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Review

Valorization of solid waste in sugar factories with possible applications in India : A review

M. Balakrishnan*, V.S. Batra

The Energy & Resources Institute (TERI), Darbari Seth Block, India Habitat Center, Lodhi Road, New Delhi 110 003, India

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ABSTRACT

Sugar production is a major agro-based industry in India that generates various solid wastes viz. sugarcane trash, bagasse, press mud and bagasse fly ash. This work examines the state-of-the-art in innovative value added products that can be obtained from the transformation of these wastes. Challenges in implementing these waste valorization solutions are also highlighted. It is observed that the extent of research and adoption of these solutions vary considerably. Both industry involvement as well as government encouragement is required in translating the research findings into commercial products.

1. Introduction

India is one of the largest growers of sugarcane with an estimated production of around 300 million tons in the marketing year 2009–10 (Singh, 2009). Sugar-distillery complexes, integrating the production of cane sugar and ethanol, constitute one of the key agro-based industries. There are presently nearly 500 sugar factories in the country along with around 300 molasses based alcohol distilleries (Indiastat, 2010; Tewari et al., 2007). Fig. 1 depicts the process details and the major solid waste streams generated in the sugar manufacturing process. These include sugarcane trash, bagasse, press mud and bagasse fly ash. The key characteristics of these solid wastes and the approach used for their management are summarized below.

- *Sugarcane trash*: This refers to the leaves, tops etc. that are obtained upon sugarcane harvesting. This is a lignocellulosic material with an approximate composition of 40% cellulose, 25% hemicellulose and 18–20% lignin. About 0.09–0.11 ton trash is generated per ton of sugarcane harvested (Singh et al., 2008a). The trash is conventionally disposed off by burning in the fields.
- *Bagasse*: This is the fibrous residue obtained from sugarcane juice extraction and consists of cellulose (50%), hemicellulose (25%) and lignin (25%) (Ezhumalai and Thangavelu, 2010; Abhilash and Singh, 2008). About 0.25–0.30 tons bagasse is produced per ton of sugarcane (Pessoa et al., 1997). It has a calorific value of 8021 kJ/kg and is commonly used as a fuel in boilers to generate steam and electricity through cogeneration (Babu and Ramakrishna, 1998). Other applications include use as a raw material in agro-residue based pulp and paper mills.
- *Bagasse fly ash*: This is the waste generated by the combustion of bagasse. Apart from silica which is the major component, it contains other metal oxides as well as unburned carbon (Table 1) (Umamaheswaran and Batra, 2008). Around 0.005–0.066 tons fly ash (without the carbon) is generated per ton of sugarcane crushed (Iyer et al., 2002). This waste is typically disposed off in pits; it is also applied on land for soil amendment in some areas. Approximately 0.97 million tonnes of unburned carbon is available from bagasse fly ash alone in India.
- *Press mud*: This is the solid residue obtained in the sugarcane juice clarification process. It is a complex product containing crude wax (5–14%), fiber (15–30%), crude protein (5–15%), sugar (5–15%), SiO (4–10%), CaO (1–4%), PO (1–3%), MgO (0.5–1.5%) and total ash (9–10%) (Partha and Sivasubramanian, 2006). The estimated generation is 0.03 ton per ton cane

* Corresponding author. Tel.: +91 11 24682100/41504900; fax: +91 11 24682144/24682145.
E-mail address: malinib@teri.res.in (M. Balakrishnan).

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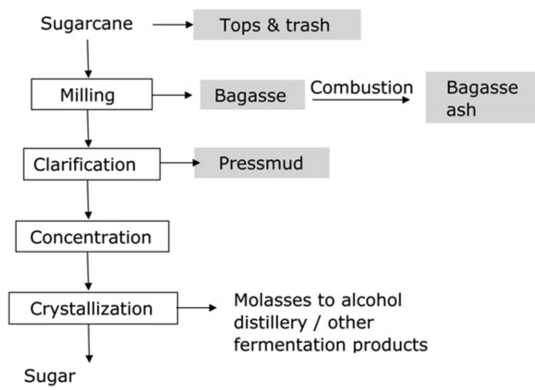

Fig. 1. Solid wastes generated in cane sugar production.

processed (Yadav and Solomon, 2006). Press mud is typically disposed off by direct application to land as a fertilizer; it is also used as filler for biocomposting with distillery spentwash.

Not all the waste management approaches used in the sugar-manufacturing sector are environment friendly. For instance, disposal of bagasse fly ash by dumping is not attractive because of the large land area requirement and pollution concerns due to air-borne particulate matter. Further, because of the presence of unburned carbon, these dumps are prone to catch fire spontaneously; as such, they need to be regularly sprinkled with water. The practice of burning sugarcane trash is yet another contributor to air pollution.

With this background, the aim of this manuscript is to examine innovative value added products that can be obtained from the transformation of sugar industry wastes. Such initiatives, in turn, are expected to promote alternative approaches to waste management in this sector. The concept of industries based on sugarcane by-products has been examined earlier (Yadav and Solomon, 2006). This work presents the state-of-the-art in this field especially focusing on high value products and their applications. Challenges in adopting these waste valorization solutions are also highlighted.

2. Products from sugarcane trash and bagasse

2.1. Fuels and chemicals

Combustion of bagasse in boilers for steam and electricity generation is commonly used in sugar mills. To improve energy recovery, a combination of bagasse and sugarcane trash has been investigated as a fuel in biomass integrated-gasifier/gas turbine combined cycle (BIG/GTCC) operations. This has been especially advocated in sugarcane producing countries like Cuba and Brazil (Larson et al., 2001). Supplementing bagasse with trash is reported to enhance electricity generation by 500% (UNDP, 2007); however, the presence of alkali metals (Na and K) in the resulting producer gas is detrimental to the gas turbine blades (Gabra et al., 2001). Though extensive work has been done on this topic, no commercial BIG/GT system is reportedly operational (Leal, 2009; IEA, 2007). The developments are mostly taking place in the developing countries and the technology needs to be adapted to conditions in sugar manufacturing countries (Leal, 2009). Other factors such as feed availability (competition with other user industries), logistics of supply and cost also need to be considered.

Table 1
Composition of bagasse fly ash (Umamaheswaran and Batra, 2008).

Compound	% Weight
SiO_2	65.03
Al_2O_3	0.49
Fe_2O_3	0.49
TiO_2	0.08
P_2O_5	1.14
CaO	2.75
MgO	3.26
Na_2O	0.06
K_2O	1.73
Cl	0.12
MnO	0
SO_3	0
Loss on Ignition	24.84

The production of fuel ethanol from bagasse is another major application. Dedini SA, Brazil has reported industrial scale production of ethanol from bagasse using an efficient pre-treatment method involving organic solvents and dilute acid hydrolysis (Biopact, 2007). In another initiative, a 3 ML/year bagasse based ethanol plant was commissioned in Thailand using the dilute acid steam explosion pre-treatment process (Johnson et al., 2010). However, reduction in operation costs still remains a challenge in this application; as such, extensive research on various pre-treatment methods are still underway (Zheng et al., 2009). This application has seen active industry participation as a result of high interest in renewable fuels and their anticipated market. This, in turn, has contributed towards joint research and scale-up.

Unlike bagasse that is available in the sugar mill, sugarcane trash is dispersed in the fields. Thus an effective collection mechanism is required if trash is to be employed in the sugar factory for cogeneration. Alternatively, decentralized options such as conversion of trash into charcoal powder and briquette can be explored. Charcoal making kilns developed by Appropriate Rural Technology Institute of India (ARTI) have been installed in sugarcane fields and the resulting charcoal/briquettes can be used as fuel in domestic stoves (ARTI, 2007). Making of charcoal briquettes from sugarcane trash is being taken up in certain areas of Tamil Nadu in southern India (The Hindu, 2010). Yet another option is trash mulching with dry leaves and also the lower green leaves. The use of sugarcane trash mulch reportedly improves soil properties, water use efficiency and nutrient uptake (Mahimairaja et al., 2008; Ram et al., 2006); it also increases the yield of crops like groundnut and castor (TNAU, 2003) and assists in weed control (iKisan, 2000).

In addition to fuels like ethanol, bagasse has been investigated as a starting material for the production of chemicals (Pandey et al., 2000). The cellulose/hemicellulose fractions have been modified for products like biodegradable plastics (Shaikh et al., 2009), adhesives (Vieira et al., 2009) etc. The bagasse has also been used as a source of cellulose whiskers (de Morais Teixeira et al., 2011; Bhattacharya et al., 2008); such whiskers have considerable potential in reinforcing composites (La Mantia and Morreale, 2011; Satyanarayana et al., 2009). The lignin component has been used as a phenol substitute in phenolic molded-type resins (Piccolo et al., 1997; Hoareau et al., 2006), as a pesticide for insect pests (Khanam et al., 2006) and for making nanostructured films for heavy metal adsorption (Pereira et al., 2007). The driver here is the shift from petroleum based raw materials towards renewable biomass resources for chemicals production (biorefining). This is another application where industry participation in joint research with universities exists (e.g. Lane, 2010) and is expected to contribute towards scale up and commercialization.

2.2. Adsorbents

Bagasse has been explored as a low cost adsorbent for pollutant removal from aqueous streams. In addition to as-received bagasse, chemically modified bagasse and activated carbons from bagasse have also been examined. Both steam activation and chemical activation routes have been explored (Kalderis et al., 2008a; Valix et al., 2004). Surface areas in the range 500 m^2/g to more than 1000 m^2/g have been reported. The adsorption of heavy metals has been extensively studied (Garg et al., 2007, 2008a, b; Homagai et al., 2010; Gurgel et al., 2008; Karnitz jr et al., 2007, 2009), besides the removal of micropollutants like phenol (Hameed and Rahman, 2008; Kalderis et al., 2008b), dyes (Amin, 2008) etc. Most of these reported works focus on equilibrium and kinetics of the adsorption process.

Use of bagasse as activated carbon has been reported since the sixties (Ruiz and Rolz, 1971). However there is no apparent commercial production with this raw material. This could be due to reluctance in adopting chemical activation that has been used in many studies for obtaining high surface area. Post use disposal of waste streams generated in chemical activation using salts like zinc chloride is a concern. In fact, activated carbon production in India is almost completely based on steam activation. Yet another issue is the low density of bagasse that could lead to problems in proper feeding in rotary kilns that are typically used for activated carbon production. Finally factors such as seasonal and variable availability of bagasse, location of activated carbon production clusters away from sugar factories adversely impact the overall process economics.

3. Products from bagasse fly ash

3.1. Adsorbents

Bagasse fly ash has been examined extensively as an inexpensive adsorbent for various applications. The properties of bagasse fly ash as an adsorbent originate from its high carbon content (up to 25%) (Umamaheswaran and Batra, 2008; Batra et al., 2008).

Several studies have been reported using bagasse fly ash as a low cost adsorbent for removal of heavy metals like lead, chromium, nickel, cadmium, zinc, selenium (Gupta et al., 2003; Gupta and Ali, 2004; Gupta and Sharma, 2003; Taha, 2006; Wasewar et al., 2009). Other adsorbates include textile dyes (Mane et al., 2007; Mohan et al., 2002), colour in industrial wastewater (Jain et al., 2009), pesticides (Gupta and Ali, 2001; Gupta et al., 2002; Akhtar et al., 2007), phenol (Srivastava et al., 2006), pyridine derivatives (Lataye et al., 2008). It has also been tested for organics removal from dairy wastewater (Kushwaha et al., 2010).

While bagasse fly ash has been studied as an adsorbent, the constituent unburned carbon has not attracted much attention. The unburned carbon has already gone through a devolatisation and carbonization process in the power plant burner where emission controls are in use. In contrast, stand alone carbonization units (such as those making wood charcoal) are typically in the small and tiny scale in India and are highly polluting (Adam, 2009). Thus the unburned carbon fraction is an attractive precursor for activated carbon preparation. This fraction can be readily enriched from the fly ash using simple techniques such as sieving or gravity separation; it can also be deashed by acid treatment (Batra et al., in press). The separated unburned carbon can be further steam activated to get surface areas more than 500 m^2/g. The activated carbon so obtained has been successfully tested for removal of micropollutants like phenol (Singh et al., 2008b).

Utilization of bagasse fly ash as an adsorbent has been reported in the literature since the eighties (Keogh, 1988). However issues of consistency of ash properties, post use disposal/treatment of the exhausted adsorbate, and the overall process economics appear to be factors yet to be resolved. The separation of unburned carbon from fly ash is not expected to be difficult to implement in the sugar factories. However, detailed product testing and identification of buyers for the carbon is required. Aspects involving disposal of the used carbon product also needs to be examined.

Indian government agencies mandating fly ash use focus on fly ash from coal based thermal power plants and its bulk utilization in making roads, bricks, cement, mine filling etc. (Dhadse et al., 2008). Research and utilization of biomass ash and its products is not being similarly encouraged possibly because the generation is relatively lower compared to coal fly ash (112 MT generated in 2008 and estimated to increase substantially) (Dhadse et al., 2008). Further, biomass ash generation tends to be disperse, except in sugar factories and in rice mills where bagasse and rice husk are consumed in-house as fuel.

3.2. Ceramic filters

More recently, bagasse fly ash has been used as a starting material for low cost ceramic membrane filters suitable for various gas-solid and solid–liquid separation (Batra and Tewari, 2006). Ceramic membranes offer the benefits of better chemical and physical stability especially at extremes of pH and temperature and a relatively longer working life. However high cost (approximately 10 times higher than organic polymeric membranes) (Mueller and Witte, 2006) poses a limitation to its widespread adoption. The bagasse fly ash ceramic membranes can be customized to obtain the required pore size distribution (Fig. 2). Filters with pore size in the 1 μm - 10 μm range have been successfully investigated for three different applications viz.

- Cleaning of hot producer gas from a biomass gasifier; the filters were used for particulate removal prior to tar removal for power generation application (TERI, 2005)
- Membrane bioreactor (MBR) for wastewater treatment wherein the filters were used for sludge retention in the bioreactor; both domestic and industrial (alcohol distillery) wastewater have been tested in a submerged MBR (Tewari et al., 2010; Gupta et al., 2008; Satyawali et al., 2005)
- Clarification of sugarcane juice in the sugar manufacturing process; the aim was to remove particulate and colloidal matter from hot limed juice to enhance sugar quality and reduce loss in molasses (Balakrishnan et al., 2009).

Though ceramic filters can be prepared from coal ash as well (e.g. Jedidi et al., 2011), bagasse ash has the advantage of being free from toxic components like heavy metals (Umamaheswaran and Batra, 2008). For the bagasse fly ash filters and the applications developed by us, tie-ups with industry are being pursued with the aim of joint industrial trials and subsequent commercialization.

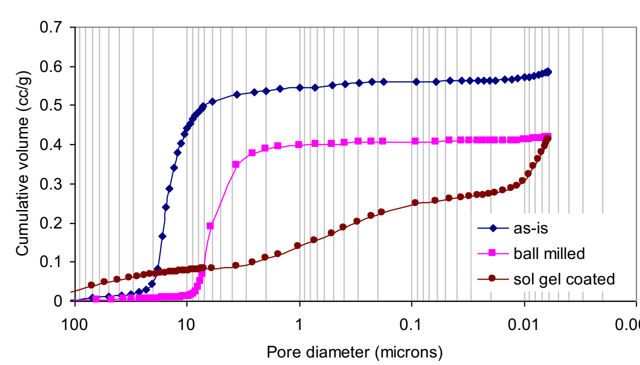

Fig. 2. Ceramic filters from bagasse ash with different separation layers.

3.3. Other products

Bagasse fly ash has also been examined as an additive in cement and concrete (Paya et al., 2002). The properties of the unburned carbon fraction have also been investigated and other applications suggested (Batra et al., in press). For instance, the unburned carbon fraction has surface area of 120 m^2 g^{-1} which is comparable to Carbon Black N339, a popular additive in the rubber industry (surface area of 96 $\pm$ 5 m^2 g^{-1}). Thus this fraction can be examined as reinforcement similar to carbon black. This fraction can also be converted into pellets with the addition of suitable additive like glycerol or carboxymethyl cellulose. Comparing the calorific value with various coal grades, it was found that the calorific values of the ash pellets were similar to those of non-coking coal grades C (>23433 and <25325 kJ kg^{-1}) & D (>21306 and <23433 kJ kg^{-1}) (Ministry of Coal, 2009). In addition to its application as an adsorbent, the activated carbon obtained from unburned carbon could also be used as a catalyst support (Batra and Lamonier, 2010). For these applications further research on efficiency and performance is required before scale up and commercialization.

4. Products from press mud

4.1. Fuels and chemicals

The extraction of residual sugar, wax and protein from sugarcane press mud has been studied (Partha and Sivasubramanian, 2006). In particular, it is possible to obtain microcrystalline wax with degree of crystallinity comparable to that of carnauba wax (Phukan and Boruah, 1999). Press mud has also been used as a substrate in solid state fermentation for production of citric and lactic acids (Shankaranand and Lonsane, 1993; Xavier and Lonsane, 1994). The organic components in press mud make it a possible source for biogas production by anaerobic digestion. Such a facility was set-up in a sugar factory in western India with the biogas obtained being piped to households in the factory premises (Kumar, 1996). The yield was reportedly 165 L biogas/kg press mud with 60% methane content. In another study, press mud treated in a biphasic reactor resulted in a yield of 9 m^3/ton biogas with 70–75% methane content (CPCB, 2007). Additionally, the resulting sludge had a high N, P, K value and is suited for use as a fertilizer. On the whole, for the production of high value chemicals from press mud, process development and scale-up, ensuring consistent product quality etc. still needs to be investigated.

4.2. Others

There are continuing studies on the ability of press mud to provide adequate nitrogen and phosphorus for specific crops (Singh et al., 2008c; Jamil et al., 2008; Muhammad and Khattak, 2009). In this context, enrichment of press mud by vermicomposting has been studied by mixing with other wastes like cow dung (Prakash and Karmegam, 2010), bagasse and sugarcane trash (Kumar et al., 2010). Press mud has also been used in aquaculture for promoting the growth of carp (Keshavanath et al., 2006). Yet another application is as an adsorbent. Based on its porous structure and presence of polar groups, it is predicted that press mud would be a good biosorbent for metal ions, dyes etc. (Gupta et al., 2011).

Utilizing press mud as a fertilizer either directly or after biocomposting with distillery effluent is a popular practice. Bulk usage is possible and the approach is perceived to be an environment friendly way of increasing the nitrogen and phosphorous contents in the soil. In contrast, other waste based soil amenders like municipal waste compost have associated environmental concerns such as accumulation of heavy metal and other pollutants in the soil over time (Déportes et al., 1995). However, recent reports indicate that decomposition of press mud generates acid leachate and also emits significant amounts of greenhouse gases (George et al., 2010). Further, press mud can also lead to immobilisation of inorganic nitrogen (Rasul et al., 2006). Because land application is well established, there is relatively less incentive for developing alternative products from this waste.

5. Conclusion

Many value added applications are possible for the solid wastes arising in sugar mills. The extent of research and adoption of these applications varies widely. For some applications such as bagasse fly ash adsorbent and bagasse activated carbon, research has been ongoing for several decades but commercialization is not apparent. This appears to be due to a combination of technical factors and lack of active participation from industries. In contrast, for applications with high value markets such as biofuels, involvement of industries has led to scale-up activities. In addition to industry participation, government involvement such as in case of coal fly ash is also expected to contribute towards commercialization of these applications.

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