Atmospheric Environment 84 (2014) 189–197

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Estimation and characterization of gaseous pollutant emissions from agricultural crop residue combustion in industrial and household sectors of Pakistan

Muhammad Irfan [a], Muhammad Riaz [a], Muhammad Saleem Arif [a,*], Sher Muhammad Shahzad [b], Farhan Saleem [a], Naveed-ur -Rahman [c], Leon van den Berg [d,e], Farhat Abbas [a]

[a] Department of Environmental Sciences, Government College University Faisalabad, Faisalabad 38000, Pakistan
[b] Department of Soil & Environmental Sciences, University College of Agriculture, University of Sargodha, Pakistan
[c] Department of Environment, Health and Safety, Interloop Ltd., Faisalabad, Pakistan
[d] Department of Aquatic Ecology & Environmental Biology, Faculty of Science, Radboud University Nijmegen, The Netherlands
[e] B-WARE Research Centre, Nijmegen, The Netherlands

HIGHLIGHTS

- Energy crisis has resulted in increased combustion of crop residues in Pakistan.
- Emission attributes of rice husk, rice straw, corncobs and bagasse were estimated.
- Rice straw had significantly higher gaseous pollutant emission factors.
- Bagasse had the highest value of total emission of gaseous pollutants.
- Rice straw and bagasse had >90% share in total gaseous pollutant emissions.

ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form
14 November 2013
Accepted 18 November 2013

Keywords:
Biomass fuel
Gaseous pollutants
Emission factors
Emission allocations
Emission inventory

ABSTRACT

A long-term energy crisis has resulted in increased combustion of biomass fuel in industrial and household sectors in Pakistan. We report results of a study on the emission characteristics of rice husk, rice straw, corncobs and bagasse since they are frequently used as biomass fuel and differed remarkably in physico-chemical and combustion characteristics. Emission concentrations and emission factors were determined experimentally by burning the biomass fuel using a burning tower. Modified combustion efficiency (MCE) of rice husk, rice straw, corncobs and bagasse was >0.97 indicating that combustion was dominated by flaming mode. Emission factors of gaseous pollutants CO, CO_2, NO_2, NO, NO_x and SO_2 for rice straw were calculated to be 17.19 ± 0.28, 1090.07 ± 24.0, 0.89 ± 0.03, 1.48 ± 0.04, 3.16 ± 0.08 and 0.38 ± 0.03 g kg^{-1} respectively which were significantly ($p < 0.05$) higher compared to those from rice husk (14.05 ± 0.18, 880.48 ± 8.99, 0.19 ± 0.01, 1.38 ± 0.02, 2.31 ± 0.04 and 0.11 ± 0.03 g kg^{-1}), corncobs (8.63 ± 0.12, 595.44 ± 10.38, 0.16 ± 0.01, 0.70 ± 0.01, 1.23 ± 0.02 and 0.02 ± 0.00 g kg^{-1}) and bagasse (12.39 ± 0.08, 937.03 ± 9.07, 0.36 ± 0.03, 1.44 ± 0.02, 2.57 ± 0.04 and 0.18 ± 0.02 g kg^{-1}). Total emissions of CO, CO_2, NO_2, NO, NO_x and SO_2 were estimated to be 3.68, 230.51, 0.05, 0.36, 0.60 and 0.03 Gg for rice husk, 33.75, 2140.35, 1.75, 2.91, 6.20 and 0.75 Gg for rice straw, 1.11, 76.28, 0.02, 0.02 and 0.03 Gg for corncobs and 42.12, 3185.53, 1.22, 4.90, 8.74 and 0.61 Gg for bagasse respectively. Rice straw, however, had significantly ($p < 0.05$) higher potential of gaseous pollutant emission factors. Bagasse had the highest values of total emissions followed by rice straw, rice husk and corncobs. Rice straw and bagasse, on cumulative basis, contributed more than 90% of total emissions of gaseous pollutants. Results reported in this study are important in formulating provincial and regional emission budgets of gaseous pollutants from burning of agricultural residues in Pakistan.

* Corresponding author. Tel.: +92 (0) 41 920 1566; fax: +92 (0) 41 920 0671.
E-mail addresses: msarif@outlook.com, msarif19@yahoo.com (M.S. Arif).

1352-2310/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.atmosenv.2013.11.046

1. Introduction

Pakistan, with an annual population growth rate of 2.4% and projected population of 18 million people, has been witnessing severe energy crisis over the last five years. At present, approximately 54% of energy requirement is met through fossil fuels such as oil and gas, and rest of the energy is obtained from biomass fuel such as wood and agricultural residues (Tahir et al., 2010). Crop residues are value added organic byproducts generated from harvesting and processing of agricultural crops.

Due to lack of knowledge regarding the significance of crop residues, they are often burned in the field (Samra et al., 2003). Agricultural open field burning is widely practiced in the rural areas and suburbs to dispose of biomass waste (Yevich and Logan, 2003). Several reasons favor burning of crop residue including cleaning and field preparation, meeting domestic energy requirements, fertilizing the field with ash and offering the pest control (Huang et al., 2012; Korontzi et al., 2006). However, the quantity of the crop residues burned and the fire intensity strongly influence the amount of carbon and nutrients released during the fire (Sharma and Mishra, 2001).

Crop residues and/or agricultural wastes are important domestic fuels since ancient times. Nearly half of the world population utilizes crop residues for domestic heating and cooking, especially in developing countries (Guoliang et al., 2008). According to estimates of Andreae and Merlet (2001) and Bond et al. (2004), burning of crop residues accounts for 540 and 475 Tg dry matter combustion per year respectively. Therefore, air quality deterioration, in cities located around major agricultural sectors, is perhaps not surprising (Cancado et al., 2006). There also have been extensive evidence of overlooking the emissions of trace gases from crop residue burning to a large extent, because these fires are often short-lived and do not offer significant time to be detected and quantified under natural conditions (Smith et al., 2007; Vander-Werf et al., 2010).

Field and domestic burning of crop residues consist of pyrolysis, smoldering and flaming processes, however, dominance of these processes and resultant gas emissions largely depend on the type of material being burnt (Andreae and Merlet, 2001). For example, agricultural residues usually follow flaming mode of burning that results in higher NO_x concentrations, dung cakes are burnt through smoldering mode and burning fuel wood normally pass through all three stages of combustion (Saud et al., 2011).

Environmental problems associated with crop residue burning include smoke, trace gases and particulate matter (Bijay-Singh and Yadvinder-Singh, 2003). Concentrations of the greenhouse gases have increased over the past 50 years as a result of anthropogenic activities including agriculture, and have accelerated the rise in average global temperature (IPCC, 2001). In particular, uncontrolled and incomplete open-field burning results in emission of toxic air pollutants and greenhouse gases which affect the atmospheric chemistry (Andreae and Merlet, 2001; Kanabkaew and Oanh, 2011). Agricultural crop residue burning is also the prime source of the micron-sized aerosols which affect the composition of atmosphere (Awasthi et al., 2011; Saud et al., 2011). Trace gases emitted during burning, carbon monoxide and nitrogen oxide, are the main precursors of tropospheric ozone (O_3), decreasing the concentrations of tropospheric hydroxyl radical (OH) (Mauzerall et al., 1998); the later holds potential threats to environment, ecosystem and human health (Cheng et al., 2000).

Emission factor is a crucial parameter used to estimate and quantify emission of trace gases and aerosols from biomass burning which describes compounds or substances emitted per amount of dry fuel burned (Andreae and Merlet, 2001; Yang et al., 2008). Emission factors of gaseous pollutants vary with time and space, and also depend on type, quality and composition of biomass fuel (Shah et al., 1997). Emission factors, measured over longer time periods, are helpful in making emission inventories to control air pollution at local, national and regional levels. Emission factors, from different biomass burning, are integral components for making emission inventories and budgets.

Although studies on emissions from biomass burning are well documented across the globe (e.g. Delmas and Servant, 1982; Lacaux et al., 1993) including studies of Saud et al. (2011) in India and Zhang et al. (2008) in China, the research area is yet to be explored in Pakistan. It should be noted that there are limited emission factors available in developing countries, and those reported in the literature often varied dramatically due to difference in fuel properties and combustion conditions. In addition, emission factors measured in the laboratory may differ from those obtained in field measurements (Roden et al., 2006, 2009; Shen et al., 2010). Therefore, there is need to assess emission characteristics of biomass burning in Pakistan since sever energy crisis have forced large population to use firewood, crop residues and animal dung for meeting energy demands, especially in rural and peri-urban areas.

Keeping in context of the above discussion, a field scale study was performed to evaluate the emission characteristics of commonly burned agricultural biomass wastes in Pakistan i.e. rice straw, rice husk, corn cobs and bagasse. Furthermore, to our knowledge, this is the first study determining emission concentrations, emission factors and emission inventories of trace gases from burning of crop residues in Pakistan. The current study was designed to:

- investigate the emissions of different gaseous pollutants (CO, CO_2, NO_2, NO, NO_x, SO_2) from burning of rice straw, rice husk, corncobs and bagasse.
- characterize and compare the emission factors of rice straw, rice husk, corncobs and bagasse burning
- prepare emission inventories to estimate total emissions of trace gases

2. Materials and methods

2.1. Selection, sampling and preparation of crop residue samples

Rice straw, rice husk, corncobs and bagasse were used in this study because they are burnt in the agricultural fields as waste products and in homes and/or industries for energy in Pakistan. Samples of crop residues were collected in triplicate from farmers' fields and agricultural processing industry around Faisalabad and Kasur in Punjab, Pakistan (Fig. 1). Rice straw and bagasse were collected from Gatwala and corncobs were collected from Jarranwala, suburbs of Faisalabad. However, rice husk samples were obtained from Kasur. Samples were air dried under outdoor ambient conditions for several days before the start of experiment. When uniformly air-dried, samples were kept in sealed plastic bags.

2.2. Construction and design of burning tower

For this experiment, a metallic combustion tower was designed with an aim to facilitate the analysis by channelizing the smoke through one stack (Fig. 2). The tower consisted of an inverted funnel shaped cylindrical bottom having 1.2 m diameter and 1.0 m height. A stack with internal diameter of 0.2 m and length of 1.2 m was attached at the top end of the cylindrical bottom (Fig. 2a). The stack was at 1.2 m height from the ground. The cylindrical bottom was supported with iron rods to keep it at 0.2 m height from ground level (Fig. 2b). A metallic burning table of 0.4 m × 0.4 m dimension was also constructed using a coarse iron wire-gauze which has 0.2 m long legs at its four corners. The stack had an

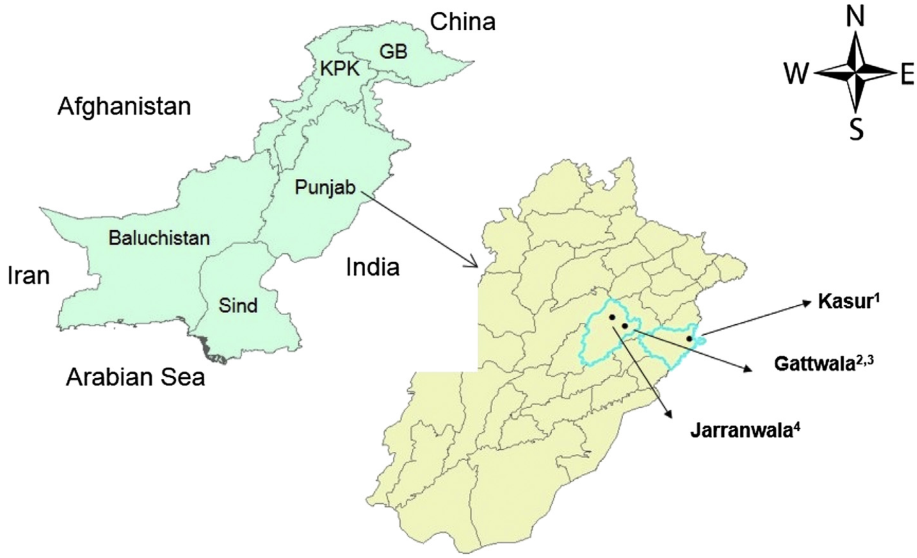

Fig. 1. Sampling locations of rice husk, rice straw, corncobs and bagasse in Punjab, Pakistan. [1]Rice husk, [2]Rice straw, [3]Bagasse, [4]Corncobs.

opening at 0.6 m height from its bottom for insertion of the instrumental probe and recording of different parameters. Keeping the burning material on the perforated metallic stand, at 0.2 m height, ensured uniform 3-D movement of gases and ample supply of oxygen to facilitate uniform burning under ambient conditions.

2.3. Emission analysis

2.3.1. Principle of flu gas analyzer

Trace gas emissions were measured using a digital flu gas analyzer, testo 350-S (testo AG, Germany) by following a modified protocol of Li et al. (2009). The analyzer draws gases from the stack with the help of sampling probe. Gases pass through the sensors and sensors, based on the principle of selective ion potentiometery, measure the electrochemical potential differences. The range of the instrument for emission concentrations of CO_2 was 0–50 vol. % whereas range was 0–10000, 0–3000, 0–500 and 0–5000 ppm for CO, NO, NO_2 and SO_2 respectively. The accuracy of the instrument for CO, NO, NO_2 and SO_2 emission concentrations was ±5% of the measured value.

2.3.2. Experimental process

Before each burning test, the selected crop residue was weighed and placed on metallic perforated burning table designed especially to facilitate residue burning (Fig. 3). After ignition, sampling probe of the analyzer was inserted into the stack to measure trace gas concentrations from the start to the end of each burning cycle of residue combustion at 10 s interval (Jenkins et al., 1996). Experimental conditions and design of the combustion tower allowed natural and uniform ventilation during each burning event. Time was noted for each burning event and when burning process was completed, ash was collected and weighed to calculate percent mass loss. Each crop residue burning test was repeated three times throughout the experiment; however, where

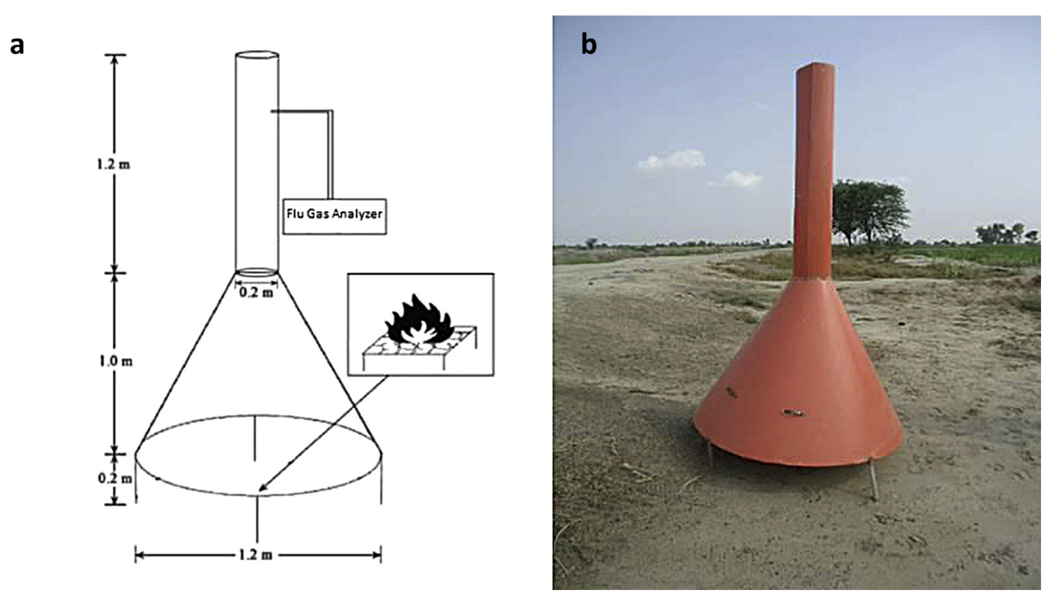

Fig. 2. Experimental set up: (a) schematic diagram, (b) actual burning tower.

Fig. 3. Air dried biomass on metallic stand before burring: (a) rice husk, (b) rice straw, (c) bagasse, (d) corn cobs.

appropriate, mass weighted means of the data are presented in tables and figures.

2.4. Analytical protocols

2.4.1. Moisture content and mass loss

Moisture content was measured gravimetrically by drying crop residue samples at 90 °C for 48 h in a pre-heated oven. Samples were cooled in a desiccator before they were reweighed and moisture content was calculated on percent dry mass basis. Mass loss was calculated by weighing the fuel samples before and after the combustion process was completed (ash content). Mass loss was also presented on percent mass basis.

2.4.2. Total carbon (C), nitrogen (N) and sulfur (S) contents of biomass

Oven-dried crop residue samples from moisture content determination were further used for the measurements of total C, N and S contents. For C and N analysis, the oven-dried samples were ground using a ball mill (Retsch MM301) to homogenize the samples prior to analysis on a Carlo Erba Na 1500 CNS analyzer (Thermo Fisher Scientific, Waltham, MA). C and N content of the samples were calibrated using the standards atropine and acetanilide and an internal reference sample. For S analysis, 100 mg residue material was digested under high pressure with nitric acid and hydrogen peroxide in sealed Teflon vessels using a Milestone destruction microwave oven (MLS 1200 mega). After digestion, the samples were analyzed for S contents on an inductively-coupled plasma emission spectrophotometer (ICP, Spectroflame Flame VML2). Standard reference solutions for S were analyzed for calibration on ICP. C, N and S contents of residue samples were expressed on percent dry mass basis.

2.4.3. Stack gas velocity, flu temperature, burning cycle and emission concentrations of gaseous pollutants

The stack gas velocity (m s^{-1}), flu temperature (°C), burning cycle (s) and emission concentrations of CO, CO_2, NO_2, NO, NO_x and SO_2 (ppmv) were measured using the digital flu gas analyzer (testo 350-S). At the start of the burning cycle, the probe of the analyzer was inserted into the stack through the designed hole to record the said parameters for each fuel burning event every 10 s until the burning cycle was complete. Emission concentrations were used to calculate emission factors of the gaseous pollutants (Guoliang et al., 2008).

2.5. Calculation of emission factors

Fuel based emission factors of gaseous pollutants represent mass of the specie released per unit fuel weight (Andreae and Merlet, 2001). Emission factors of gaseous pollutants were calculated using the mass balance equation described by Jenkins et al. (1996) and Guoliang et al. (2008) and were expressed on g per kg dry weight of the fuel:

$$E_i = \frac{10^{-3}}{m_{fd}} \int_{t0}^{tf} A_s u C_i \frac{w_i}{22.4} dt \quad (1)$$

Where

E_i = Emission factor for species i
m_{fd} = Mass of crop residue used in the each burning test
t_0 = Initial start time for each burning test
t_f = Finishing time for the test
A_s = Stack area (0.03 m^2)
u = Average stack gas velocity
C_i = Sample concentration of species i, and
w_i = Molecular weight of species i

2.6. Quantification of crop residue production and burning in Pakistan

Crop residues production was estimated from crop production data (Government of Pakistan, 2011–12) and relevant residue generation rate or ratio (Singh and Gu, 2010) using following relationship:

$$\text{Crop residues (Mt)} = \text{Crop production (Mt)} \times \text{crop to residue ratio} \quad (2)$$

Total amount of residue burnt, for each residue, was quantified as under:

$$\text{Total residue burnt (Mt)} = \text{Total crop residue (Mt)} \times \text{Residue dry matter fraction} \times \text{Crop residue burnt (\%)} \quad (3)$$

Dry matter fraction for each crop residue was obtained from Streets et al. (2003) and crop residue percent being burnt was estimated to be 25% for each crop residue (Iqbal and Goheer, 2008).

2.7. Estimation of total annual trace gases emissions

Total annual emission of each gaseous pollutant from burning of biomass fuel was calculated using following relationship described by Kanabkaew and Oanh (2011) and Yang et al. (2008):

$$\text{Total annul emissions} = M \times \text{EF} \quad (4)$$

Where,

E = Total annual emission (Gg)
M = Quantity of crop residues burnt in a year (Mt dry mass of residue)
EF = Emission factors of gaseous species (g kg^{-1} fuel dry mass)

2.8. Modified combustion efficiency (MCE)

Ward et al. (1992) described combustion efficiency (CE) as the ratio of carbon released as CO_2 to the total mass of carbon in the fuel biomass. CE may be considered helpful in determination of the completeness of the combustion as well as indication of process and/or processes dominant during the combustion. CE is usually measured as under:

$$\text{CE} = C_{CO_2}/C_{Total}$$

Where C_{CO_2} is the carbon emitted in CO_2 form and C_{Total} is the total amount of carbon in gaseous and particulate emissions. In the current study, C_{CO_2} and C_{CO} were measured but particulate matter contents were not measured; hence, the modified combustion efficiency (MCE) was calculated following relationship proposed by Zhang et al. (2008):

$$\text{MCE} = C_{CO_2}/[C_{CO_2} + C_{CO}] \quad (5)$$

2.9. Statistical analysis

Data regarding moisture content (%), mass loss (%), C (%), N (%), S (%), flu temperature (°C), stack gas velocity (m s^{-1}), burning cycle (s), gaseous pollutant emission concentration (ppmv) and gaseous emission pollutant factors (g kg^{-1}), measured and/or calculated on replicate samples, were subjected to one way analysis of variance (ANOVA). Tukey's HSD postdoc test was used for multiple means comparisons technique only for those parameters where significant treatment effects were found. However, where appropriate, figures and tables contain means of three replicates.

3. Results and discussion

3.1. Biomass characteristics

Physical and chemical characteristics of rice husk, rice straw, corncobs and bagasse are summarized in Table 1. Moisture content ranged from 9.74 ± 0.43% for rice husk to 12.06 ± 0.18% for bagasse. Mass loss percent values were 85.66 ± 0.17% for rice husk, 81.07 ± 0.07% for rice straw, 97.06 ± 0.04% for corncobs and 89.59 ± 0.62% for bagasse. Mass loss percent of corncobs was significantly ($p < 0.05$) higher compared to that from rice husk, rice straw and bagasse.

C, N and S contents of crop residues are also shown in Table 1. C contents of corncobs and bagasse were 44.70 ± 0.04 and 43.87 ± 0.10% respectively which were significantly ($p < 0.05$) higher than C content of rice husk (36.29 ± 1.60%) and rice straw (39.16 ± 0.05%). N contents were 0.47 ± 0.03% for rice husk, 0.59 ± 0.04% for rice straw, 0.44 ± 0.03% for corncobs and 0.62 ± 0.02% for bagasse. S contents of rice straw, 0.17 ± 0.01%, were the highest among the crop residue used in this study and were significantly ($p < 0.05$) different from rice husk, corncobs and bagasse.

The moisture content, mass loss, C, N and S contents of biomass fuel have a significant impact on the burning and emission characteristics of biomass. In our study, bagasse had the highest moisture contents compared to rice husk, rice straw and corncobs. The moisture content of rice straw (11.05%) was in accordance with the range of moisture content (10–12%) for rice straw previously reported by Buzarovska et al. (2008). However, the moisture content of the rice husk was higher compared to that 7.20% observed by Ileleji and Zhou (2008). This higher moisture content of rice husk could be attributed to regional climatic conditions. The results of mass oxidized (mass loss) for bagasse was similar to those reported by Sahai et al. (2011). However, mass loss values for rice straw, rice husk and corncobs was found to be 81.07, 85.66 and 89.59% which differed slightly from the reported 90% value of mass loss for these crop residues (Sahai et al., 2011). In this study, we have also reported C, N and S contents of crop residues since the chemical composition of the crop residue is an important factor in determining the emission factors of gaseous pollutants as argued by Zhang et al. (2008).

3.2. Burning characteristics

Flu temperature, stack gas velocity, burning cycle and modified combustion efficiency (MCE) for rice husk, rice straw, corncobs and bagasse are presented in Table 2. Flu temperatures of rice straw

Table 1
Moisture content, mass loss, total carbon, total nitrogen and total sulfur content of rice husk, rice straw, corncobs and bagasse.

Parameter	Rice husk	Rice straw	Corncobs	Bagasse
Moisture content (%)	9.74 (0.43) a	11.05 (0.27) ab	11.43 (0.28) a	12.06 (0.18) a
Mass loss (%)	85.66 (0.17) c	81.07 (0.07) d	97.06 (0.04) a	89.59 (0.62) b
Total carbon (%)	36.29 (1.60) b	39.16 (0.05) b	44.70 (0.04) a	43.87 (0.10) a
Total nitrogen (%)	0.47 (0.03) bc	0.59 (0.04) ab	0.44 (0.03) c	0.62 (0.02) a
Total sulfur (%)	0.06 (0.00) b	0.17 (0.01) a	0.03 (0.00) c	0.07 (0.00) b

Values are means of three replicates. Standard errors of means are enclosed in parenthesis. In a row, for specified parameter, means with different letters differ significantly from each other at $p < 0.05$.

(245.50 ± 6.16 °C) and bagasse (263.50 ± 5.01 °C) were significantly higher ($p < 0.05$) compared to that for rice husk (115 ± 2.31 °C) and corncobs (197.57 ± 2.72 °C). Values of stack gas velocity were 12.33 ± 0.10, 14.34 ± 0.91, 14.17 ± 0.29 and 18.39 ± 0.30 m s^{-1} for rice husk, rice straw, corncobs and bagasse respectively. Bagasse had significantly ($p < 0.05$) higher stack gas velocity values compared to rice husk, rice straw and corncobs. There were significant ($p < 0.05$) differences in length of burning cycle for rice husk, rice straw, corn cobs and bagasse. MCE ranged from 0.976 for rice husk and rice straw to 0.980 for bagasse. Bagasse had significantly ($p < 0.05$) higher MCE compared to rice husk, rice straw and corncobs.

In this study, stack gas velocity was measured under ambient conditions since it determines speed of gaseous pollutant emissions from open burning of residue biomass and depends on the ambient environmental conditions like air flow to ensure optimum oxygen concentrations for complete and efficient burning (Wardoyo et al., 2006). Bagasse showed the highest value of stack gas velocity in this study. Burning cycle could also serve as important determinant of combustion efficiency of biomass and depends on physical and chemical characteristics of fuel biomass (Ward et al., 1992). MCE was measured to distinguish between flaming and smoldering mode of combustion during crop residue burning. MCE in our study was 0.976, 0.976, 0.978 and 0.980 for rice husk, rice straw, corncobs and bagasse respectively which falls in the range of 0.9–1.0 suggested by Reid et al. (2005) for fires following flaming as dominant mode of combustions. However, it is also an established fact that smoldering and flaming mode of combustions cannot be separated completely when biomass is burnt under field conditions. Nevertheless, MCE of crop residues in our study support the well-documented claim that agricultural crop residue burn under flaming mode under field and laboratory conditions (Saud et al., 2011; Zhang et al., 2008).

3.3. *Emission factors of gaseous pollutants*

Emission factors (EFs) of gaseous pollutants, calculated from emission concentrations, of rice husk, rice straw, corncobs and bagasse are shown in Fig. 4. The mean emission factors of CO_2 for rice husk, rice straw, corncobs and bagasse were 880.48 ± 8.99, 1090.1 ± 24.0, 595.44 ± 10.4 and 937.03 ± 9.07 g kg^{-1} respectively (Fig. 4a). Emission factor of CO_2 of rice straw were significantly ($p < 0.05$) higher compared to rice husk, corncobs and bagasse. Emission factors of CO from rice husk (14.04 ± 0.18 g kg^{-1}), rice straw (17.19 ± 0.28 g kg^{-1}), corncobs (14.04 ± 0.18 g kg^{-1}) and bagasse (12.39 ± 0.08 g kg^{-1}) followed order similar to that of CO_2 emission factors (Fig. 4b). Emissions factors of NO_2 were 0.19 ± 0.03, 0.89 ± 0.03, 0.16 ± 0.01 and 0.36 ± 0.03 g kg^{-1} for rice husk, rice straw, corncobs and bagasse respectively (Fig. 4c). Emission factors of NO_2 from rice straw were significantly ($p < 0.05$) higher compared to that from rice husk, rice straw, corncobs and bagasse. Emission factors of NO from rich husk, rice straw and bagasse were 1.38 ± 0.02, 1.48 ± 0.04 and 1.44 ± 0.01 g kg^{-1} respectively (Fig. 4d); they were significantly ($p < 0.05$) higher from NO emission factors of corncobs (0.70 ± 0.01 g kg^{-1}). Emission factors of NO_x ranged from 1.23 ± 0.01 g kg^{-1} for corncobs to 3.16 ± 0.08 g kg^{-1} for rice straw (Fig. 4e). Emission factors of SO_2 were 0.11 ± 0.03, 0.38 ± 0.03, 0.02 ± 0.00 and 0.18 ± 0.02 g kg^{-1} from burning of rice husk, rice straw, corncobs and bagasse respectively (Fig. 4f). Emission factors of SO_2 from rice straw were found to be highest and significantly ($p < 0.05$) different from rice husk, corncobs and bagasse.

Emission factor is an important tool to estimate total gaseous pollutant emissions to help making pollution inventories and policy decision to mitigate air pollution (van Leeuwen and Hermens, 1995; Andreae and Merlet, 2001; Yang et al., 2008). Emission factors for different crop residues have been widely reported in literature, especially of rice straw. The rice straw produced the highest emission factors of the trace gases in the current study. The emission factors of CO, CO_2, NO_2, NO, NO_x and SO_2 from rice straw were calculated to be 17.19 ± 0.28, 1090.1 ± 24.0, 0.89 ± 0.03, 1.48 ± 0.04, 3.16 ± 0.08 and 0.38 ± 0.03 g kg^{-1} respectively which showed considerable agreement with data of some previous studies on rice straw e.g. emission factors of CO_2 101 g kg^{-1} (Smith et al., 1993), NO_x 3.43 g kg^{-1} (Guoliang et al., 2008) and NO_2 0.79 g kg^{-1} (Zhang et al., 2008). However, emission factors of CO and SO_2 were found to be different than those reported in literature e.g. Jenkins et al. (1996) reported 31.41 and 0.62 g kg^{-1} emission factors of CO and SO_2 respectively which were higher than those reported in our study. The emission factors of CO, CO_2, NO_2, NO, NO_x and SO_2 from bagasse were 12.39 ± 0.08, 937.03 ± 9.07, 0.36 ± 0.03, 1.44 ± 0.02, 2.57 ± 0.04, and 0.18 ± 0.02 g kg^{-1} respectively. Emission factors of NO_x and NO for bagasse from this study were comparable to 2.6 g kg^{-1} NO_x (Dennis et al., 2002) and 1.7 g kg^{-1} NO (Brocard et al., 1996). However, emission factors of CO, CO_2, NO_2 and SO_2 from bagasse were lower from those previously reported e.g. CO 34.7 g kg^{-1} and CO_2 1130 g kg^{-1} (Kanabkaew and Oanh, 2011), NO_2 1.6 g kg^{-1} (Brocard et al., 1996), SO_2 0.23 g kg^{-1} (Kato, 1996) and 0.50 g kg^{-1} (Gadi et al., 2003). These differences in emission factors could be due to factors like moisture content and local climatic conditions (Goldammer et al., 2009), physical and chemical differences in the crop residue composition of different regions (Lobert and Warnatz, 1993) and, especially N contents for the variations in NO_x emission factors (Zhang et al., 2008).

The emission factors from corncobs and rice husk have not widely been reported in the literature and this is perhaps the first attempt in this regard. The emission factors of CO, CO_2, NO_2, NO, NO_x and SO_2 from burning of corncobs were observed to be 8.63 ± 0.12, 595.44 ± 10.38, 0.16 ± 0.01, 0.70 ± 0.01, 1.23 ± 0.02 and 0.02 ± 0.00 g kg^{-1} respectively. The results of emission factors of SO_2 and NO_x were in reasonable agreement with 0.04 g kg^{-1} for SO_2 by Cao et al. (2008) and 1.27 g kg^{-1} for NO_x by Zhang et al. (2008) which were based on the burning of aggregated maize crop waste. However, the emission factors of CO and CO_2 from our study for corncobs differed from those reported by Andreae and Merlet (2001) for CO (53 g kg^{-1}) and Zhang et al. (2008) for CO_2

Table 2
Flu temperature, stack gas velocity, burning cycle and modified combustion efficiency (MCE) of rice husk, rice straw, corncobs and bagasse.

Parameter	Rice husk	Rice straw	Corncobs	Bagasse
Flu temperature (°C)	115 (2.31) c	245.50 (6.16) a	197.57 (2.72) b	263.50 (5.01) a
Stack cas velocity (m s^{-1})	12.33 (0.10) c	14.34 (0.91) b	14.17 (0.29) b	18.39 (0.30) a
Burning cycle (s)	953.33 (5.24) b	990 (4.04) a	618.33 (4.91) d	783.33 (8.25) c
Modified combustion efficiency (MCE)	0.976 (0.00) a	0.976 (0.00) a	0.978 (0.00) b	0.980 (0.00) c

Values are means of three replicates. Standard errors of means are enclosed in parenthesis. In a row, for specified parameter, means with different letters differ significantly from each other at $p < 0.05$.

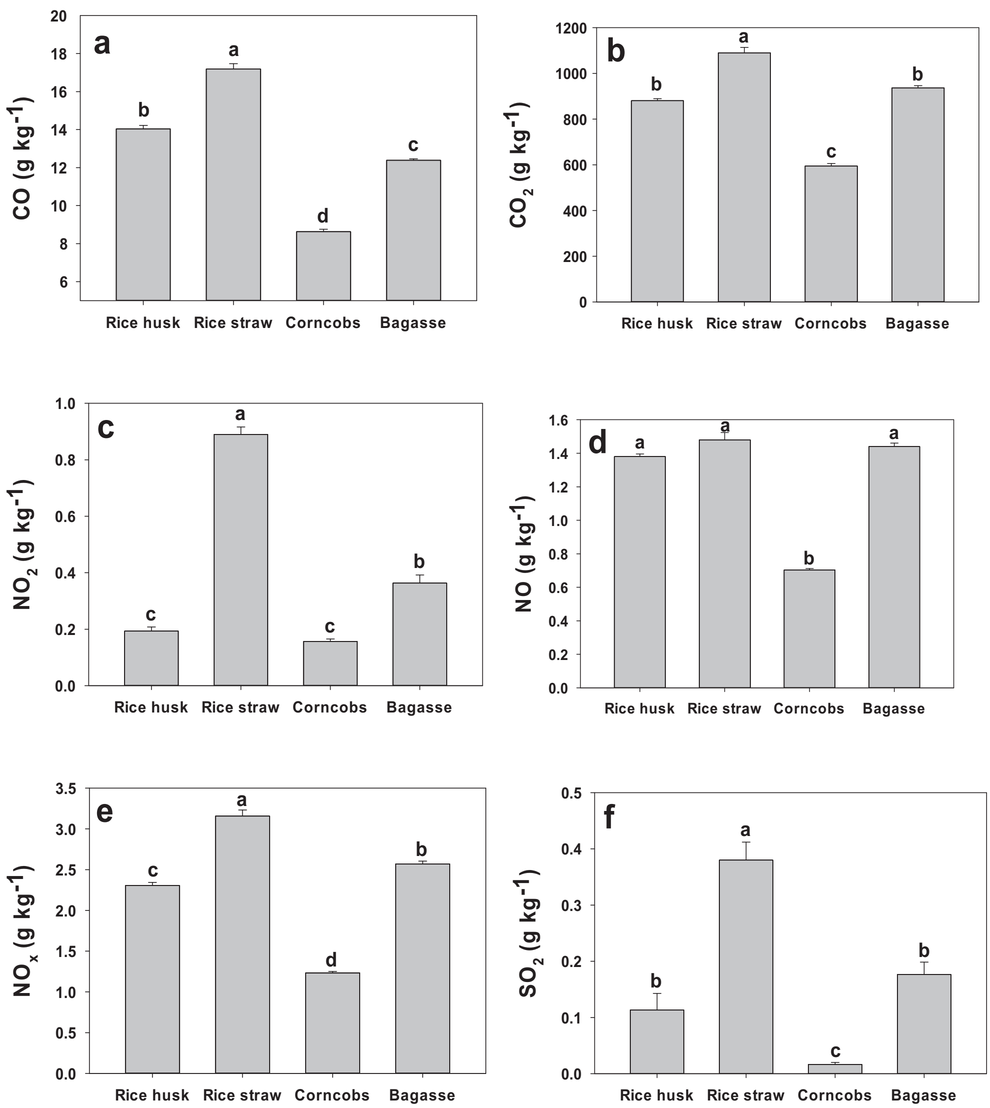

Fig. 4. Gaseous pollutant emission factors from burning of rice husk, rice straw, corncobs and bagasse: (a) CO, (b) CO_2, (c) SO_2, (d) NO_x, (e) NO_2, (f) NO (units: g kg^{-1}). Values are average of three replicates. Error bars are standard error of means ($n = 3$). Bars with different letters differ significantly from each other at $p < 0.05$.

(1160 g kg^{-1}). This difference could be due to the reason that they measured emission factors by burning aggregate maize crop residue; however, in contrast, we used corncobs which could result in different emission factors through changes in the composition of biomass (Lobert and Warnatz, 1993). The emission factors of CO, CO_2, NO_2, NO, NO_x and SO_2 from burning of rice husk were 14.04 ± 0.18, 880.48 ± 8.99, 0.19 ± 0.01, 1.38 ± 0.02, 2.31 ± 0.04 and 0.11 ± 0.03 g kg^{-1} respectively. The results suggested considerable differences in emission factors of rice straw and rice husk due to the very fact that they were sampled from different locations.

3.4. Emission estimates, inventories and allocation of gaseous pollutants

Rice husk, rice straw, corncobs and bagasse are important residue producing crops being used as biomass fuel in Pakistan. In order to prepare emission estimates, inventories and allocations, quantity of crop residues was estimated to be 1232, 9240, 1281 and 19153 Mt for rice husk, rice straw, corncobs and bagasse respectively (Table 3). Based on the dry matter fraction (Streets et al., 2003) and percent of the crop residues being combusted (25%; Iqbal and Goheer, 2008), total crop residue burned for rice husk, rice straw, corncobs and bagasse was found to be 262, 1964, 128 and 3400 Mt respectively (Table 4). Bagasse had the highest values for residue production and combustion followed by rice straw, rice husk and corncobs respectively.

Total emissions (Gg) from crop residues for CO, CO_2, NO_2, NO, NO_x and SO_2 are presented in Table 5. Total emissions from bagasse were 42.12, 3185.53, 1.22, 4.90, 8.74 and 0.61 Gg for CO, CO_2, NO_2,

Table 3
Estimation of production of rice straw, rice husk, bagasse and corncobs in Pakistan in 2011–12.

Residue type	Crop production (Mt)[a]	Crop to residue ratio[b]	Total crop residue production (Mt)[c]
Rice husk	6160	0.20	1232
Rice straw	6160	1.50	9240
Corncobs	4271	0.30	1281
Bagasse	58,038	0.33	19,153

[a] Government of Pakistan (2011–12).
[b] Singh and Gu (2010).
[c] Metric tons.

Table 4
Estimation of residue burnt in Pakistan in 2011–2012.

Residue type	Total crop residue (Mt)	Dry matter fraction[a]	Crop residue/dry matter burnt (%)[b]	Total residue burnt (Mt)[c]
Rice husk	1232	0.85	25	262
Rice straw	9240	0.85	25	1964
Corncobs	1281	0.40	25	128
Bagasse	19,153	0.71	25	3400

[a] Streets et al. (2003).
[b] Iqbal and Goheer (2008).
[c] Metric tonns.

NO, NO_x and SO_2 respectively. Total emissions from bagasse for CO, CO_2, NO and NO_x were the highest compared to those from rice straw, rice husk and corncobs. However, total emissions of NO_2 (1.75 Gg) and SO_2 (0.75 Gg) from the rice straw were found to be highest compare to the other crop residues (Table 5). Total emissions for each gaseous pollutant from burning of crop residue were 80.66 Gg for CO, 5632.67 Gg for CO_2, 3.04 Gg for NO_2, 8.19 Gg for NO, 15.70 Gg for NO_x and 1.42 Gg for SO_2. Calculated from Table 5, emission allocations for gaseous pollutants from rice husk and bagasse together accounted for 94.1, 94.6, 97.7, 95.4, 95.2 and 95.8% total emission of CO, CO_2, NO_2, NO, NO_x and SO_2. Our study also showed that the cumulative contribution of rice husk and corncobs to the total emissions of gaseous pollutants was marginal.

Total emissions of gaseous pollutants from burning of rice husk, rice straw, corncobs and bagasse were many fold lowered compared to those reported in studies from China (Zhang et al., 2008) and India (Saud et al., 2011). However, China and India are the largest countries of the world with remarkably higher agricultural crop production and crop residue generation. We estimated total emissions of gaseous pollutants considering burning of only 25% crop residue as is the case in China suggested by Gao et al. (2002) and Iqbal and Goheer (2008); however, recent energy crisis in Pakistan has led to far higher utilization of crop residues as biofuel which may mean that actual total emission could be higher. We have observed that bagasse contributed largely to the budgets of gaseous pollutants especially of CO, CO_2 and NO_x in Pakistan. This could be related to the considerably higher emission factors and the most importantly, larger amounts of bagasse production as compared to rice straw, rice husk and corncobs. The rice straw and the bagasse contributed more than 90% of total emission of gaseous pollutants. Field burning of rice husk, rice straw, corncobs and bagasse is not commonly practiced in Pakistan; however, these crop residue are largely consumed in industrial and rural sectors. In addition, household income of large percent of farmers in Pakistan is low whereas energy supply and cost is becoming expensive so they usually opt to use crop residues to meet domestic energy requirements. The latter claim is supported by studies of Cao et al. (2008) and Chen (2001) who found that field burning of crop residues was related to income level of farmers.

Table 5
Estimation of total gaseous pollutant emissions (Gg) from the crop residue burning in Pakistan in 2011–12.

Residue type	Total emissions (Gg)[a]					
	CO	CO_2	NO_2	NO	NO_x	SO_2
Rice husk	3.68	230.51	1.75	2.91	6.20	0.75
Rice straw	33.75	2140.35	0.05	0.36	0.60	0.03
Corncobs	1.11	76.28	0.02	0.02	0.16	0.61
Bagasse	42.12	3185.53	1.22	4.90	8.74	0.03
Total	**80.66**	**5632.67**	**3.04**	**8.19**	**15.70**	**1.42**

[a] 1 Gg = 1×10^9 g.

We have reported emission factors and total emissions from combustion of crop residues which are commonly used in industrial and household sectors of Pakistan. According to best of our knowledge, this is the first study reporting emission inventories of gaseous pollutants from burning of agricultural residues. Results described in the study are assumed to be helpful in making national and provincial estimates of gaseous pollutants from frequently consumed agricultural residue biomass. However, it should be noted that variations in fuel properties and combustion conditions could lead to rather rough estimates of emission factors with high degree of uncertainty.

4. Conclusions and future research

Recent energy crisis has led to increased dependency on agriculture-based biomass fuel combustion in agro-industrial and household sectors in Pakistan. Rice husk, rice straw, corncobs and bagasse represent common biomass fuels in Pakistan. Biomass fuels differed markedly for physical, chemical and combustion characteristics. Modified combustion efficiency (MCE) ranged from 0.976 to 0.980 indicating flaming as the mode of combustion under ambient conditions. This study reports experimentally measured gaseous pollutant emission concentrations, emission factors and emission inventories of rice husk, rice straw, corncobs and bagasse combusted under ambient outdoor conditions using specially designed burning tower. Emission factors of CO, CO_2, NO_2, NO, NO_x and SO_2 were determined to be 14.05 $\pm$ 0.18, 880.48 $\pm$ 8.99, 0.19 $\pm$ 0.01, 1.38 $\pm$ 0.02, 2.31 $\pm$ 0.04 and 0.11 $\pm$ 0.03 g kg^{-1} for rice husk, 17.19 $\pm$ 0.28, 1090.07 $\pm$ 24.0, 0.89 $\pm$ 0.03, 1.48 $\pm$ 0.04, 3.16 $\pm$ 0.08 and 0.38 $\pm$ 0.03 g kg^{-1} for rice straw, 8.63 $\pm$ 0.12, 595.44 $\pm$ 10.38, 0.16 $\pm$ 0.01, 0.70 $\pm$ 0.01, 1.23 $\pm$ 0.02 and 0.02 $\pm$ 0.00 g kg^{-1} for corncobs and 12.39 $\pm$ 0.08, 937.03 $\pm$ 9.07, 0.36 $\pm$ 0.03, 1.44 $\pm$ 0.02, 2.57 $\pm$ 0.04 and 0.18 $\pm$ 0.02 g kg^{-1} for bagasse. Results of emission factors of gaseous pollutants from burning of rice husk, rice straw, corncobs and bagasse were in reasonable agreement with those reported elsewhere. Total emissions of CO, CO_2, NO_2, NO, NO_x and SO_2 from burning of biomass fuels were estimated to be 80.66, 5632.67, 3.04, 8.19, 15.70 and 1.42 Gg respectively. On cumulative basis, rice straw and bagasse contributed more than 90% of total emissions of gaseous pollutants. Results of this study are important in formulating provincial and regional budgets of gaseous pollutants from burning of agricultural residues. However, biomass fuels like cotton sticks and dung cake needs to be assessed for their role in emission of gaseous pollutants in future since they also represent important biofuels in rural sectors of Pakistan.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2013.11.046

References

Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Glob. Biogeochem. Cycles 15, 955–966.
Awasthi, A., Agarwal, R., Singh, N., Gupta, P.K., Mittal, S.K., 2011. Study of size and mass distribution of particulate matter due to crop residue burning with seasonal variation in rural area of Punjab, India. J. Environ. Monitor. 13, 1073–1081.
Bijay-Singh, Yadvinder-Singh, 2003. Environmental implications of nutrient use and crop management in rice-based ecosystems. In: Mew, T.W., Brar, D.S., Peng, S., Dawe, D., Hardy, B. (Eds.), Rice Science: Innovations and Impact for Livelihood. International Rice Research Institute, Los Ban, the Philippines, pp. 463–477.
Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res. 109, 1029.

Brocard, D., Lacaux, C., Lacaux, J.P., Kouadio, G., Yoboue, V., 1996. Emissions from the combustion of biofuels in Western Africa. In: Levine, J.S. (Ed.), Biomass Burning and Global Change. MIT Press, Cambridge, MA, pp. 350–360.
Buzarovska, A., Gaceva, G.B., Grozdanov, A., Avella, M., Gentile, G., Errico, M., 2008. Potential use of rice straw as filler in eco-composite materials. Aust. J. Crop Sci. 1, 37–42.
Cancado, J.E.D., Saldiva, P.H.N., Pereira, L.A.A., Lara, L.B.L.S., Artaxo, P., Martinelli, L.A., Arbex, M.A., Zanobetti, A., Braga, A.L.F., 2006. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. Environ. Health Perspect. 114, 725–729.
Cao, G., Zhang, X., Gong, S., Zheng, F., 2008. Investigation on emission factors of particulate matter and gaseous pollutants from crop residue burning. Environ. Sci. 20, 50–55.
Chen, X.F., 2001. Economics analysis on pollution from straw burning and managing rural China. Chin. Rural Econ. 2, 47–52.
Cheng, Z.L., Lam, K.S., Chan, L.Y., Wang, T., Cheng, K.K., 2000. Chemical characteristics of aerosols at coastal station in Hong Kong. I. Seasonal variation of major ions, halogens, mineral dusts between 1995 and 1996. Atmos. Environ. 34, 2771–2783.
Delmas, R., Servant, J., 1982. The origins of sulfur compounds in the atmosphere of a zone of high productivity (Gulf of Guinea). J. Geophys. Res. 87, 11019–11026.
Dennis, A., Fraser, M., Anderson, S., Allen, D., 2002. Air pollutant emissions associated with forest, grassland, and agricultural burning in Texas. Atmos. Environ. 36, 3779–3792.
Gadi, R., Kulshestha, U.C., Sarkar, A.K., Garge, S.C., Parashar, D.C., 2003. Emissions of SO_2 and NO_x from biofuels in India. Tellus Ser. B 55, 787–795.
Gao, X., Ma, W., Ma, C., Zhang, F., Wang, Y., 2002. Analysis of the current status of utilization of crop straw in China. J. Huazhong Agric. Univ. 21, 242–247.
Goldammer, J.G., Statheropoulos, M., Andreae, M., 2009. Impacts of vegetation fire emissions on the environment, human health, and security: a global perspective. In: Bytnerowicz, A., Arbaugh, M., Riebau, A., Andersen, C. (Eds.), Wildland Fires and Air Pollution, Developments in Environmental Science, vol. 8. Elsevier, Amsterdam, pp. 3–36.
Government of Pakistan, Finance Division, 2011–12. Available at: http://www.finance.gov.pk/survey/chapter_11/02-Agriculture.pdf (accessed 05.05.12.).
Guoliang, C., Xiaoye, Z., Sunling, G., Fangcheng, Z., 2008. Investigation on emission factors of particulate matter and gaseous pollutants from crop residue burning. J. Environ. Sci. 20, 50–55.
Huang, X., Li, M., Li, J., Song, Y., 2012. A high-resolution emission inventory of crop burning in fields in China based on MODIS Thermal Anomalies/Fire products. Atmos. Environ. 50, 9–15.
Ileleji, K.E., Zhou, B., 2008. The angle of repose of bulk corn stover particles. Powder Technol. 187, 110–118.
IPCC (Intergovernmental Panel on Climate Change), 2001. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 881.
Iqbal, M.M., Goheer, M.A., 2008. Greenhouse gas emissions from agro-ecosystems and their contribution to environmental change in the Indus basin of Pakistan. Adv. Atmos. Sci. 25, 1043–1052.
Jenkins, B.M., Turn, S.Q., Williams, R.B., Goronea, M., Abd-El-Fattah, H., Mehlschaun, J., Raubach, N., Chang, D.P.Y., Kang, M., Teadue, S.V., Raabe, O.G., Campbell, D.E., Cahill, T.A., Pritchett, L., Chow, J., Jones, A.D., 1996. Atmospheric Pollutant Emission Factors from Open Burning of Agricultural and Forest Biomass by Wind Tunnel Simulations. California Air Resources Board Project No. A932-126. California Environmental Protection Agency, California, USA.
Kanabkaew, T., Oanh, N.T.K., 2011. Development of spatial and temporal emission inventory for crop residue field burning. Environ. Model. Assess. 16, 453–464.
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.
Korontzi, S., Mccarty, J., Loboda, T., Kumar, S., Justice, C., 2006. Global distribution of agricultural fires in croplands from 3 years of Moderate Resolution Imaging Spectroradiometer (MODIS) data. Glob. Biogeochem. Cycles 20, 2021.
Lacaux, J.P., Cachier, H., Delmas, R., 1993. Biomass burning in Africa: an overview of its impact on atmospheric chemistry in fire in the environment. In: Crutzen, P.J., Goldammer, J.G. (Eds.), Fire in the Environment: the Ecological, Atmospheric, and Climatic Importance of Vegetation Fires. John Wiley, New York, USA, pp. 159–191.
Li, X., Wang, S., Duan, L., Hao, J., Nie, Y., 2009. Carbonaceous aerosol emissions from household biofuel combustion in China. Environ. Sci. Technol. 43, 6076–6081.
Lobert, J.M., Warnatz, J., 1993. Emissions from the combustion process in vegetation. In: Crutzen, P.J., Goldammer, J.G. (Eds.), Fire in the Environment: the Ecological, Atmospheric, and Climatic Importance of Vegetation Fires. John Wiley, New York, USA, pp. 15–37.
Mauzerall, D.L., Logan, J.A., Jacob, D.J., Anderson, B.E., Blake, D.R., Bradshaw, J.D., Heikes, B., Sachse, G.W., Singh, H., Talbot, B., 1998. Photochemistry in biomass burning plumes and implications for tropospheric ozone over the tropical South Atlantic. J. Geophys. Res. 103, 8401–8423.
Reid, J.S., Koppmann, R., Eck, T.F., Eleuterio, D.P., 2005. A review of biomass burning emission part II: intensive physical properties of biomass burning particles. Atmos. Chem. Phys. 5, 799–825.
Roden, C.A., Bond, T.C., Conway, S., Benjamin, A., Pinel, O., 2006. Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. Environ. Sci. Technol. 40, 6750–6757.
Roden, C.A., Bond, T.C., Conway, S., Pinel, A.B.O., McCarty, N., Still, D., 2009. Laboratory and field investigations of particulate an carbon monoxide emissions from traditional and improved cookstoves. Atmos. Environ. 43, 1170–1183.
Sahai, S., Sharma, C., Singh, S.K., Gupta, P.K., 2011. Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India. Nutr. Cycl. Agroecosyst. 89, 143–157.
Samra, J.S., Singh, B., Kumar, K., 2003. Managing crop residues in the rice-wheat system of the Indo-Gangetic plain. In: Ladha, J.K., Hill, J.E., Duxbury, J.M., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice-wheat Systems: Issues and Impact. American Society of Agronomy, Madison, WI, USA, pp. 173–195.
Saud, T., Mandal, T.K., Gadi, R., Singh, D.P., Sharma, S.K., Saxena, M., Mukherjee, A., 2011. Emission estimates of particulate matter (PM) and trace gases (SO_2, NO and NO_2) from biomass fuels used in rural sector of Indo-Gangetic Plain, India. Atmos. Environ. 45, 5913–5923.
Shah, J.J., Nagpal, T., Brandon, C., 1997. Urban Air Quality Management Strategy – a Guidebook. The World Bank, Washington DC, USA.
Sharma, P.K., Mishra, B., 2001. Effect of burning rice and wheat crop residues: loss of N, P, K and S from soil and changes in nutrient availability. J. Indian Soc. Soil Sci. 49, 425–429.
Shen, G.F., Yang, Y.F., Wang, W., Tao, S., Zhu, C., Min, Y.J., Xue, M.A., Ding, J.N., Wang, B., Wang, R., Shen, H.Z., Li, W., Wang, X.L., Russell, A.G., 2010. Emission factors of particulate matter and elemental carbon for crop residues and coals burned in typical household stoves in China. Environ. Sci. Technol. 44, 7157–7162.
Singh, J., Gu, S., 2010. Biomass conversion to energy in India – a critique. Renew. Sustain. Energy Rev. 14, 1367–1378.
Smith, K.R., Khalil, M.A.K., Rasmussen, R.A., Thorneloe, S.A., Manegdeg, F., Apte, M., 1993. Greenhouse gases from biomass and fossil fuel stoves in developing countries: a Manila pilot study. Chemosphere 26, 479–505.
Smith, R., Adams, M., Maier, S., Craig, R., Kristina, A., Maling, I., 2007. Estimating the area of stubble burning from the number of active fires detected by satellite. Remote Sens. Environ. 109, 95–106.
Streets, D.G., Yarber, K.F., Woo, J.H., Carmichael, G.R., 2003. Biomass burning in Asia: annual and seasonal estimates and atmospheric emissions. Glob. Biogeochem. Cycles 17, 1099–1118.
Tahir, S.N.A., Rafique, M., Alaamer, A.S., 2010. Biomass fuel burning and its implications: deforestation and greenhouse gases emissions in Pakistan. Environ. Pollut. 158, 2490–2495.
van Leeuwen, C.J., Hermens, J.L.M., 1995. Risk Assessment of Chemicals: an Introduction. Kluwer Academic Publishers, Dordrecht, The Netherlands.
Vander-Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., Defries, R.S., Jin, Y., van Leeuwen, T.T., 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos. Chem. Phys. 10, 11707–11735.
Ward, D.E., Susott, R.A., Kaufman, J.B., Babbit, R.E., Cummings, D.L., Dias, B., Holben, B.N., Kaufman, Y.J., Rasmussen, R.A., Setzer, A.W., 1992. Smoke and fire characteristics for cerrado and deforestation burns in Brazil: BASE-B experiment. J. Geophys. Res. 97, 14601–14619.
Wardoyo, A.Y.P., Morawska, L., Ristovski, Z., Marsh, J., 2006. Characterization particle number and mass emission factors from combustion Queensland trees. Environ. Sci. Technol. 40, 5696–5703.
Yang, S., He, H., Lu, S., Chen, D., Zhu, J., 2008. Quantification of crop residue burning in the field and its influence on ambient air quality in Suqian, China. Atmos. Environ. 42, 1961–1969.
Yevich, R., Logan, J.A., 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. Glob. Biogeochem. Cycles 17, 1095.
Zhang, H., Ye, X., Cheng, T., Chen, J., Yang, X., Wang, L., Zhang, R., 2008. A laboratory study of agricultural crop residue combustion in China: emission factors and emission inventory. Atmos. Environ. 42, 8432–8441.