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LETTER

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**Abstract**

In the recent past, the emerging India economy is highly dependent on conventional as well as renewable energy to deal with energy security. Keeping the potential of biomass and its plentiful availability, the Indian government has been encouraging various industrial sectors to generate their own energy from it. The Indian sugar industry has adopted and made impressive growth in bagasse (a renewable biomass, i.e. left after sugarcane is crushed) based cogeneration power to fulfil their energy need, as well as to export a big chunk of energy to grid power. Like fossil fuel, bagasse combustion also generates various critical pollutants. This article provides the first ever estimation, current status and overview of magnitude of air pollutant emissions from rapidly growing bagasse based cogeneration technology in Indian sugar mills. The estimated emission from the world's second largest sugar industry in India for particulate matter, NO_x, SO₂, CO and CO₂ is estimated to be $444 \pm 225 \text{ Gg yr}^{-1}$, $188 \pm 95 \text{ Gg yr}^{-1}$, $43 \pm 22 \text{ Gg yr}^{-1}$, $463 \pm 240 \text{ Gg yr}^{-1}$ and $47.4 \pm 9 \text{ Tg yr}^{-1}$, respectively in 2014. The studies also analyze and identify potential hot spot regions across the country and explore the possible further potential growth for this sector. This first ever estimation not only improves the existing national emission inventory, but is also useful in chemical transport modeling studies, as well as for policy makers.

Introduction

Energy is a basic fundamental need to drive industrial activities and development. Rising demand of energy followed by its adverse impact on environment due to large use of fossil fuels drive the need for us to harness renewable energy across the globe. 'Biomass' refers to organic matter stored energy during photosynthesis and is the fourth largest extensively used renewable energy source after fossil fuels, such as coal, oil and natural gas. Biomass is one of the most plentiful and well-utilized renewable energy sources contributes nearly 10% of world's primary energy supply mix which is likely to rise to 30 per cent by 2050 (International Energy Agency 2011, Macqueen and Korhaliller 2011). So, biomass is being promoted worldwide as a means to provide additional energy security to nations highly depending on fossil fuel (Gheewala 2011). India is one of the fastest growing

economies in South Asia and has been facing the big challenge of energy security. The government of India is encouraging all forms of energy to deal the widening energy deficit due to rising industrialization, urbanization and infrastructure development. Like many other countries, India has been promoting energy from renewable biomass. Bagasse is an important renewable biomass. Nearly 1.34 Giga Tons (GT) of sugarcane in 1999 was produced around the globe, which corresponds to 375 million tons (MT) of bagasse (Das *et al* 2004). Bagasse is burned in cogeneration technology, and is a concept which produces two different forms of energy by using a single source of fuel. Across the globe, biomass based cogeneration has become a widely used attractive alternative to the conventional fossil based energy due to its low capital investment, heat generating option, low fuel consumption and associated minimum pollution compared to fossil based power. The cumulative potential of renewable

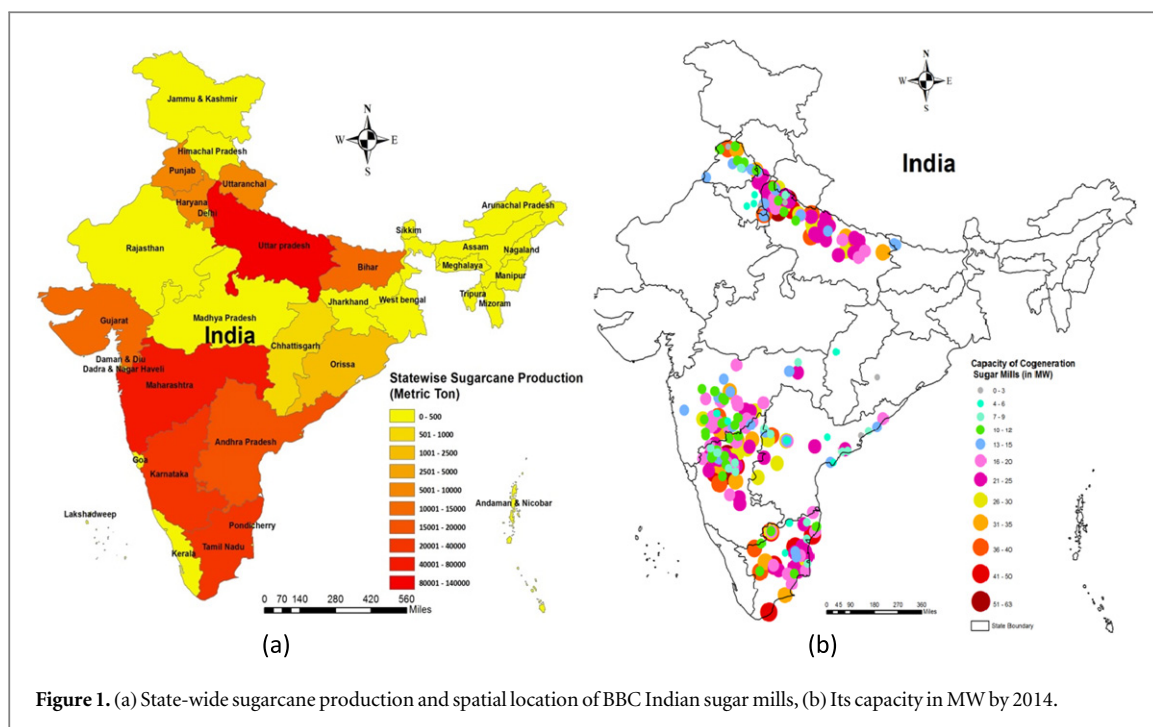


Figure 1. (a) State-wise sugarcane production and spatial location of BBC Indian sugar mills, (b) Its capacity in MW by 2014.

energy from bagasse in India is highlighted by Purohit and Michaelowa (2007). The potential of biomass based power generation could be approximately 23 000 megawatt (MW), whereas bagasse alone could contribute nearly 5000 MW (Ministry of New and Renewable Energy 2015, Energy Statistic 2013). This is likely to increase to 9700 MW by 2017 (KPMG Report 2007).

India is the second largest producer of sugarcane in the world, next to Brazil. The sugar industry is the second largest agro processing industry after cotton textiles in India (USAID 1993). Growing demand of energy has put India in an energy deficit, driving a rise in power costs, causing interruptions to grid power, etc. These are the grim realities behind continuous power shortage in India. Renewable energy technologies are the best alternative to conventional and nuclear energy. India has plentiful renewable energy sources. Traditionally, rural people are highly dependent on biomass for cooking. In order to fulfil the rising energy demand, under the BOOT (build, own, operate and transfer) model initiative from the government (Central Electricity Regulatory Commission 2008), sugar industries are encouraged to generate their own energy need using renewable biomass. In recent years, bagasse has become one of the most important biomass energy sources in the sugar processing industry, through cogeneration power technology. Sugar industries need both electrical energy as well as steam (thermal energy) for their operation. The combustion of bagasse also releases air pollutants. However, the environmental benefit of bagasse burning is very important due to its relatively low emissions compared to conventional fossil fuels. The present study provides a first ever estimation and

overview of critical emission from rapidly growing bagasse based cogeneration (BBC) power in Indian sugar mills (ISM). The magnitude of emission from this sector has not been estimated nor analyzed before. We estimated some of the important air pollutants (i.e. particulate matter (PM), NO_x , SO_2 and CO) and CO_2 from the world's second largest sugar industry for 2014. The study quantifies and identifies the emission hot spot regions across the country and will contribute to improve emission inventories used for global/regional chemical transport modeling for air quality studies and other applications (Pawar *et al* 2012 and Chate *et al* 2013).

Activity data and methodology

Sugar industry in India

Nearly 70% of the Indian population depends on agricultural practices for their livelihood. Sugarcane is the world's largest crop grown in the tropical and extra-tropical belt. In the recent past, India has become the world's second largest producer of sugarcane with approximately 350 million tonnes (MT) in 2014. The spatial distribution of the sugar producing states is depicted in figure 1(a). Sugarcane is mostly produced in a few states like Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu, Punjab and Haryana, which contributes more than 90% of the national total production. ISM is confined of approximately 650 sugar mills where nearly 582 mills are operational as of 2014 (Indian Sugar Mills Association 2015). The present total sugarcane crushing capacity of all mills is approximately 2.3 million tonnes crushed per day (TCD). Bagasse has a net calorific value of around 8–9 MJ kg^{-1} . Cogeneration is a cost effective technology

Table 1. Typical characteristics of Bagasse.

| | |
|--------------|-------|
| Fixed carbon | 11.1% |
| Volatile | 35.9% |
| Moisture | 50% |
| Ash | 3% |

Source: (Janghathaikul and Gheewala 2006).

to generate electricity along with thermal energy (steam), simultaneously. This technology has been adopted by Indian sugar mills with a crushing capacity more than 1500 TCD. There is a network of nearly 264 cogeneration based sugar mills with a combined capacity of around 1.32 million TCD as of 2014, mainly confined over major sugarcane producing states (SPSs) as shown in figure 1(b). It is noticed from figure 1(a) that these sugar mills are not uniformly distributed across India.

Bagasse based cogeneration power

The activity data for present studies are collected from numerous sources like government reports, scientific reports, individual sugar mill websites, publications, etc. Bagasse is the waste product from sugar processes and has a moisture content of approximately 48–50% by weight, responsible for combustion efficiency (Bio Energy Consult 2014). The typical characteristic of bagasse is given in table 1. In the past few years, India has had tremendous growth in bagasse based power. The total installed capacity of BBC sugar plants in India has increased from 484 MW in 2003 to 5614 MW in 2014. There has been a ten fold growth in the last decade (2004–2014). Until 2014, only 57% (1.32 million TCD) of the total capacity was utilized to generate 5614 MW of renewable energy. The spatial location of these sugar mills with capacity is shown in figure 1(b). It is clearly seen that the highest sugar producing states have major BBC mills. Figure (2) shows the state level total BBC mills capacity. Utter Pradesh has the most bagasse based produced energy followed by Karnataka, Maharashtra and Tamil Nadu. Nearly 60% of energy generated is being pumped into the grid power, and the remaining 40% is being utilized by sugar factories to fulfil their daily energy consumption. In the sugar industry, efficient technology could save up to 35% of fuel use (Purohit and Michaelowa 2007, Smouse *et al* 1998).

Most large captive sugar mills are built over these particular regions for easy access to farmers. The average operating days for sugar mills is around 150 days per year (Indian Sugar Mills Association 2015, Singh *et al* 2007), but the bagasse generated during crushing could be stored and easily used for fuel in plants for another 50 days in a year. The bagasse to sugarcane ratio could vary from 23% to 37% (Mishra *et al* 2014 and Quintero *et al* 2008) but we have considered 31%

in the present study. India is capable of producing up to 110 MT of bagasse. In the present study, the existing cogeneration sugar mills produce approximately 63.5 MT of bagasse out of 210 MT of sugarcane crushed. It is also seen that nearly 10% of total bagasse produced in country is used as material in paper and other industries.

Efficiency of energy production BBC depends mainly on two factors i.e. technology used and moisture content. Higher temperatures and pressures are critical in order to increase the efficiency and energy output (Purohit and Michaelowa 2007, Mishra *et al* 2004). In general, Indian cogeneration sugar mills adopt a wide range of technologies to achieve efficiencies up to 95% in case of private mills and up to 65% in case of government and cooperative mills (Indian Sugar Mills Association 2015). Some of the important extensively used technologies in the Indian sugar industry are back-pressure stream turbine, extraction-cum-condensing route and condensing route based on a dual fuel system etc.

Emission estimation

A ‘bottom up’ approach has been adopted in the present study. All emissions were estimated on the basis of activated data at individual sugar mill level. Sugar mills are considered as stationary large point sources. Activity data like exact geographical location, plant level bagasse use, capacity of cogeneration power plant and corresponding tentative days of operation are few important parameters collected for each sugar mill. It is assumed that uncertainty in above activity data is limited as compared to emission factor (EF). The present emission estimation is similar to procedure adopted two earlier paper (Ohara *et al* 2007, Sahu *et al* 2015). It is assumed that 10% of total bagasse produced from industry is used in other industries. The total emission for bagasse used in sugar industry thus has been calculated using following equation (1) which is the product of activity, and the emission factor depending on emission control measured.

$$TO_j = \sum_i^a FU_i \times EF_j \quad (1)$$

Where, a = no. of sugar mills

TO_j = Total emission for specific pollutant (j)

FU_i = Bagasse amount for specific sugar mill (i)

EF_j = Emission factor for specific pollutant (j)

As per the 2011 census, Indian geography is divided into 36 major states and union territories which are further divided into 672 districts. We have mapped the state and district boundaries using the geographical information system (GIS) environment. The locations of each sugar mills i.e. LPS are identify and mapped. The final emissions are estimated at $0.25^\circ \times 0.25^\circ$ resolution for use in modelling studies.

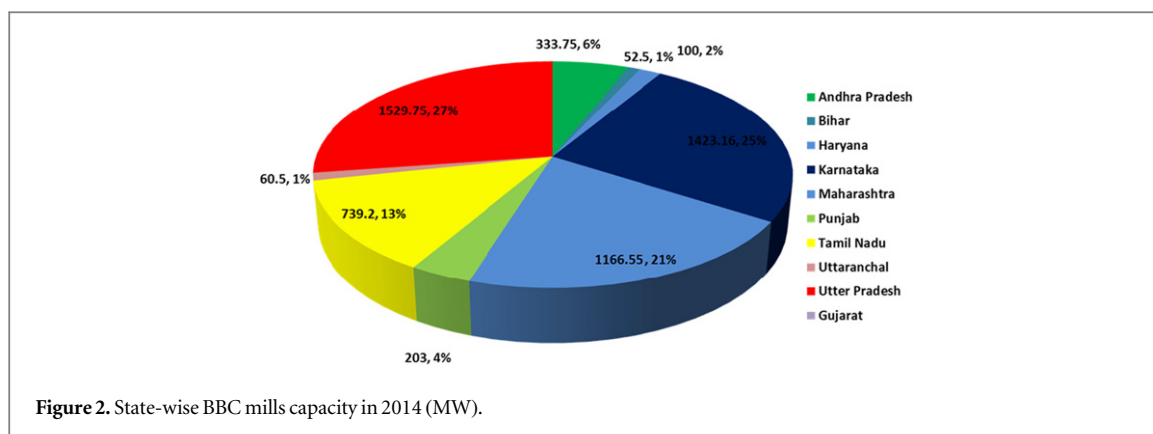


Figure 2. State-wise BBC mills capacity in 2014 (MW).

Table 2. Emission factor for bagasse burning.

| SO ₂ | NO _x (NO ₂) | CO ₂ | CO | TSP/(PM) | References |
|--------------------------|------------------------------------|--------------------------|---------------------------|---------------------|---------------------------------|
| 0.23 ^a | 0.68 ^a | | | | Kato 1996 |
| 0.33 [§] | (2.68 ^{#§}) | 7264.21 [§] | 44.64 [§] | 29.43 [§] | Janghathaikul and Gheewala 2006 |
| 0.5 ± 0.5 ^a | 3.3 ± 0.9 ^a | | | | Gadi <i>et al</i> 2003 |
| | 0.6 | 780 | | (7.8 ^a) | USEPA 1993 |
| 0.76 | | 840.65 | 8.14 | | Quintero <i>et al</i> 2008 |
| 0.18 ± 0.02 ^a | 2.57 ± 0.04 ^a | 937.0 ± 9.0 ^a | 12.39 ± 0.08 ^a | | Irfan <i>et al</i> 2014 |
| 0.76 | 3.3 ± 0.9 | 840.65 | 8.14 | 7.8 | Present Work |

^a g/kg⁻¹, # NO₂ as NO_x, § (kg/MWh), () indicate NO₂ instead of NO_x and PM instead of TSP.

Emission factor

EF is a very sensitive parameter to the emission inventory development process, because a change in EF a certain factor could change the entire sector by the same factor. Bagasse is a biomass of varying composition, heating value and consistency. The EF for bagasse could vary with time and geography. In a limited literature, the given EF for bagasse is a divergent range. The uncertainty associated with EF may be high. Unlike EF for other anthropogenic sectors, EF for bagasse combustion is very limited. It is difficult to get an appropriate EF suit to the Indian sugar industry. We found some general scenarios of emission control in sugar mills in India. As per the Central Pollution Control Board (CPCB) comply standard, all sugar mills are supposed to install ESP/bag filter/high efficient scrubbers to control the particulate matter emission (<150 mg Nm⁻³), but it seen that only 43 out of 118 sugar mills complied with the standards, indicating there is lack of proper emission control in various mills (CPCB 2006). It is assumed in the present study that emission controls in ISM are not good enough to control emission due to a lack of proper and regular maintenance. The emission factor in Kg MWh⁻¹ adopted by Janghathaikul and Gheewala (2006) gives unrealistic CO₂ and SO₂ emission over India, so we did not consider this for the present study. In connection to adopted EFs, we have adopted EFs which could be applied to available activity data for Indian sugar industry. Our first priority was to have EFs developed indigenously (i.e. Gadi *et al* 2003) followed by selection of EFs based on

fuel consumption pattern rather than power consumption pattern. Keeping the CPCB report in mind, we adopted EFs which is little higher side of available EFs. The EF provided by Quintero *et al* (2008) appears to be the more realistic one in terms of units (i.e. g kg⁻¹) applicable to our activity data. We have adopted an EF based on our best judgment and suitable to Indian condition. The adopted EF in the present study is tabulated in table 2.

Result and discussion

The first ever estimated PM, NO_x, SO₂, CO and CO₂ emissions from bagasse used in ISM during 2014 were 444 Gg yr⁻¹, 188 Gg yr⁻¹, 43 Gg yr⁻¹, 463 Gg yr⁻¹ and 47.4 Tg yr⁻¹, respectively. The spatial distribution of PM and NO_x are shown in figures 3(a) and (b), respectively. It is clearly observed from figure 3(a) that a high emission of the order of 1000–9000 tons yr⁻¹ is found over the confined region over Indo-Gangatic plain (IGP), Maharashtra, Karnataka and Tamil Nadu and some parts of Andhra Pradesh etc. High pollution loading over the IGP region is always a matter of discussion among international/national researchers (Kaushar *et al* 2009 and Sahu *et al* 2012). The present finding also indicate that bagasse is another emerging source of pollution over IGP. IGP region, which accounts for 15% of Indian geography and nearly 440 million inhabitants, is responsible for 34% (149 Gg yr⁻¹) of PM emission from BBC. Relatively lower emission hot spots varying from 600–2000 tons yr⁻¹ are well scattered over the north-western part of

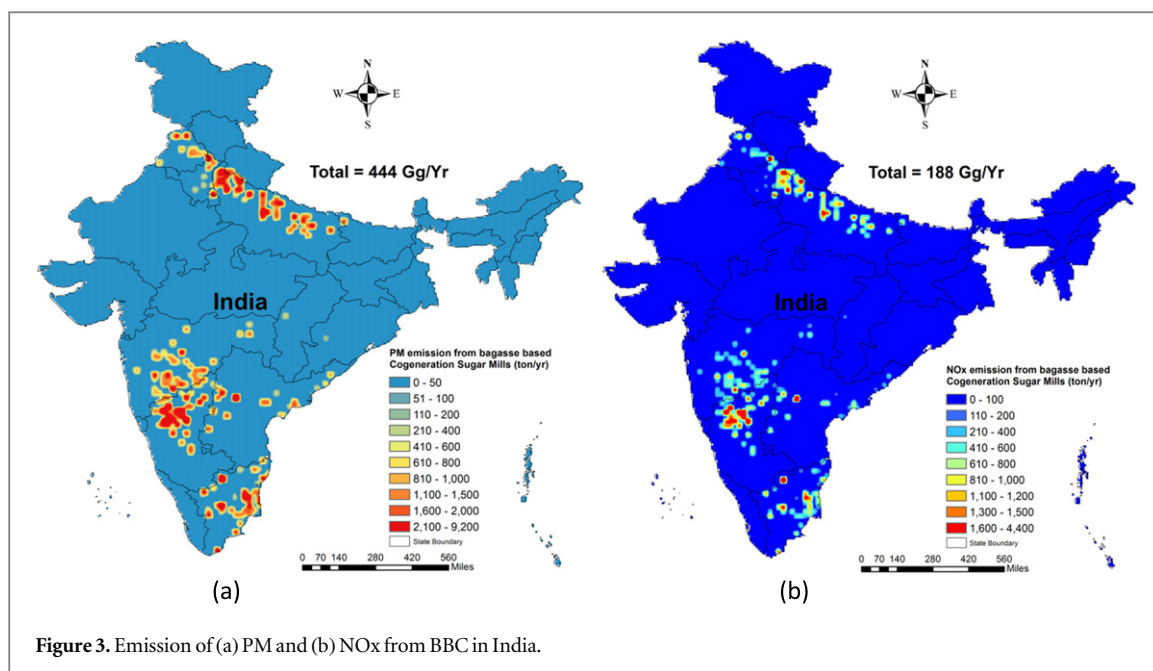


Figure 3. Emission of (a) PM and (b) NOx from BBC in India.

the IGP region (i.e. adjoining part of northern Haryana and Punjab), the southern part of Maharashtra, northern Karnataka and a major part of Tamil Nadu etc. We can also see some more intense emission hot spots of around 5000–9000 tons yr^{-1} situated over the western tip of Uttar Pradesh and northern part of Karnataka. Especially high captive private sugar mills over said above regions are among the best capacity utilization mills in India. Moreover, bagasse is mostly used to generate energy rather than for other purposes, which leads to the export of surplus power to state/national grid, therefore is a profitable business. We can conclude that emission from this sector is not so well scattered across India due to the uneven distribution of sugarcane production. In terms of district level analysis, this indicates that just the top ten districts have the highest cogeneration mills of nearly 1956 MW contributing to nearly 35% of the total emission from this sector. Districts like Belgaum, Bagalkot, Solapur, Gadag, Dharmapuri, Rangareddi, Dharwad, Hardoi, Muzffarnagar and Bijnor are responsible for 25.8 Gg yr^{-1} , 25.1 Gg yr^{-1} , 19.5 Gg yr^{-1} , 17.4 Gg yr^{-1} , 12.1 Gg yr^{-1} , 11.4 Gg yr^{-1} , 11.3 Gg yr^{-1} , 11.1 Gg yr^{-1} , 10.4 Gg yr^{-1} and 9.9 Gg yr^{-1} of PM emission, respectively.

The state levels of bagasse used and corresponding emissions of various pollutants has been tabulated in table 3. In IGP, Uttar Pradesh is a major source of emissions due to its intense use of bagasse. Although, Uttar Pradesh has the highest BBC, it is also the largest contributor to total emission. Still Uttar Pradesh produces comparatively much less emission compared to other states like Karnataka, Maharashtra and Tamil Nadu where sugarcane production is much less compared to Uttar Pradesh. This indicates that Uttar Pradesh has much more potential to utilize bagasse for energy. Similarly, Maharashtra, Bihar and Andhra

Pradesh could even produce more energy out of available bagasse. It is seen that at present, Karnataka and Tamil Nadu are able to produce nearly 1423 MW and 739 MW of renewable energy from 35 732 MT and 33 919 MT of sugarcane, respectively. These two states could utilize bagasse for energy in a more efficient way drive. Until 2014, only 57% of capacity was utilized to generate 5614 MW of renewable energy. We found that the efficiency and utilization of capacities of sugar mills over Uttar Pradesh, Maharashtra, and Andhra Pradesh are underutilized compared to mills in Karnataka and Tamil Nadu. This could be due to lack of penetration of co-generation technology in these areas which may link to financial issues or government subsidies. We are expecting more sugar mills over this region to adopt the present technology for energy production. Moreover, if you follow the KPMG Report (2007) of a 50% growth in sugar production from 19.5 MT in 2007 to 28.5 MT in 2017 then the efficiency and capacity of co-generation mills is expected to improve in the next couple of years. Another 5000 MW of bagasse based energy is achievable in the next couple of years. In the future, states like Uttar Pradesh, Andhra Pradesh and Maharashtra will contribute to renewable energy growth. We can conclude that states like Karnataka and Tamil Nadu have reached saturation point and have comparatively little potential to generate further renewable energy from bagasse. Although Bagasse generates considerable amounts of pollutants, it is the best alternative to utilize biomass to generate power and reduce the dependency on conventional fossil based energy. A green renewable energy like solar and wind could further reduce the emission from this emerging sugar sector. Adopting an improved emission control technology like wet scrubber could reduce the PM emission up to 90% and will reduce other gaseous pollutants too,

Table 3. Bagasse used and pollution generated from top 10 states.

| State Name | TCD Capacity | Cogeneration Power (MW) | Bagasse (MT) | PM (Gg yr-1) | NO _x (Gg yr-1) | CO (Gg yr-1) | SO ₂ (Gg yr-1) | CO ₂ (Tg yr-1) |
|----------------|--------------|-------------------------|--------------|--------------|---------------------------|--------------|---------------------------|---------------------------|
| Andhra Pradesh | 90 400 | 333.75 | 3.4 | 26.4 | 11.2 | 27.5 | 2.6 | 2.8 |
| Bihar | 27 500 | 52.5 | 0.5 | 4.2 | 1.8 | 4.3 | 0.4 | 0.4 |
| Chhattisgarh | 3500 | 6 | 0.1 | 0.5 | 0.2 | 0.5 | 0.0 | 0.1 |
| Haryana | 26 600 | 100 | 1 | 7.9 | 3.3 | 8.2 | 0.8 | 0.8 |
| Karnataka | 26 7900 | 1423 | 14.5 | 112.5 | 47.6 | 117.3 | 10.9 | 12.0 |
| Maharashtra | 21 9200 | 1166.5 | 12 | 92.2 | 39.0 | 96.1 | 8.9 | 9.8 |
| Punjab | 35 250 | 203 | 2.1 | 16.1 | 6.8 | 16.7 | 1.6 | 1.7 |
| Tamil Nadu | 12 3900 | 739 | 7.5 | 58.4 | 24.7 | 60.9 | 5.7 | 6.2 |
| Utter Pradesh | 49 1750 | 1530 | 15.5 | 120.9 | 51.2 | 126.1 | 11.7 | 12.9 |
| Uttarakhand | 19 750 | 60.50 | 0.6 | 4.8 | 2.0 | 0.5 | 5.0 | 0.5 |

significantly. In the coming years, the contribution of bagasse based emission could be increased to 6% of the national total if other alternative energy sources are not adopted in the sugar industry.

In the present emission inventory, EFs are the major source of uncertainty, which could be as high of order of 2. The fuel activity data and capacity have minimum uncertainty which could be of order of $\pm 10\%$. Keeping the present emission control scenarios of the sugar industry in our mind, we have already considered the higher side of EFs as well as EFs developed indigenously. We do believe that the uncertainty will be reduced to greater extent by considering the above factor in our present estimation. For calculation of uncertainty, we have considered EFs provided by researchers with minimum inconsistency and similar categories in terms of units. This will not only reduce the uncertainty range but also increase accuracy of emission estimation. The calculated uncertainty range PM, NO_x, SO₂, CO and CO₂ would be 444 ± 225 Gg yr⁻¹, 188 ± 95 Gg yr⁻¹, 43 ± 22 Gg yr⁻¹, 463 ± 240 Gg yr⁻¹ and 47.4 ± 9 Tg yr⁻¹, respectively.

We compared our present estimation with national emissions to see the relative contribution of the present sector to the national total. We found that present NO_x emission contributed to nearly 2.5% of the national total in 2011 (Sahu *et al* 2012) and nearly 2% of the national total estimated for 2008 (Kurokawa *et al* 2013). In the case of PM, the emission accounts to 7% of the national PM estimation for 2008 (Kurokawa *et al* 2013). This PM emission could have been four times as big in mega cities like Delhi and its surrounding region in 2010 (Sahu *et al* 2011). Although the magnitude of emissions is small compared to the national total, the magnitude of hot spots are more confined over specific geography. An accurate spatial allocation of these emissions to emanate a particular region will have a much greater impact on air quality issues.

Conclusion

The objective of this first estimation of emissions from the Indian sugar industry, which is second largest in

world, has been achieved in the present work. The emission of PM, NO_x, SO₂, CO and CO₂ were determined to be 444 ± 225 Gg yr⁻¹, 188 ± 95 Gg yr⁻¹, 43 ± 22 Gg yr⁻¹, 463 ± 240 Gg yr⁻¹ and 47.4 ± 9 Tg yr⁻¹, respectively. All potential emission hot spots were identified and analyzed. The present sector was found to be another emerging renewable biomass sector responsible for deteriorating air quality over the IGP. The magnitude of bagasse related emission is very intense over some confined smaller regions, which need proper mitigation to curb the pollution. Karnataka and Tamil Nadu are two states which have optimized the use of bagasse resources most effectively. It is found that there is still a huge potential to generate another 5000 MW renewable energy from bagasse. The emission is likely to double in the coming couple of years if no action is taken in this direction. If better emission reduction technology like wet scrubber is implemented then emissions could be reduced up to 90% in case of particulate matter and will reduce gaseous pollutants significantly from the present level. The results of this study are important not only from a policy point of view, but are also useful to improve the national emission inventory in terms of pinpointing emerging emission sources. Apart from pollution point of view, these cogeneration mills are able to utilize the plentiful available biomass resources in the country and help the nation to deal with energy deficit and reduce dependency on conventional fossil based energy.

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