, maturation and harvest. Grain and stover yield are statistically unrelated in both hybrids and varieties (Blümmel *et al*., 2009). Stover yield is directly proportional to realizable bagasse yield (Kumar *et al*., 2010). High grain yields could be associated with above average stover yields. In a recent comprehensive investigation of grain-stover relationships in (non-sweet) sorghum cultivars tested by the Directorate of Sorghum Research (DSR), formerly the National Research Center for Sorghum (NRCS), Hyderabad, India, during the 2002–2006 period, Blümmel and co-workers (2010) observed that grain yields accounted for only 14 percent of the variation in stover yield, i.e. grain and stover yields in sorghum were only weakly positively associated. These findings suggest that grain and stover yield should both be recorded in sorghum improvement, since stover yields cannot be accurately predicted by grain yield measurements. Grain yields do not need to be achieved at the expense of fodder for livestock or feedstock for ethanol production, and vice versa.

Bagasse

The solid bagasse that remains after pressing sweet sorghum has several potential uses. One potential use is as animal feed, directly after chopping or after ensiling (Linden, Henk and Murphy, 1987). It has also been used as a source of pulp for the paper industry (Belayachi and Delmas, 1997). Another potential use of the bagasse is as a fuel source for the processing plant. With the addition of a solid-fuel boiler, the bagasse can be used to provide process heat to run the plant. With its heating value it is likely to require only 20–30 percent of the available biomass to fuel the plant (Bennett and Anex, 2009). In addition, processes for conversion of lignocellulosic material to ethanol are becoming more economically viable, making sweet sorghum bagasse a possible source of biomass for such a process. Studies have demonstrated that a large portion of the insoluble carbohydrate (cellulose and hemicellulose) from sorghum can be readily converted to ethanol (Sipos *et al*., 2009).

Foam and froth

Lot of foam and froth is generated during juice boiling. This can be collected separately and used to feed livestock or as organic fertilizer.

Steam

The steam generated during concentration of juice to syrup is a good source of energy, which can be used for several purposes, such as boiling water, which in turn can be used to increase juice extraction, heat treatment of juice before boiling, etc., by installing the necessary equipment to capture the outgoing steam.

Vinasse

Vinasse, also known as stillage, is the liquid co-product after removal of the final products during sugar processing. In a distillation process, vinasse is the liquid remaining after separation of ethanol. In the decentralized model of sorganol production, the dewatering and/or distillation system will produce 10–15 litre of waste vinasse (distillate) for every litre of ethanol produced in the later stages, depending on the initial ethanol concentration of the fermentation broth. The large volume generated and the high organic loading in the waste water make it a major environmental challenge for most commercial applications. Reports of bagasse characterization for sugar cane feedstocks show biochemical oxygen demand (BOD) levels ranging from 25 to 60 g/L, with nitrogen levels from 300 to 2500 mg/L and phosphorus levels from 10 to 300 mg/L. The limited data on sweet sorghum bagasse show comparable results, with BOD = 46 g/L, nitrogen = 800 mg/L and phosphorus = 1990 mg/L (Wilkie, Riedesel and Owens, 2000). Due to its high BOD, disposal into waterways is not an option. One potential option is land application of the vinasse as irrigation water and fertilizer. Several reports suggest that both dilute and concentrated vinasse (from sugar cane) can be used on agricultural fields (Parnaudeau *et al*., 2008; De Resende *et al*., 2005). The vinasse or stillage produced from distillation of sweet sorghum ethanol has been reported to contain 0.2 percent nitrogen, 0.22 percent P_2O_5 and 0.3 percent K_2O. A study conducted in Brazil to determine the long-term effects of disposal of this material onto sugar cane fields found that vinasse applications of 80 m^3/ha increased mean yields of both cane and sugar by 12–13 percent (De Resende *et al*., 2005). A number of other disposal options could be considered, such as anaerobic digestion for production of methane (biogas), on-site combustion for production of energy, or composting to produce bio-fertilizers.

GRAIN UTILIZATION

Rainy season sweet sorghum grain is subject to mould damage if rainfall coincides with grain development, maturation and harvest, which often happens in major sorghum growing regions of India. The moulds have detrimental effects on yield and quality of sorghum grain, including decreasing its nutritive value, and producing mycotoxins and other toxic metabolites. Hence, it is not fit for human consumption, but preferred for alcohol production, and farmers use it as livestock and poultry feed, as the mycotoxins are below permissible threshold levels, and such grain is also inexpensive (Bandyopadhyay *et al.,* 1998; Reddy *et al.,* 2000; Thakur *et al.,* 2006). However, non-mouldy grain from where grain maturation does not coincide with rains and the grain from mould-tolerant sweet sorghum cultivars can be used as food for human consumption by making products like porridge, flat bread (*roti*), *bhakri* (stiff *roti*), flakes, chips, papad, baked products including yeast-leavened breads, cakes, muffins, cookies, biscuits, pasta and health foods. The grain yields among sweet sorghum cultivars vary widely and are cultivar (Table 2) and environment dependent. Hybrids have on average higher grain yield than the original varieties, but all other productivity-related variables were higher in the original varieties. Average grain yields were 10.8 percent (hybrids) and 6.0 percent (varieties) of total biomass yield. This proportionally low partitioning into grain yields probably reflects a sweet sorghum breeding target of high sugar yields in stems. Still, grain yields of up to 2.6 t/ha were recorded in both cultivar types (Table 2) and sweet sorghum grain can contribute significantly to rural food security. Mean juice yield in hybrids amounted to about 47 percent of stem yield, while it was 54 percent for the older varieties. Yields of bagasse plus stripped leaves were on average higher than the juice yields in both hybrids and the varieties, potentially providing 5.8 t/ha (hybrids) and 6.7 t/ha (varieties) of fodder (Table 2).

Grain structure and composition

The sorghum kernel is a naked caryopsis and consists of three main anatomical parts: pericarp (outer layer), endosperm (storage tissue) and germ (embryo), which generally account for 6, 84 and 10 percent of the seed mass, respectively. Sorghum is the only cereal grain known to have starch in the mesocarp layer of the pericarp. The endosperm, composed of the aleurone layer and peripheral corneous and floury areas, is the main storage tissue. The 1000-grain weight of sorghum varieties ranges from 19.0 to 28.5 g (Sehgal, Kawatra and Singh, 2004). Starch is the major grain component in sorghum, followed by protein. Most of the sorghum starch contains 70–80 percent branched amylopectin and 20–30 percent amylose. Waxy or glutinous sorghum varieties contain starch that is 100 percent amylopectin. Sorghum contains high levels of insoluble fibre with low levels of beta glucans. Most of the crude fibre is present in the pericarp and endosperm cell walls. This fibre is composed mainly of cellulose, hemi-cellulose and small quantities of lignin (Table 3).

TABLE 2
Yields of grain, leaf, stem, stover, juice, bagasse and bagasse plus stripped leaves (B+L) in 34 cultivars of sweet sorghum at Directorate of Sorghum Research (DSR) in 2005

	Mean (and range) in dry matter yields (t/ha)						
	Grain	Leaf	Stem	Stover	Juice	Bagasse	B+L
Hybrids (H)							
Mean	1.6 (10.8%)	1.5 (10.1%)	8.1 (54.7%)	11.7 (79%)	3.8 (25.7%)	4.3 (29%)	5.8 (39%)
Range	0.8–2.6	0.6–2.5	4.7–12.4	7.1–14.9	1.3–7.1	2.6–5.5	3.8–7.9
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.009
LSD (*P* <0.005)	0.6	0.5	2.0	2.9	1.8	0.1	2.2
Varieties (V)							
Mean	1.0 (6%)	1.8 (10.8%)	10.7 (64%)	13.9 (83.2%)	5.8 (34.7%)	4.9 (29.3%)	6.7 (40.1%)
Range	0.1–2.6	0.9–2.6	6.9–14.7	8.5–18.8	2.8–8.6	3.2–6.1	4.5–8.1
P	<0.0001	<0.0001	0.03	0.05	0.12	0.02	0.005
LSD (*P* <0.005)	0.5	0.57	4.2	5.15	–	1.9	2.1
P (H vs V)	0.007	0.07	0.002	0.02	0.002	0.05	0.02

Notes: Stover yield estimates include panicles after grain removal; values in parentheses are proportion of each component in the total biomass. *P* = probability; LSD = least square difference. *Source*: Blümmel *et al*., 2009.

TABLE 3
Typical composition of sorghum and sweet sorghum grain

Constituent	Mean	Range	Constituent	Mean	Range
Proximate analyses			**Protein fractionation**		
Protein (%)	11.6	8.1–16.8	Prolamine (%)	52.7	39.3–72.9
Ether extract (%)	3.4	1.4–6.2	Glutelins (%)	34.4	23.5–45.0
Crude fibre (%)	2.7	0.4–7.3	Albumins (%)	5.7	1.6–9.2
Ash (%)	5.8	1.2–7.1	Globulins (%)	7.1	1.9–10.3
Nitrogen-free extract (%)	79.5	65.3–81.0	Prolamine (%)	52.7	39.3–72.9
Fibre			**Essential amino acids (as g/16 g N)**		
Dietary insoluble fibre (%)	7.2	6.5–7.9	Lysine	2.1	1.6–2.6
Dietary soluble fibre (%)	1.1	1.0–1.2	Leucine	14.2	10.2–15.4
Acid-detergent fibre (%)	3.3	2.9–3.6	Phenylalanine	5.1	3.8–5.5
			Valine	5.4	0–5.8
			Tryptophan	1	0.7–1.3
			Methionine	1	0.8–2.0
			Threonine	3.3	2.4–3.7
			Histidine	2.1	1.7–2.3
			Isoleucine	4.1	2.9–4.8

Notes: As data from sweet sorghum grain is limited, data are mostly from grain sorghum. All values are expressed on a dry matter basis. *Sources*: Bach Knudsen and Munck,1985; Rooney, Kirleis and Murty, 1986; Monti, Di Virgilio and Venturi, 2008.

TABLE 4
Ash and mineral concentrations in the grain of grain sorghum and sweet sorghum

Sorghum type	Ash	N	C	Al	Ca	Cl	Fe	K	Mg	Na	P	S	Si
Grain sorghum	47	13	434	242	1824	6252	141	5587	2451	192	2150	1084	10671
Sweet sorghum	58	14	424	218	2417	5129	159	7125	2895	171	2620	1000	14321

Notes: Ash, N and C are expressed as g/kg DM; the other elements as mg/kg DM. *Sources*: Jambunathan and Subramanian, 1988; Monti, Di Virgilio and Venturi, 2008.

Utilization as ruminant feed

Both feed and food uses of sweet sorghum grain are compatible; not all grains will have desirable food processing properties, so the poorer quality grain might go into feeds. Obviously, care must be taken to avoid problems with mycotoxins. Sorghum grain is rich in many minerals, including Ca, Mg, P and K (Table 4). Sorghum is a very good feed grain as long as it is properly supplemented for the particular species being fed. Sorghums without a pigmented testa have 95 percent or greater of the feeding value of yellow dent maize for all species of livestock. In India, on average, 250 g grains are consumed per dairy animal per day. Consumption of sorghum grain by dairy cattle is highest in northern India and lowest in southern India. Considering the large population of animals and government policy in support of milk production, the requirement of grains by feed industries will be quite high. Considering the nutritional value of sorghum (Tables 3 and 4) and the probable shortage of grain and roughages, coupled with limitations on other fodder crops cultivation in Asia and sub-Saharan Africa, there is wide scope for more inclusion in feed formulations of sorghum grain harvested from decentralized sweet sorghum production systems.

Utilization as poultry feed

The demand for sorghum for poultry feed largely depends on the price and availability of maize. Inclusion of sorghum at up to 10 percent for layers and 15 percent for broilers is common. However, this rate increases in years of higher maize price. The present non-food share of sorghum grains usage in India is predicted at 77 percent for poultry, 16 percent for dairy, 6 percent for ethanol production and 1 percent for starch production (Dayakarrao *et al*., 2003). The chemical composition and nutritive value of sweet sorghum grain means it is rich in proteins, starch, fibre, vitamins and minerals. Anti-nutritional factors can be broadly classified as those naturally present in the grains and those developed due to contamination, which modify the nutritive value. Some of them have serious health consequences. Phytic acid, a major phosphorous store in the grain, is present at levels on par with that in maize and is not a problem in diets for chickens. Polyphenols (luteoforol and apiforol) in the seed coat confer bird and mould tolerance (Reddy *et al*., 2007). However, these compounds reduce digestibility and lead to growth retardation in chickens. Detoxifying methods such as moisturizing with alkali, dilute aqueous ammonia, sodium carbonate solution, formaldehyde, etc., reduce tannins (polyphenols) to tolerable levels in the diet (below 0.26 percent tannins). Aflatoxin contamination is frequent in mouldy sorghum grain (Waliyar *et al*., 2008). Published data indicate that sorghum grain can replace up to 60 percent of maize in broiler diets and up to 100 percent in the diet of layers without affecting performance (Reddy and Rao, 2000). However, to be competitive, the sorghum grain market price needs to be about 10 percent lower than that of maize.

Other alternative uses

Sweet sorghum grain can be processed into diverse products to exploit its nutritive value. If the toxin levels are high, it is safe to process sorghum grain to produce ethanol or alcohol and vinegar. Sorghum grain is usually processed by dry milling to make flour for bread. Other processing methods include rolling, steaming, flaking, popping, parching, malting, brewing and fermentation. In rural areas, dehulling (pearling) is practised. These processing techniques, alone or in combination, result in a variety of products and co-products from sorghum grain, such as leavened bread, *injera*, porridge, pasta, grits (semolina), starch, glucose powder, liquid glucose, high fructose syrup, glue, xylitol, spirit, alcohol, beer and non-alcoholic beverages (malta, milo). In 2010, the state government of Maharashtra in India announced a US$ 0.25 promotional benefit per litre of ethanol produced from mouldy sorghum grains by the distilleries. This is expected to boost rainy season sweet sorghum cultivation, as the stalk will be purchased by the ethanol distillery and the grain by other distilleries and feed manufactures. However, in view of the shortage of human labour, this will be feasible only if mechanical harvesters are available.

Utilization of bagasse

Farmers in the drylands require varieties specifically developed with appropriate combinations of food, feed and fodder traits for use in crop-livestock systems, which will increase farmer income from the sale of grain, feed and fodder. From DCUs the major co-product is bagasse – the fibrous matter that remains after sweet sorghum stalks are crushed to extract their juice. For each 10 t of sweet sorghum crushed, the DCU produces 5 to 6 t of wet bagasse, depending on the genotype, season of crushing, juice extraction efficiency, temperature, etc. The high moisture content of wet bagasse, typically 40 to 50 percent, makes it unsuitable for direct use as a fuel. However, such fresh bagasse is preferred for use as livestock feed. Fodder from crop residues such as stover and straw does not require the allocation of additional land and water because they are a co-product of grain production. This makes crop residues and co-products the single most important – and affordable – fodder resource for small-scale farmers. Thus, any improvement in the nutritive value of crop residues, however small, can have considerable value and impact. Although cereal crop residues generally have low nutritive quality, genetic variation is being exploited to develop dual-purpose types that combine improved fodder quality with acceptable grain production. In many regions of sub-Saharan Africa and Asia the contribution of pastures to livestock feed has declined and been replaced by feed grains, crop residues and other concentrates (Parthasarathy Rao and Birthal, 2008). The problem of finding enough feed for animals raised by small-scale farmers is becoming almost as acute and politically significant as ensuring food security for people. While crop residues, particularly straw, already provide a large component of livestock feed, their nutritive value is often so low that farmers must supplement livestock diets with feed grain and other concentrates.

Bagasse fodder quality and composition

The potential feed value of sweet sorghum bagasse-based livestock feed is described in Table 5 (Blümmel *et al*., 2009). Nitrogen content was increased in bagasse residue plus stripped leaves (BRSL) compared with whole stover because of the higher leaf content in the BRSL, but all other laboratory fodder quality traits were higher in stover than in BRSL. For example, mean *in vitro* digestibility values for BRSL were around 5 percentile units lower than those of whole stover (Table 5). This reduction in fodder quality seems insignificant considering that highly digestible carbohydrates must have been removed in the extract, which amounted to 47 and 54 percent of stem yields in hybrids and varieties, respectively. This loss of highly digestible carbohydrates was perhaps compensated for by physical changes in the bagasse, facilitating faster and higher microbial colonization and ultimately digestion of residual fibre particles.

The chemical composition and physical properties of sweet sorghum bagasse (Table 6) shows that it has low ash and sulphur content, while being rich in minerals like Ca, Mg, Fe, Na and Zn (Negro *et al*., 1999).

Bagasse vs forage crops

Fresh bagasse can be sold directly to fodder traders, as shown by an arrrangement faciliated in 2009 and 2010 by the International Livestock Research Institute (ILRI) and partners in the National Agricultural Innovation Project (NAIP) decentralized sweet sorghum project set up in Ibrahimbad, Andhra Pradesh, India. After some iterations in fine-tuning bagasse to fodder transactions, an arrangement was implemented in 2010 to sell fresh bagasse leaving the crushing unit to fodder traders from Hyderabad at a rate of 70 paise per kg (US$ 0.016). The fodder traders chopped the bagasses and transported it by lorry to their customers, 70 km away in Hyderabad. The price of 70 paise per kg fresh bagasse is remarkable given that the whole (i.e. unextracted) sweet sorghum stalks were valued only slightly higher, at 80 paise (US$ 0.018) per kg, but probably reflects the substantially lower water content of the fresh bagasse.

TABLE 5
Nutritional parameters in hypothetical diets composed of bagasse and leaves of 34 cultivars of sweet sorghum

	Morphological and nutritional composition of bagasse residue and the stripped leaves (BRSL)							
	Bagasse (%)	**Leaf (%)**	**N%**	**NDF (%)**	**ADF (%)**	**ADL (%)**	**IVOMD (%)**	**ME** (MJ/kg)
Hybrids (H)								
Mean	73.7	26.3	0.73	64.5	41.4	4.9	44.6	6.5
Range	56.1–83.9	16.1–43.9	0.58–1.04	59.2–71.0	36.9–47.5	4.1–6.0	39.3–49.1	5.7–7.3
P	<0.0001	<0.0001	0.001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD	8.6	8.6	0.22	3.4	2.4	0.44	2.6	0.43
Varieties (V)								
Mean	72	28	0.83	64.6	39.8	4.9	46.6	6.8
Range	60.5–81.9	18.1–39.5	0.73–0.92	60.6–70.9	36.7–45.0	4.3–6.0	42.0–50.4	6.1–7.5
P	0.0005	0.0005	0.75	0.0001	0.0006	<0.0001	0.0002	0.0003
LSD	8.6	8.6		3.8	0.63	0.55	4.04	3.37
P (H vs V)	0.55	0.55	0.0004	0.82	0.11	0.82	0.03	0.02

Notes: N = Nitrogen; NDF = neutral-detergent fibre; ADF = acid-detergent fibre; ADL = acid-detergent lignin; IVOMD = *in vitro* organic matter digestibility; ME = metabolizable energy; *P* = probability; LSD = least significant difference at *P* <0.005. *Source*: Blümmel *et al*., 2009.

TABLE 6
Chemical and physical properties of sweet sorghum bagasse

Parameter	Value	Parameter	Value
pH (H_2O)	6.8	S (%)	<0.01
Electrical conductivity (S/m)	0.027	P_2O_5 (%)	0.08
Organic matter (%)	95.2	K_2O (%)	0.20
Total nitrogen (%)	0.5	Na_2O (%)	0.08
Ash (%)	4.8	Mg (as MgO, %)	0.08
Ether-soluble fraction (%)	10.9	Ca (as CaO, %)	0.19
Ethanol-toluene extracts (%)	8.7	Cu (ppm)	48
Cellulose (%)	41.7	Zn (ppm)	35
Klason lignin (%)	18.9	Cr (ppm)	29
Elemental analysis		Pb (ppm)	20
C (%)	45.4	Fe (as Fe_2O_3, %)	0.15
N (%)	0.5	Mn (as MnO, %)	<0.2
H (%)	6.1	Cd (ppm)	<3.0

Source: Negro *et al*., 1999.

Silage making and quality assessment

For silage preparation, the recommended moisture level is generally 60 percent, and the fodder is chopped for better compaction and anaerobic fermentation, leading to better quality silage. For fresh bagasse leaf residue (BLR), it was observed that the moisture content was 48–52 percent, and experiments were conducted to ensile the fresh material, both whole and chopped, with no further processing (moisture addition or silage additives) to make it as cost effective and practicable as possible. The results showed that ensiling of whole and chopped BLR for 30 days without any additives resulted in good quality silage as assessed by the appearance and smell of the silage. The quality of silage was assessed further by feeding experiments with 4 adult Deccani rams, where the silage was supplemented with 150 g concentrate/animal/day. The trial lasted for 21 days. Intake and nitrogen balance of chopped sweet sorghum BLR was similar to the silage prepared from whole BLR and the intake on a dry matter basis as a percentage of body weight was 2.5 percent (Table 7) (Kumar *et al*., 2010).

ANIMAL STUDIES WITH SWEET SORGHUM BAGASSE

Nitrogen content, *in vitro* digestibility and metabolizable energy (ME) content of the sweet sorghum bagasse plus stripped leaves-based feed block (BRSLB) were significantly lower than in the commercial sorghum stover-based feed block (CFB), and the BRSLB was significantly superior to normal sorghum stover, but there were no differences in the NDF contents (Table 8). As expected, the laboratory quality indices were lowest for the sorghum stover. An important aspect of the work was to investigate the palatability of feed blocks when sorghum stover was entirely replaced by BRSL. The feeding trials with five murrah bulls (14 day adaptation period and 10 day collection period) showed that there was no (statistical) difference in feed intake between the CFB and the BRSLB (Table 8). For both blocks, the voluntary dry matter feed intake was high at 3.5 (CFB) and 3.7 percent (BRSLB) of animal live weight. Intakes of crop residues by non-lactating livestock are commonly around 2.0 percent or less of live weight (McDonald,

TABLE 7
Performance of sheep fed sweet sorghum bagasse and leaf residue as whole and chopped silage

Sweet sorghum bagasse and leaf residue	Dry matter intake (g/d)	Dry matter intake (as % body weight)	Dry matter digestibility (%)	Organic matter digestibility (%)	Nitrogen balance (g/d)
Chopped	415.4	2.5	59.3 a	60.2 a	5.7
Whole	414.0	2.5	63.1 b	64.3 b	4.8

Notes: a, b = Values followed by different letters in columns denote significant differences (P <0.05). *Source*: Kumar *et al.,* 2010.

TABLE 8
Comparative feeding results in bulls fed a marketed commercial sorghum stover-based feed block (CFB), an experimental sweet sorghum bagasse/stripped leaves-based feed block (BRSLB) and sorghum stover of the type used in the CFB

Diet	Nitrogen (% DM)	NDF (% DM)	*In vitro* digestbility (% DM)	ME (MJ/kg)	Intake (kg/day)	Intake (g/day per kg LW)	Weight change (kg/day)
CFB	1.81 a	56.1 a	57.5 a	8.21 a	7.31 a	35 a	0.82 a
BRSLB	1.65 b	56.2 a	54.6 b	7.77 b	7.52 a	37 a	0.73 a
Sorghum stover	0.45 c	70.2 b	50.5 b	7.30 b	2.31 b	13 b	-0.38 b

Notes: NDF = neutral-detergent fibre; DM = dry matter; ME = metabolizable energy; LW = live weight; CFB = commercial sorghum stover-based feed block; BRSLB = experimental sweet sorghum bagasse plus stripped leaves-based feed block; sorghum stover is the type used in the CFB. Different suffixes in columns denote significant differences (P <0.05). *Source*: Blümmel *et al*., 2009).

Edwards and Greenhalgh, 1988). In fact, the intake of sorghum stover when fed as sole feed was only 1.3 percent of live weight (Table 8). However, when fed as part of the well-balanced CFB, stover intake was increased. Since sorghum stover was more than 50 percent of the CFB, the intake of sorghum stover was more than 1.75 percent of the live weight in CFB-fed bulls. These findings underline the importance of balanced supplementation in improving the utilization of a basal diet and in optimizing the utilization of crop residues for livestock production. There was no significant difference between the daily liveweight gain of the bulls fed CFB (0.82 kg/day) and the bulls fed BRSLB (0.73 kg/day), which confirms the value of BRSL as a feed block ingredient.

Addition of non-protein nitrogen sources like ammonium sulphate and biuret, either alone or in combination with urea, calcium carbonate or starch sources can also be tried to further improve digestibility, N-content and intake while making silage.

The nutrient digestibility and nutritive value of sweet sorghum bagasse was determined in sheep (deccani rams) and buffalo (murrah bulls) through a digestion-*cum*-metabolism trial using a difference technique. A 7-day adaptation period, 14-day preliminary period and 7-day collection period was used for the trial. The results show that the dry matter intake (as percentage of body weight) with sweet sorghum bagasse was 1.43 in buffaloes and 1.60 in sheep (Table 9). The digestibility (percent) values of proximate nutrients and fibre fractions of sweet sorghum bagasse calculated by different methods in sheep and buffaloes are presented in Table 10. The digestible crude protein (DCP) of sweet sorghum bagasse was 1.0 percent in both sheep and buffaloes, while the total digestible nutrients (TDN) value was 50.7 percent in sheep and 51.8 percent in buffaloes (Kumar *et al.,* 2010).

In another animal experiment, fresh unchopped BLR when supplemented with 500 g cotton cake in milch buffaloes resulted in feed intakes of 22 to 26 kg (fresh matter basis), corresponding to 3.3 percent intake when expressed as a percentage of body weight, indicating that BLR is quite palatable and well accepted by the milch buffaloes (Kumar *et al.,* 2010). The level of milk production was around 3 L/day, and during the one-month feeding period the body condition of the animals also improved, as indicated by the heart girth measurements and the condition of the body coat. After the experiment the animals were fed as per the farmer's usual practice of grazing supplemented with paddy straw and limited rice bran, and it was observed that animals on average lost around

TABLE 9
Effect of supplementing sunflower cake to sweet sorghum bagasse (SSB) on dry matter intake in graded Murrah buffalo bulls and Deccani rams

Parameter	Buffalo	Sheep
Body weight (kg)	344.2 ± 5.99	43.2 ± 1.31
DMI (kg/day)		
Roughage	4.91 ± 0.13	0.69 ± 0.03
Concentrate	0.72 ± 0.00	0.19 ± 0.00
Total	5.63 ± 0.13	0.88 ± 0.03
DMI (g/kg body weight)		
Roughage	61.5 ± 1.21	40.9 ± 1.25
Concentrate	9.0 ± 0.24	11.4 ± 0.25
Total	70.5 ± 1.32	52.3 ± 1.25
DMI (as % body weight.)		
Roughage	1.43 ± 0.03	1.60 ± 0.05
Concentrate	0.21 ± 0.01	0.45 ± 0.01
Total	1.64 ± 0.04	2.04 ± 0.05

Notes: DMI = dry matter intake. Each value is an average of four observations. *Source*: Kumar *et al.,* 2010

TABLE 10
Nutrient digestibility and nutritive value of sweet sorghum bagasse in graded Murrah buffalo bulls and Deccani rams

Nutrient component	Digestibility (%)	
	Buffalo bulls	Deccani rams
Dry matter	52.47 ± 1.39	50.75 ± 1.84
Organic matter	58.96 ± 0.26	58.82 ± 0.69
Crude protein	40.19 ± 0.83	41.61 ± 0.80
Ether extract	60.97 ± 1.61	58.14 ± 0.31
Crude fibre	51.54 ± 0.40	52.23 ± 0.83
Nitrogen-free extract	58.40 ± 0.84	55.72 ± 1.02
Nutritive value (%)		
DCP	0.98 ± 0.02	1.02 ± 0.02
TDN	51.78 ± 0.43	50.67 ± 0.42

Notes: DCP = digestible crude protein; TDN = total digestible nutrient. Each value is an average of four observations. *Source*: Kumar *et al., 2010*.

20 kg within the first 15 days. Farmers appreciated that fresh sweet sorghum bagasse and leaf residue was well accepted by the buffaloes, but pointed out that chopping would have further improved the intake and reduced the refusal of thick stalk pieces. Interestingly, farmers observed that the milk of the fresh BLR fed animals was creamier than those on the previous grass diet due to increased fat content (Kumar *et al.,* 2010).

Other uses

Sweet sorghum bagasse, other than for animal feed, can be used as raw material for a range of purposes, including biofertilizer production, paper making and co-generation. One of the options for bagasse utilization is as organic soil amendment. However, the direct incorporation into the soil of raw wastes such as the bagasse is not usually suitable because they may cause undesirable effects, such as phytotoxicity and soil nitrogen immobilization. It is well known that composting is one of the most suitable ways of transforming wastes into more stable products that are safe and beneficial to plant growth. The finished compost has a low C/N ratio of 13, compared to 90 in the original substrate bagasse, and also has improved levels of macro- and micro-nutrients (Negro *et al*., 1999).

For the paper industry, cereal straw and sugar cane bagasse are two abundant raw materials in addition to wood from the forest. However, these raw materials are in short supply due to restrictions on cutting trees in the forest, electricity generation from bagasse and residues, and residue use as livestock feed. Hence, sweet sorghum bagasse was assessed for its suitability for paper making (Belayachi and Delmas, 1997). The quality of the pulp obtained from sweet sorghum bagasse is excellent for the paper industry. The pulp exhibits a degree of cohesion higher than 80 percent; a low kappa number, indicating good delignification; a high degree of polymerization; and exceptional physico-mechanical properties, meeting the requirements of the paper industry, and is expected to be the best alternative to sugar cane bagasse and cereal residues.

Co-generation is the simultaneous production of electricity and process heat from a single dynamic plant. Globally, biomass-based co-generation has been widely applied in forest industries and agro-industries such as sugar factories, rice mills and palm oil factories. The 30 KLPD Tata Chemicals Limited (TCL) plant at Nanded, Maharashtra, India, has a 2 MW per hour power generation capacity using bagasse, thus making it self-sufficient in energy.

Sweet sorghum bagasse, with a bulk density of 70–90 kg/m^3 and ash levels of 4–5 percent, is highly suitable for gasification (Rajavanshi and Nimbkar, 2005).

UTILIZATION OF FOAM, VINASSE AND STEAM

Literature is scanty in these areas. The foam, froth and vinasse that is taken out during concentration of juice to syrup is rich in nutrients and can be used in composting of bagasse as well as directly as organic fertilizer. Vinasse needs to be subjected to nutrient analysis. Similarly the steam generated while boiling can be captured and used as a source of heat. This heat can be channelled to warm water when the DCU is aiming for more juice extraction efficiency. Alternatively, it can be used for pre-heating of the juice before boiling.

ECONOMIC IMPORTANCE OF BAGASSE FOR THE SWEET SORGHUM VALUE CHAIN IN THE DECENTRALIZED SYSTEM

The current rate of conversion of a tonne of sweet sorghum stalk to juice is 26.9 percent (269 litres) with 700 kg available as wet bagasse. After drying, about 30 percent (210 kg) of that wet bagasse (700 kg) is available as fuel or as fodder for livestock. In DCUs, about 45 percent of the dry bagasse (95 kg) is utilized as fuel (heating the pans) for converting juice to syrup, and the remaining 55 percent (115 kg) of the bagasse can be used or sold as fodder for livestock. During the early phases of DCU development, bagasse was sold direct to fodder traders with no value addition, and at a low price. However, during subsequent seasons, based on feedback from traders, dried bagasse of sweet sorghum was chopped to realize a higher value. Accordingly, efforts were made toward chopping sweet sorghum bagasse, doubling returns to Rs. 1/kg (US$ 0.0022) for chopped sweet sorghum bagasse. This value addition through change in physical form of the bagasse increases the overall income from sweet sorghum in the ethanol value chain under the decentralized system. Additionally, sweet sorghum bagasse sold as fodder in the region of sorghum-based crop-livestock systems also helps in meeting the fodder requirements for the growing population of milch animals.

Reduction in cost of syrup production from sale of bagasse

The sale of chopped bagasse as fodder reduces the overall cost of processing syrup for ethanol production. The value realized for 115.5 kg of bagasse that is left over after use as fuel for the pans will be Rs. 115.5 (US$ 2.6) at current rate of Rs. 1/kg of fodder (costs of chopping not accounted for). Hence, the cost of processing a tonne of stalk, which is currently Rs. 1231 (US$ 28) (for both raw material and processing), will reduce by Rs. 115.5 (1231 115.5 = 1115.5) and thus the unit cost of syrup production, which was Rs. 25.65 (US$ 0.58) will reduce to Rs. 23.23 (US$ 0.53), a reduction of Rs. 2.40/kg (US$ 0.05) or 9 percent decline in cost. Since there is further scope for value addition from bagasse sold for fodder (pellets), higher returns can be realized by selling a better product and thus further reducing syrup cost.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The commercial viability of the decentralized model of the sweet sorghum value chain depends on the efficient utilization of co-products in addition to the efficiency of operation and price of the main product, i.e. syrup. The following gaps have been identified based on several years of operation of DCUs in India:

- At present, there is a very limited period of operation of the crushing unit (less than 20–25 days) as the cultivar maturity window is not large. Research should aim at developing sweet sorghum genotypes with adaptability across seasons and months of the year.
- DCUs are being operated only for the rainy season crop (June–September). The post-rainy and summer season crops require an assured irrigation source, thereby increasing the cost of cultivation. Currently there are no suitable sweet sorghum cultivars adapted to post-rainy season conditions. The lower temperatures and shorter day lengths of this season hinder both biomass production and sugar accumulation in the tropical sweet sorghums, which are thermosensitive.
- The majority of the existing sweet sorghum cultivars are not multi-purpose, so do not meet the varying needs of the local agricultural systems. For example, high IVOMD, along with high sugar and biomass yield, are preferable for ensiling to meet livestock feed requirement. In areas where bio-composting is common, biomass with a high C:N ratio is not preferred. Research on hay-type sorghum species suggests that between 1950 and 2000 stem and leaf crude protein decreased and leaf NDF increased due to overemphasis on biomass quantity rather quality (Bolsen *et al*., 2003).
- Juice extraction efficiency and syrup conversion efficiency are low. A scenario analysis conducted at ICRISAT showed that improving these even by 5 percent has significant bearing on the economics of the whole value chain.
- As syrup is the main product of a DCU, its quality parameters need to be improved to meet the requirements of diverse end users (such as suitability for use in food, beverage and pharmaceutical industries). Research also needs to focus on improving organoleptic characteristics.
- Commercial dairies are increasingly using the fresh bagasse, after chopping, to feed cattle. Education and training is needed for farmers to raise awareness of the multiple uses of bagasse, such as for feed block making, ensiling or bio-composting.
- Little or no information is available on the utilization of co-products like vinasse, steam, foam and froth. Hence research efforts are needed in using steam for heating or boiling the juice, and in exploring the use of nutrient-rich vinasse, foam and froth as livestock feed and biofertilizers.
- Capacity building of staff at every step – not only syrup production, but also co-product utilization – would go a long way toward improving the operational efficiency and economic viability of DCUs.
- The varied products and co-products of the DCU need to be positioned to exploit locally existing market opportunities, i.e. an inclusive market-oriented development (IMOD) approach, as this brings the DCU closer to the rural farming communities.
- There are no studies on life cycle assessment (LCA) of DCUs with reference to carbon and energy balances. Such assessment studies would help all the stakeholders to understand the real value of this novel system, aside from economic viability analysis.

CONCLUSIONS

The potential uses of co-products from sweet sorghum DCUs for livestock feeding are unequivocally established. Considering the available genetic variability for fodder traits and ensiling parameters of sweet sorghum, the novel DCU system offers unforeseen opportunities, not only for meeting livestock feed demand of poor farmers, but also for offering an environmentally sound agro-enterprise that has tremendous implications for organic recycling related to carbon sequestration, GHG emissions and ecological balance. However, challenges remain pertaining to economic viability and marketability of the products and co-products of DCUs, requiring better linkages of poor and marginal farmers with emerging markets. These challenges must be addressed as a priority if there is to be greater involvement of rural agrarian communities in sweet sorghum cultivation.

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