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Emissions of SO_2 and NO_x from biofuels in India

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ABSTRACT

Concentrations of oxides of S and N in the atmosphere are strongly influenced by the emissions taking place from the burning of biofuels. This is particularly important in the developing countries where most of the energy requirement in the rural sector is met from biofuels. An experimental setup has been built to carry out controlled biomass burning and to derive emission factors for SO_2 and NO_x (NO and NO_2) from various biofuels commonly used in India. Using these emission factors and the consumption data obtained from Tata Energy Research Institute's (TERI) Energy Data Directory and Yearbook 1998–99, the budget of SO_2 and NO_x from biofuels used in India has been estimated as 0.4 ± 0.3 and 1.0 ± 0.4 Tg, respectively, for the year 1990.

1. Introduction

Biofuels are used by more than 50% of the world's population as a major source of domestic energy (Boleij et al., 1989). In the developing countries biomass energy use is predominant in rural areas, where it often supplies over 70% of the total energy requirements (Hall, 1991). The major sources of biofuels are fuel wood, crop residues, dungcakes and charcoal. These are burnt in a variety of cooking stoves made locally to suit local needs. These are also burned in rural industries and in the urban service establishments. It is common to use bagasse in the sugar industry and rice husk in rice mills.

India is experiencing rapid economic and population growth. It is estimated that by 2010 over four billion people will be living in the Indian sub-continent and eastern Asia. At current growth rates the Asian energy demand in general is doubling every 12 yr. Biomass is major source of energy in India, and 45% of the total primary energy consumption is based on biomass. The household sector is the major end user, consuming 83% of the total biomass energy leading to per capita biomass consumption of 380 kg for the year 1990–91 (Narang et al., 1999). With the growing population and energy requirement the demand for biofuels will also increase. The use of fuel wood alone in India is predicted to increase by a factor of three from 1985 to 2015 (World Resources, 1993). Increased energy use will result in a large increase of SO_2 and NO_x emissions leading to regional increase in precursors to acid deposition, tropospheric ozone and ambient aerosols. Developing an accurate and detailed picture of nitrogen oxide and sulfur dioxide emissions in India from biofuels serves multiple purposes. It is an output of the energy sector that links the growth of population and economic development of the region with the damage it causes to the environment by the release of these gaseous pollutants. These pollutants can be transported over long distances and across political boundaries, resulting in regional elevated oxidant levels, acid deposition and visibility impairment (Husar et al., 2000). This is evident from the studies conducted during INDOEX Campaigns (Kulshrestha et al., 2001), which show large effects of continental emissions on the acidity of rain and aerosol loading North of the Inter Tropical Convergence Zone over the Indian Ocean. A significant part of these emissions seems to be associated

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with biomass burning. Thus the studies of emissions from biofuels in India are important to assess their contribution and to take steps to develop mitigation options.

Over the last three decades, several attempts have been made at the governmental level to estimate the aggregate energy demand and consumption of biofuels in the rural and urban sectors in India. There is a lack of up-to-date information on non-commercial energy sources. The majority of the population in rural areas and small towns is able to meet most of its fuel requirement almost free of cost by burning fuel wood, crop residues and dungcakes. Information on household rural energy consumption is available only from surveys. Tata Energy Research Institute, New Delhi has prepared a comprehensive report based on the surveys conducted in rural and urban sectors by different agencies (TEDDY, 1998). Based on their report the total annual consumption of biofuels in the rural (villages and countryside) and urban sector (towns and metropolitan cities) in India is 486 Tg, with the breakup as shown in Table 1.

Several authors have studied emissions ratios or emission factors from various biomasses, which are given in Table 2. Spiro et al. (1992) calculated emissions by extrapolating the data from aircraft measurements in the biomass burning plumes over the Amazon basin as reported by Andreae et al. (1988). They observed the mean sulfur/CO_2 and CO/CO_2 enhancement ratios in the plumes as 0.85 g S per kg CO_2 and 0.085 kg C per kg C, respectively; assuming that CO and CO_2 account for all of the carbon burned, the sulfur dioxide emission factor is 0.78 g S per kg C (0.62 g SO_2 per kg dry matter). Venkataraman et al. (1999) estimated SO_2 emissions for India for different anthropogenic sources using the emission factors reported by Andreae et al. (1988) for biomass burning. Hurst et al. (1996) estimated NO_x and other trace gas emissions during the Savanna fires in Australia by collecting smoke samples from the fire plumes aboard aircraft, and calculated the emission factors using the mean trace-gas composition of the plume, mean mass loads of fuel and ash, and the mean C and N contents of fuel and ash measured. Delmas et al. (1995) conducted experiments in a combustion chamber with Savanna plants collected just before FOS/DECAFE-91 (Fire of Savanna/Dynamique et Chimie Atmospherique en Forêt Equatoriale-Dynamics and Atmospheric Chemistry in Equatorial Forest) experimental fires to obtain laboratory measurements of emission factors of various compounds from Savanna plant burnings. Lacaux et al. (1996) estimated NO_X emission factors for each phase of combustion of various plots during the FOS/DECAFE-91 and SAFARI-92 (Southern African Fire-Atmosphere Research Initiative) experiments organised in Africa to determine the gas and aerosol emissions due to prescribed Savanna fires. Brocard et al. (1996) calculated the emissions from traditional charcoal making in the CHARCOAL/DECAFE-92 experiment and from firewood and charcoal burning under the FIREWOOD/DECAFE-94 programme. The above teams calculated the emissions of nitrogen compounds relative to the emission of carbon in form of CO_2. Bhattacharya and Mitra (1998) reported that 109 Gg NO_x as NO_2 is contributed from biomass burning in India; their estimates are based on calculations using emission ratios as per the IPCC (1995) reference manual. Smith (1988) developed emission factors from actual measurements of the emissions from biofuels in typical stoves in developing country settings like India and China. Andreae et al. (1996) summarised the data obtained during SAFARI-92 and calculated the SO_2 and NO_x emissions based on a mass balance of carbon released and the various emission ratios relative to CO_2 determined in the smoke. For Asia, Arndt et al. (1997) evaluated the anthropogenic and volcanic SO_2 emissions for 1987–88, Streets and Waldhoff (1998) estimated atmospheric emissions of SO_2 and NO_x from biofuels, and Van Aardenne et al. (1999) evaluated NO_x emissions due to anthropogenic activities. These studies are based on RAINS-ASIA (Regional Air Pollution Information and Simulation Model for Asia) methodology, and the emission factors used by them are based on the results reported by Smith (1988), Spiro et al. (1992) and OECD/IEA (Organization for Economic Co-operation and Development/International Energy Agency) (1991). The literature cited above shows the various field/laboratory experiments conducted to measure emission factors and emission ratios. The measurement of emission

Table 1. *Annual consumption of biofuels in rural and urban sector (in Tg) for 1990*

Fuel	Rural (Tg)	Urban (Tg)	Consumption (Tg)
Fuel wood	252	20	272
Dungcakes	107	5	112
Agricultural residue	99	–	99
Charcoal	–	3	3

Table 2. *SO_2 and NO_x emission factors as reported by different researchers*

Fuel type	SO_2	NO_x	Reference
Wood			Smith (1988)
Residential heating	0.23 g kg^{-1}	0.77 g kg^{-1}	
Residential cooking	0.6 g kg^{-1}	0.7 g kg^{-1}	
Cowdung	6 g kg^{-1}		
Biomass burning	0.78 g S kg C^{-1} (0.62 g kg^{-1})	–	Spiro et al. (1992)
Fuel wood (Savanna plants)	–	0.5 g N kg^{-1} (1.64 g kg^{-1})	Delmas et al. (1995)
Firewood (Australian Savanna fires)	–	2.1 g kg^{-1}	Hurst et al. (1996)
Fuel wood (SAFARI 92 and FOS/DECAFE-91)	–	0.37–2.09 g N kg^{-1} (1.22–6.87 g kg^{-1})	Lacaux et al. (1996)
Firewood	–	0.69 ± 0.18 gN/kg (2.27 ± 0.59 g kg^{-1})	Brocard et al. (1996)
Charcoal production		0.02 ± 0.02 g N kg^{-1} (0.07 ± 0.07 g kg^{-1})	
Firewood (Savanna fires)	0.6 g kg^{-1}	3.1 g kg^{-1}	Andreae et al. (1996)
Bagasse	0.23 g kg^{-1}	0.68 g kg^{-1}	Kato et al. (1996)
Fuel wood	0.18 g kg^{-1}	1.23 g kg^{-1}	
Fuel wood		–	Arndt et al. (1997)
Residential cooking	0.6 g kg^{-1}		
Residential heating	0.23 g kg^{-1}		
Dung	6.0 g kg^{-1}		
Agricultural waste	0.52 g kg^{-1}		
Fuel wood	0.58 g kg^{-1}	0.70 g kg^{-1}	Streets and Waldhoff (1998)
Crop residue	0.52 g kg^{-1}	1.3 g kg^{-1}	
Animal waste	1.24 g kg^{-1}	0.24 g kg^{-1}	
Firewood, vegetable waste and dung	–	0.10–0.12 G g PJ^{-1} (2–2.4 g kg^{-1})	Van Ardenne et al. (1999)
Wood	2.25 g kg^{-1}	–	Venkataraman et al. (1999)
Cattle dung, agriculture residue, forest biomass, grassland	1.55 g kg^{-1}		
Fuel wood	0.8 g kg^{-1}	2 g kg^{-1}	Garg et al. (2001)
Dung	0.6 g kg^{-1}	0.86 g kg^{-1}	
Agriculture residue	0.6 g kg^{-1}	0.86 g kg^{-1}	
Charcoal	–	2.76 g kg^{-1}	

factors from different categories of biofuel, which could represent the typical usage in Indian conditions, has not been studied in detail. This paper presents laboratory measurements of SO_2 and NO_x emission factors representing the burning of biofuel in the rural sector in India. An effort has also been made to evaluate their budgets.

2. Experimental

An experimental setup consisting of a U-shaped chimney has been designed and fabricated at National Physical Laboratory (NPL), New Delhi to carry out biofuel burning in the laboratory, with all the plumes passing through a high-volume sampler (HVS). One end of the chimney rests on the filter support of the HVS and the other end is about 25 cm above the ground. The chimney is fixed tightly onto the HVS to ensure complete suction of all the plumes during the burning of the biofuel sample. Figure 1 illustrates a cross-sectional view of the experimental setup.

A known amount of biofuel is kept on an electric heater below the chimney. The ceramic plate of the heater has 20–25 holes of 0.5 cm diameter, and the plate is kept on a stand which is 5 cm above the ground

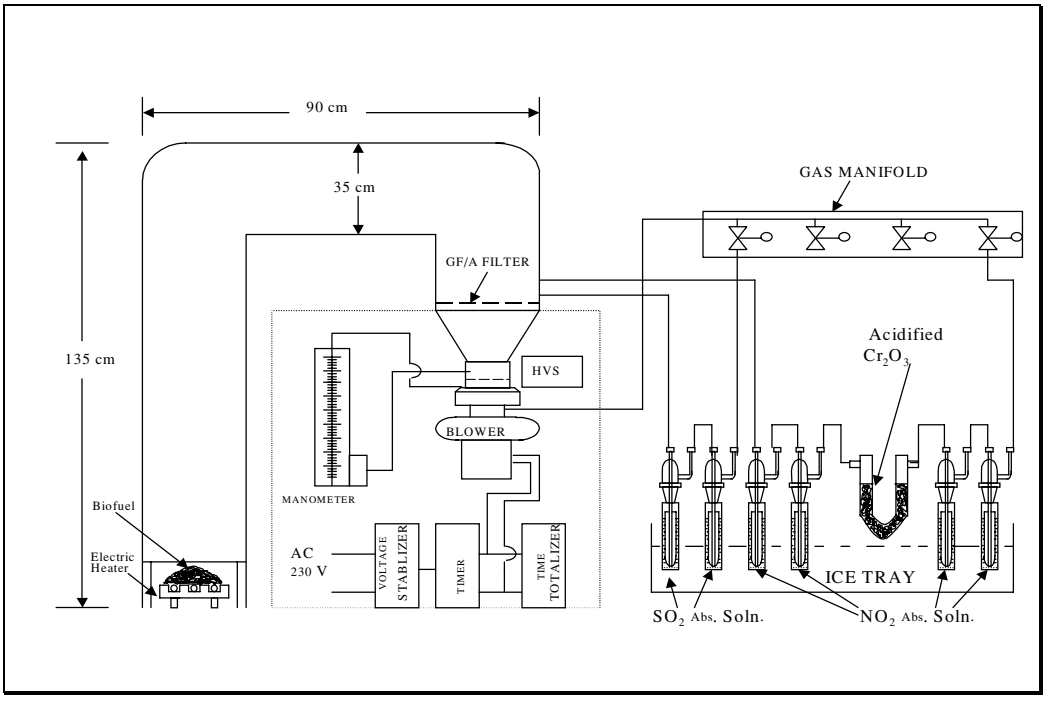

Fig. 1. Cross-sectional view of the experimental setup.

to ensure proper oxygen supply during combustion. When switched on, the heater gets hot quickly, initiates burning of the biofuel and is then switched off. Biofuel emits smoke for a short while as a result of pyrolysis in the initial stage. When the temperature rises enough it burns with a flame which lasts for about 10–15 min and then remains smouldering for a few minutes. The three stages (i.e., pyrolysis, flaming and smouldering) in this burning process are referred to as biomass combustion. Part of the plumes are routed through the impingers as shown in Fig. 1. A set of two impingers in series (having 20 ml of absorbing solution in each impinger) are kept in an ice bath for each of these gases during sampling. SO_2 and NO_x (NO_2 and NO) are evaluated by wet chemical methods involving the absorption of SO_2 in 0.04 M potassium tetrachloromercurate (K_2HgCl_4) and NO_2 in 0.4% sodium hydroxide (NaOH) and 0.1% sodium arsenite ($NaAsO_2$). NO is estimated after the removal of NO_2 by its absorption in an absorbing solution consisting of 0.4% NaOH and 0.1% $NaAsO_2$ in the first two impingers kept in series. The plume almost free from NO_2 is then made to pass through a U-tube containing small pieces (0.4×0.4 cm^2) of glass-fibre filter (Whatmann) impregnated with acidified chromium oxide (Harrison and Perry, 1986) to estimate NO. The NO present in the emissions is oxidized to NO_2 while passing through the U-tube. The next two impingers in series containing the absorbing solution (0.4% NaOH and 0.1% $NaAsO_2$) absorb the NO_2, which is obtained by the oxidation of NO. The absorbing solutions are then analysed colorimetrically (Perry and Young, 1977; Harrison and Perry, 1986). The flow rate of the HVS is 1.0 m^3 min^{-1}, and the impingers have a flow rate of 0.5 L min^{-1} to ensure complete absorption of SO_2 and NO_2 along with complete oxidation of NO to NO_2 by the oxidising material. The flow rate of the HVS and that passing through the impingers was calibrated by the manufacturer/supplier of the sampler, viz. Vayubodhan Pvt. Ltd., India, using the soap bubble technique with pre-calibrated apparatus certified by a Standards and Calibration cell at NPL, India.

The burning period during an experiment was for about 30 min except for charcoal, for which it takes almost 60 min to burn the fuel completely. To have maximum efficiency of absorption in the impingers, they are modified in such a way that the plume passes through a maximum height of absorbing column without

increasing the volume of absorbent. This was achieved by placing a thick coating of glass around the tube which goes inside the absorbing solution, so that the air is in contact with the absorbing solution, for a much longer time. To check the absorption of SO_2, NO_2 and NO oxidised to NO_2 in these modified impingers, the solutions in impinger 1 and 2 in series are analysed separately. It is seen that the first impinger (impinger 1) which comes in contact with the plume first absorbs almost 75% of the gas. It is assumed that 75% of the remaining 25% which is not absorbed in the first impinger is absorbed in the second impinger kept in series. Thus a correction factor of 6% is applied to calculate the total emissions. To make the background correction, the sampler was run to sample ambient air for the same time period as the burning experiment, and the ambient concentrations of SO_2, NO and NO_2 were deducted from the values obtained during the burning experiments.

The temperature variation during the experiment was observed. Initially, when the biofuel is burnt below the chimney, which is made up of aluminium sheet, the temperature rises to about 80–90 °C and later falls to near ambient. Impingers are connected to the chimney through 1 m long polypropylene tubes of 8–10 mm inner diameter. The gases emitted during burning are sucked from the chimney through these tubes and are absorbed in the absorbing solutions. The temperature of the impinger solution remains around 10–15 °C during the experiment as the impingers are kept in an ice bath; thus the temperature of the plume does not affect the efficiency of the solutions to absorb the SO_2, NO_2 and NO as NO_2. The biofuels commonly used in India, viz. fuel wood, dung cakes, bagasse and charcoal, have been studied for their emissions during burning. This experimental setup is very similar to the style of cooking or residential heating adopted in rural India, except that, instead of an electric heater plate, a stand is used that keeps the biofuel slightly raised above the ground. Sometimes in residential cooking the fuel is burnt on the ground between two bricks or in a three-sided fireplace, i.e. a typical *chulha*. During the burning process the biofuel is disturbed with an iron rod so that there is an adequate flow of air to supply oxygen for the burning process. The electric heater used here serves a dual purpose, first for igniting the biofuel and secondly as a stand which allows the supply of oxygen for combustion and makes the setup resemble the typical Indian way of cooking.

As discussed above, the rural population often collects fallen twigs under the trees and dried dead shrubs or bushes from nearby forest areas to meet their fuel requirements. These twigs are then further dried under natural sunshine before they are used. The fuel wood sold commercially in the market is mainly used by people living in urban areas and partially by the rural population. Large logs of fuel wood are available commercially. For use in cooking/heating they are normally cut down into smaller pieces. In these experiments fuel wood samples have been drawn from both sources, viz. commercial fuelwood and dry twigs (collected in and around the NPL campus). The logs of wood purchased from the market were cut into smaller pieces of approximately 3–5 cm diameter and 15–20 cm length. The twigs collected and fuel wood pieces purchased from the market were dried in a natural environment, the way the population using the fuelwood does (i.e. collecting the fuel wood and then storing it in sheds to be used in due course) and then used for burning experiments. This exercise was done keeping in mind the way the rural population uses the fuel wood along with other biofuels like dungcakes and crop residues. Data on the consumption of wood from different sources is not available. The emissions obtained in all the experiments on fuel wood have been taken into consideration to calculate the standard deviation in the emission factors, which would cover different varieties of fuel wood used.

The interference of particulate matter (including C soot) on the determination of SO_2 and NO_x was studied. The flow rate of the impingers is quite low in comparison with that of the HVS. Particulate matter corresponding to the volume of plume passing through the impingers was added to standard solutions of SO_2 and NO_2. The samples (in triplicate) were analysed and no significant difference in optical absorption was observed, indicating no interference due to particulate matter. Different quantities of the biofuel (50, 100 and 150 g) from one source were burnt to check for systematic error, if any. Here 'same source' means one lot of fuel wood cut into smaller pieces to weigh 50, 100 and 150 g. These three samples were then burnt separately. In the case of dungcakes, two samples were taken (50 and 100 g) from one cake and then experiments were conducted.

3. Results and discussion

The total volume of the plume was calculated from the rate of flow of air in the HVS. The volume of the plume passing through the impingers was

Table 3. *Estimates of emission factors for SO_2 and NO_x*

Biofuel	SO_2 (g kg^{-1})	NO as NO (g kg^{-1})	NO_2 (g kg^{-1})	NO_x (g kg^{-1})
Wood	0.7 ± 0.6	1.1 ± 0.7	1.1 ± 0.3	2.2 ± 1.0
Dungcakes	1.4 ± 0.9	0.5 ± 0.3	0.3 ± 0.3	0.8 ± 0.6
Bagasse	0.5 ± 0.5	1.7 ± 0.4	1.6 ± 0.5	3.3 ± 0.9
Charcoal (total)	0.5 ± 0.3	1.4 ± 0.3	0.7 ± 0.2	2.2 ± 0.6
Production[a]	–	–	–	0.1 ± 0.1
Consumption	0.5 ± 0.3	1.4 ± 0.3	0.7 ± 0.2	2.1 ± 0.5

[a]Taken from Brocard et al. (1996).

calculated from the rate of flow through the impingers. The quantity of SO_2, NO_2 and NO as NO_2 absorbed in the absorbing solutions and the total mass of the biofuel burnt in an experiment were used to evaluate the emission factors for SO_2, NO_2 and NO, which are presented in Table 3. The emission factor for agricultural residue is based on our studies on bagasse, as this is the major agricultural residue used for energy. When calculating the emission factor for charcoal burning, emission studies of Brocard et al. (1996) have been used to include NO_x emissions during charcoal production. The emission factors presented here are based on experiments which resemble a typical burning/cooking process. There is a high degree of natural variability in fuel quality depending upon region and seasons, which has led to a range for each emission factor. It is seen from the table that emissions of SO_2 are highest from dungcakes and low from bagasse and charcoal, but NO_x emissions from bagasse are almost double those from fuelwood and charcoal. Bagasse burns under a flaming mode, which may be responsible for the high NO_x, while dungcakes burn mainly under smoldering conditions. Burning of fuel wood covers all three stages of combustion. In the flaming mode the temperature of the fire may be in the range 600–900 °C or more, while the temperature during the smouldering phase is much lower. At high temperatures the thermal formation of NO due to reaction of atmospheric nitrogen with oxygen occurs (Kituyi et al., 2001), which may be responsible for the emission of high NO_x in the case of bagasse as compared to that from dungcakes. NO is comparable to NO_2 and is almost 50% of the NO_x, except in case of charcoal where it is more than 60% of NO_x production. Delmas et al. (1995) observed that almost 60% of NO_x comprised NO during chamber experiments conducted on Savanna plants, while during field experiments in Savanna fires almost 90% of NO_x was NO. They have linked this difference in NO_2 production in the two experiments to be due to the oxidation of NO by ozone inside the chamber, which is an irreversible reaction in which photolysis of NO_2 to NO inside the chamber was not possible, as the chamber was dark. The same phenomena could be the reason for 50% NO in our experiments as compared to NO_2, in addition to the good oxygen supply during the experiment.

Looking at the results obtained in the present study and those shown in Table 2, we see that the emission factors reported by Smith (1988) for SO_2 from fuel wood in residential cooking is almost of the same magnitude as ours, while their SO_2 emission factors for dung are almost four times those of ours. Andreae et al. (1996), Arndt et al. (1997), Streets and Waldhoff (1998), Venkataraman et al. (1999) and Garg et al. (2001) have used the same emission factors as reported by Smith (1988) for fuel wood. For dung cakes the SO_2 emission factors used by Arndt et al. (1997), based on the results of Smith (1988), are much higher than ours. Streets and Waldhoff (1998) used the SO_2 emission factors reported by Smith (1988) for dung cakes but assumed 15% efficiency for the fuel (see Table 2). For NO_x the emission factors reported by Smith (1988) and Delmas et al. (1995) are lower than those obtained in the present study. The emission factors reported in Table 2 have been converted to g per kg dry matter wherever required, by using calorific values for different fuels from IPCC data (1997).

Using the annual consumption of various biofuels in India (Table 1) and the emission factors given in Table 3, the budgets of SO_2 and NO_x are estimated and presented in Table 4. The budget estimates have limitations, as the data for consumption are rather scarce. The biofuel consumption data (TEDDY, 1998) are mainly based on surveys conducted by governmental agencies, as mentioned earlier. It is observed from Table 4 that SO_2 emissions are almost one third

Table 4. *Budget estimates of SO_2 and NO_x for 1990 for various biofuels commonly used in India*

Biofuel	SO_2 (Gg)	NO_x (Gg)
Wood	187.7 ± 163.2	595.7 ± 272.0
Dungcakes	160.2 ± 103.0	89.6 ± 60.5
Bagasse	46.7 ± 46.7	320.7 ± 84.4
Charcoal	1.5 ± 0.9	6.6 ± 1.8
Total	396.1 ± 313.8	1012.6 ± 418.7

of NO_x emissions from biofuels, which is in general agreement with the relative emissions of SO_2 and NO_x reported by Crutzen and Andreae, 1990.

Some efforts have been made to estimate SO_2 and NO_x budgets for India. Akimoto and Narita (1994) included all sources to estimate SO_2 and NO_x emissions from countries in the South East Asia and Indian subcontinent, but did not include the use of dung, which is widespread in the Indian subcontinent. Kato (1996) studied the emissions from various sources in Asia and estimated the SO_x and NO_x emissions. Van Aardenne et al. (1999) evaluated the NO_x emissions from anthropogenic activities, while Streets et al. (2000) developed SO_2 emission trends for the time period 1985–1997 based on RAINS-Asia methodology, for Asian countries. The groups mentioned above have included all sources and have projected total emissions from India.

Table 5 presents the estimates of different groups along with the results obtained in the present study. Spiro et al. (1992) gave an estimate of 5.6 Tg SO_2 yr^{-1} from India for 1980, of which 2.2% (123 Gg) is contributed from biomass burning. Arndt et al. (1997) estimated SO_2 emissions from anthropogenic and volcanic emissions in Asia and have projected the emission from this region to exceed those from US and Europe by 2020, with a warning that many ecosystems will be unable to absorb these increased acid depositions, leading to irreversible ecosystem damage. For estimating SO_2 emissions from biofuels in India, they used the biofuel consumption data reported by Joshi (1991). Total emissions of SO_2 estimated by Arndt et al. (1997) are 5.1 Tg for 1990, while emissions from biomass are 907 Gg. Their estimates from biofuels (907 Gg) are much higher than our estimates (396 Gg), as the emission factor used by them for dungcakes is very large incomparison with that obtained in the present study. This difference is despite our consumption values being higher than the values used by them except for dungcakes, where their consumption value is almost 15 Tg higher than the TEDDY (1998) data used in the present study. Parashar et al. (1998) estimated NO_x from various anthropogenic sources in India and reported 109 Gg from agricultural biomass burning, based on the data of Bhattacharya and Mitra (1998), which do not include the consumption of biofuels in the household sector. Their estimates are based on the emission ratios as per the IPCC (1997) guidelines. Venkataraman et al. (1999) compiled an emission inventory on industrial fuel use and biomass

Table 5. *SO_2 and NO_x emissions from India as reported by different researchers*

Source	SO_2 (Tg)	NO_x (Tg)	Reference
Anthropogenic sources & volcanic eruptions	3.08 in 1987	2.56 in 1987	Akimoto and Narita (1994)
Energy sources	1.65 in 1975 2.01 in 1980 3.01 in 1987	1.38 in 1975 1.67 in 1980 2.56 in 1987	Kato (1996)
Biofuels Anthropogenic sources	0.91 in 1990 5.1 in 1990		Arndt et al. (1997)
Biofuels Biomass burning Anthropogenic sources	0.88	0.46 0.109 4.83–8.38	Streets and Waldhoff (1998) Parashar et al. (1998)
Anthropogenic sources		3.48 in 1990 5.62 in 2000	Van Aardenne et al. (1999)
Total biomass Anthropogenic sources	0.94 for 1990 2.0 for 1990		Venkataraman et al. (1999).
All sources	3.4 in 1985 4.44 in 1990 5.04 in 1995 6.28 in 1997		Streets et al. (2000)
Biomass burning All sources	0.24 4.64	0.65 3.46	Garg et al. (2001)
Biofuels	0.4 ± 0.3	1.0 ± 0.4	This study

burning, and estimated SO_2 as 4.0 Tg, with 0.94 Tg from biomass burning which includes biofuels, forest biomass and grasslands. The emission factors used by them are given in Table 2. Their estimates from biomass burning are higher than our estimates because the emission factors obtained in the present study, except for dungcakes, are much lower than the ones used by them. The second difference is that we have taken urban fuel wood and charcoal consumption into account and have not included emissions from forest biomass and grassland. Streets and Waldhoff (1998) developed an inventory of biofuel use in Asia for 1990 and estimated SO_2 emissions from India as 880 Gg and NO_x emissions as 459 Gg. Their SO_2 estimates are higher than ours, whereas their NO_x estimates are much lower. This difference is probably due to the difference in the consumption values and emission factors. The SO_2 emission factors for fuelwood, crop residue and animal waste used by Streets and Waldhoff (1998) are comparable to our emission factors, while their emission factors for NO_x are quite low. Therefore their NO_x budget estimates are lower than our estimates. Garg et al. (2001) have estimated sub-regional and sector level distributions of SO_2 and NO_x emission inventories for all the 466 Indian districts. The SO_2 and NO_x emission coefficients are taken as per the IPCC (1997) guidelines and have been converted to g per kg dry matter in Table 2 for comparison. The emissions reported by them from biomass burning are on the lower side of the range of our estimates. This is probably because the emission factors used by Garg et al. (2001) for calculating emissions are lower than the factors obtained in the present study.

Further work is in progress to improve the reliability of these emission estimates by conducting experiments on different varieties of biofuels being used in different regions of India.

4. Conclusions

The evaluation of emission factors, based on the laboratory studies carried out on various biofuels, shows that SO_2 emissions are lowest from bagasse and highest from dungcakes, while for NO_x it is the opposite. Based on the annual consumption for 1990, the budgets for SO_2 and NO_x have been estimated as 0.4 ± 0.3 Tg and 1.0 ± 0.4 Tg, respectively, for biofuels commonly used in India.

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REFERENCES

Akimoto, H. and Narita, H. 1994. Distribution of SO_2, NO_x and CO_2 emissions from fuel combustion and industrial activities in Asia with $1^\circ \times 1^\circ$ resolution. *Atmos. Environ.* **28**, 213–225.

Andreae, M. O., Browell, E. V., Garstang, G. L., Gregory, R. C., Hariss, R. C., Hill, G. F., Jacob, D. J., Pereira, M. C., Sachse, G. W., Setzer, A. W., Dias, P. L. S., Talbot, R. W., Torres, A. L. and Wofsy, S. C. 1988. Biomass burning emission and associated haze layers over Amazonia. *J. Geophys. Res.* **93**, 1509–1527.

Andreae, M. O, Atlas, E., Cachier, H., Cofer, W. R., III, Geoffrey, W. H., Helas, G., Koppmann, R., Lacaux, J. P. and Ward, D. E. 1996. Trace gas and aerosol emissions from Savanna fires. In: *Biomass burning and global change*, (ed. J. S. Levine), Publisher, Place, 278–295.

Arndt, R. L., Carmichael, G. R., Streets, D. G. and Bhatti, N. 1997. Sulphur dioxide emissions and sectoral contributions to sulphur deposition in Asia. *Atmos. Environ.* **31**, 1553–1572.

Bhattacharya, S. and Mitra, A. P. 1998. *Greenhouse gas emissions in India for the base year 1990*. Scientific Report No. 11, Global Change Centre, National Physical Laboratory, New Delhi.

Boleij, J. S. M., Ruigewaard, P., Hoek, F., Thairu, H., Wafula, E., Onyango, F. and De Koning, H. 1989. Domestic air pollution from biomass burning in Kenya. *Atmos. Environ.* **23**, 1677–1681.

Brocard, D., Lacaux, C., Lacaux, J. P., Kouadio, G. and Yoboue, V. 1996. Emissions from the combustion of biofuels in Western Africa. In: *Biomass burning and global change*, (ed. J. S. Levine), Publisher, Place, 350–360.

Crutzen, P. J. and Andreae, M. O. 1990. Biomass burning in the Tropics: Impact on Atmospheric chemistry and biogeochemical cycles. *Science* **250**, 1669–1678.

Delmas, R., Lacaux, J. P., Menaut, J. C., Abbadie, L., Roux, X. L., Helas, G. and Lobert, J. 1995. Nitrogen compound emission from biomass burning in Tropical African

savanna FOS/DECAFE 1991 experiment (Lamto, Ivory coast). *J. Atmos. Chem.* **22**, 175–193.

Garg, A., Shukla, P. R., Bhattacharya, S. and Dadhwal, V. K. 2001. Sub-region (district) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility. *Atmos. Environ.* **35**, 703–713.

Hall, D. O. 1991. Biomass energy. *Energy Policy* **19** 711–737.

Harrison, R. M. and Perry, R. (eds.) 1986. *Handbook of Air Pollution Analysis* (2nd edn.). Chapman and Hall, London.

Hurst, D. F., Griffith, D. W. T. and Cook, G. D. 1996. Trace gas emissions from biomass burning in Australia. In: *Biomass burning and global change*, (ed. J. S. Levine), Publishers, Place, 787–794.

Husar, R. B., Husar, J. D. and Laurent, M. 2000. Distribution of continental surface aerosol extinction based on visual range data. *Atmos. Environ*. **34**, 5067–5078.

IPCC. 1995. *Guidelines for national greenhouse gas inventories.* Reference Manual, Intergovernmental Panel on Climate Change, Bracknell, USA.

IPCC. 1997. *Revised Guidelines for National Greenhouse gas inventories*. Reference Manual, Intergovernmental Panel on Climate Change, Bracknell, USA.

Joshi, V. 1991. Biomass burning in India. In: *Global biomass burning*, (ed. J. S. Levine), MIT press, Cambridge, MA, USA, 185–193.

Kato, N. 1996. Analysis of structure of energy consumption and dynamics of emission of atmospheric species related to the global environmental change (SO_x, NO_x and CO_2) in Asia. *Atmos. Environ*. **30**, 757–785.

Kituyi, E., Marufu, L., Wandiga, S. O., Jumba, I. O., Andreae, M. O. and Helas, G. 2001. Carbon monoxide and nitric oxide from biofuel fires in Kenya. *Energy Conversion & Management* **42**, 1517–1542.

Kulshrestha, U. C., Jain, M., Sekar, R., Vairamani, M., Sarkar, A. K. and Parashar, D. C. 2001. Chemical characteristics and source apportionment of aerosols over Indian Ocean during INDOEX-1999. *Curr. Sci.* **80**, 180–185.

Lacaux, J. P., Delmas, R., Jambert, C. and Kuhlbusch, T. A. J. 1996. NO_x emissions from Savanna fires. *J. Geophys. Res*. **101**, 23 585–23 595.

Narang, H. P., Parashar, D. C., Bhattacharya, S. C. and Abdul Salam, P. 1999. A study of biomass as a source of energy in India. *RERIC Int. Energy J*. **21**, 11–23.

OECD/IEA, 1991. *Greenhouse gas emissions, the energy dimension*. OECD/IEA, Paris.

Parashar, D. C., Kulshrestha, U. C. and Sharma, C. 1998. Anthropogenic emissions of NO_x, NH_3 and N_2O in India. *Nut. Cycl. Agroecol.* **52**, 255–259.

Perry, R. and Young, R. J. (eds.) 1977. *Handbook of air pollution analysis*. Chapman Hall, London.

Smith, K. 1988. Air pollution: Assessing total exposure in developing countries. *Environment* **30**, 16–20; 28–35.

Spiro, P. A., Jacob, D. J. and Logan, J. A. 1992. Global inventory of sulphur emissions with $1^\circ \times 1^\circ$ resolution. *J. Geophys. Res.* **97**, 6023–6036.

Streets, D. G. and Waldhoff, S. T. 1998. Biofuel use in Asia and acidifying emissions. *Energy*, **23**, 1029–1042.

Streets, D. G., Tsai, N. Y., Akimoto, H. and Oka, K. 2000. Sulphur dioxide emissions in Asia in the period 1985–1997. *Atmos. Environ*. **34**, 4413–4424.

TEDDY. 1998. *TERI energy data directory & yearbook*. Tata Energy Research Institute, New Delhi.

Van Aardenne, J. A., Carmichael, G. R., Hiram Levy, H., II, Streets, D. and Hordijk, L. 1999. Anthropogenic NO_x emissions in Asia in the period 1990–2020. *Atmos. Environ*. **33**, 633–646.

Venkataraman, C., Bharadwaj, C. and Patwardhan, A. 1999. Anthropogenic sulphate aerosol from India: estimates of burden and direct radiative forcing. *Atmos. Environ.* **33**, 3225–3235.

World Resources Institute. 1993. *World Resources* 1992–93. World Resources Institute, New York.