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Exploiting Potentials from Interdisciplinary Perspectives with Reference to Global Atmosphere and Biomass Burning Management

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ABSTRACT

Biomass burning emitted aerosols are subject of concern in different disciplinary researches from different perspectives (climate change science from shift of balance in radiative forcing having severe repercussions on global ecosystem, while air pollution science from public health concern). By exploring particle number emission factors (PNEF), particle size distributions, and volatility of emitted ultrafine particles from burning rice straw, potential annual release of aerosols from rice straw combustion to the global atmosphere is estimated, and the issue of their management from such interdisciplinary perspectives is discussed. Between an estimated as low as 15% and as high as 75% of rice straw being burnt globally, the global annual estimate of emitted aerosols mounted from an order of 10^{21} particles/yr to the order of 10^{22} particles/yr. From looking at different estimates made therein, we advocate $D_p \leq 0.25$ µm ($PN_{0.25}$ equivalent) for adopting emission control standards. In volatility analysis flaming combustion and open burning indicated internal mixing of black carbon and organic carbon in emitted ultrafine particles, while smoldering combustion emitted ultrafine particles having little black carbon component. Up to 65% contrast in remaining volume in volatility analysis between the flaming and smoldering combustions, and positioning of open burning in between them, give us the idea of potential management of such biomass burning with controllable distinct choices. Therefore, the concept of exploiting potential from interdisciplinary dimensions is coined to enable more efficient management with least amounts of additional resources utilized, by resolving complexities through mutual cooperation of concerned disciplinary researches. It also shows a new avenue in our affairs in managing global atmosphere for the global ecosystem and public health.

Keywords: Ultrafine particles; PNEF (Particle Number Emission Factor); Global estimate; Biomass burning management; *Sustainability science*.

INTRODUCTION

Carbonaceous aerosols (Black Carbon (BC) and Organic Carbon (OC)) generally come from incomplete combustion of different biomass, biofuel, and fossil fuel combustions (Menon, 2004). Biomass burning is an issue that relates several disciplinary researches, particularly the air pollution and climate change sciences. From air pollution perspective release of harmful substances in the air is the most important concern for protecting public health. However, climate change science wants to look at the issue from a different point of view which is related to radiative forcing and other relevant climate implications (thermodynamic, semi-direct, and indirect effects). In the present work emission of aerosols from biomass burning is viewed from these different points of views.

Some of the most striking manifestations of aerosol effects in the atmosphere are recorded in temperature lowering due to volcanic aerosols, modified cloud properties in ship tracks, rainfall suppression in polluted air masses, and etc (Menon, 2004). According to the 4th IPCC report, anthropogenic aerosols (primarily sulfate, organic carbon, nitrate, and dust together) produce a cooling effect, with a total direct radiative forcing of –0.5 [–0.9 to –0.1] W/m^2 and an indirect cloud albedo forcing of –0.7 [–1.8 to –0.3] W/m^2 (IPCC, 2007). The report mentions about three roles of aerosols: the direct effect, cloud albedo effect, and surface albedo effect of black carbon on snow, though they have medium-low level of scientific understanding except the cloud albedo effect which has only low level of scientific understanding. It is likely that increase in green house gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that could otherwise have taken place (IPCC, 2007).

BC, being mostly absorbing in visible and UV regions, is usually associated with warming the atmosphere, while OC and sulfates along with their role as cloud condensation nuclei results in global cooling (Menon, 2004). As a result

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of BC emission, warmer and wetter climates could be produced locally or regionally, whereas the contrary is likely to take place in case of OC and sulfates dominant region (cooler and drier climate) (Ramanathan *et al*., 2001). Among atmospheric aerosols, BC accounts for most of the light absorption (Pöschl, 2005). However, to a lesser extent, two classes of "light-absorbing yellow or brown carbon", namely, polycyclic aromatic hydrocarbons (PAH's) and humic-like substances were also known to contribute to absorb visible light (Gelencser, 2004). Organic aerosol emission from open burning of biomasses, which is a low-temperature combustion, might be associated with higher absorption characteristic than that of high-temperature combustion like burning of fossil fuels ((Forster *et al*., 2007); and references therein). Reports on hazardous OC components emitted from biomass burning also increasing (McKenzie *et al*., 1995; Korenaga *et al*., 2001; Gullett and Touati, 2003; Lin *et al*., 2007). In evaluating BC and OC concentrations, inter-comparison of various methods reported that significant inconsistency among measurement techniques exist (Watson *et al*., 2005).

Rice is one of the most widely grown cereal crops in the world with at least 114 countries growing it in the year 2007, at least 50 of whom produced over 1 million tons, while its major counterpart is Asia (90% of world production and consumption with the top 9 producers in Asia) (IRRI, 2010). The rice straw is being open-field burnt due to agricultural considerations such as control of disease infestation for future crops (Hrynchuk, 1998) and nitrogen immobilization in case of soil incorporation (Buresh and Sayre, 2007). In many rural communities rice straw is used as a fuel in domestic cook stoves. Rice straw is also used in boilers for power generation. In Suqian agricultural region in Jiangsu province in China, around 37% of rice straw were burned in the field during 2001 to 2005 (Yang *et al*., 2008), and China is the biggest rice producing country in the world contributing to 28.19% of its production in the year 2008 (FAOSTAT, 2011). Gadde *et al*. (2009) has attempted to estimate open-field burning of rice straw in India, Thailand, and the Philippines, and has reported such estimates to be 14.3%, 48%, and 95% of rice straw, respectively. However, the level of difficulty in such estimates became apparent from looking at the methods used in doing so. The authors could have estimated those using personal communication in case of India, institutional analysis in case of Thailand, and questionnaire survey in case of the Philippines. On the other hand, respective use of rice straw for its different uses vary from year to year depending on a number of factors, thereby imparting great uncertainty (Gadde *et al*., 2009) even in such estimates obtained from the use of non-uniform methods. Still those estimates only represent one sort of burning of the straw, leaving the others unknown. From a literature survey it became apparent that there has not been adequate effort in estimating different burning of rice straw, and it is extremely difficult even to arrive at some estimates with considerable uncertainties unless attempted by research exclusively directed to do so. Factors contributing to uncertainties could include crop rotation and cropping pattern, disease risk and infestation, economic development and provisions of fuels, livestock rearing, education, and any changing trend in any of these factors. Furthermore this is a diverse activity taking place throughout the world and not localized in some particular territories. Therefore, we could not have accompanied our results with some reliable estimates of different kinds of rice straw combustion taking place around the world. Realizing the pragmatic difficulty we have rather presented emitted aerosol estimates for different estimation points using the world production of rice and converting it to the respective straw production.

In this study, we explored rice straw combustion for their potential contribution in terms of emitted aerosols in global atmosphere and focused the issue of their management from these interdisciplinary perspectives. In order to do that, particle number emission factors (PNEF), their respective size distributions, and volatility of the emitted ultrafine particles for different burning conditions have been studied in laboratory and interpreted for their importance in the current set of knowledge. The concept of exploiting potential from interdisciplinary dimensions is coined to enable more efficient management of such biomass burning which may have far-reaching implications in our efforts in managing global atmosphere for the global ecosystem and public health.

MATERIALS AND METHODS

Sampling and Combustion System

Rice straw (*Oryza sativa* ssp. *japonica*, 10.8% moisture) was sampled from a rural field in suburb Gwangju in Korea. A commercial combustion stove (d = 55 cm, h = 80 cm) consisting of a vertical chimney was used to simulate the burning conditions as shown in Fig. 1. Around 500 g biomass was burned at each of the experiments with at least 3 replicates. The air entrance port was located at the bottom of combustion chamber. The chimney was connected to a dilution chamber (d = 35 cm, h = 40 cm, providing 25 fold HEPA-filtered dilution and mixing fan installed at the bottom) before it enters the measurement instruments. Particles were sampled at an isokinetic condition at 1 m height inside the chimney. The smoldering combustion condition was produced by restricting combustion air supply and overloading the firebox with fuel, while flaming combustion condition was produced conversely. In visual observation smoldering combustion proceeded without the appearance of visible flame and releasing a thick white fume of aerosols, while the flaming combustion proceeded with the appearance of visible flame and released dense stream of black particles. An additional open field burning condition was also simulated for rice straw outside of the combustion chamber by placing soil underneath the straw. In that case a PM_{10} inlet was used to collect open burning emissions and route them to the measurement instruments.

Instrumentation and Measurement

The number of total suspended particles in the emissions was measured using ultrafine condensation particle counter (UCPC) (Model 3776, TSI Inc), which was used in calculating particle number emission factors (PNEF). The particle size distributions were measured by the SMPS

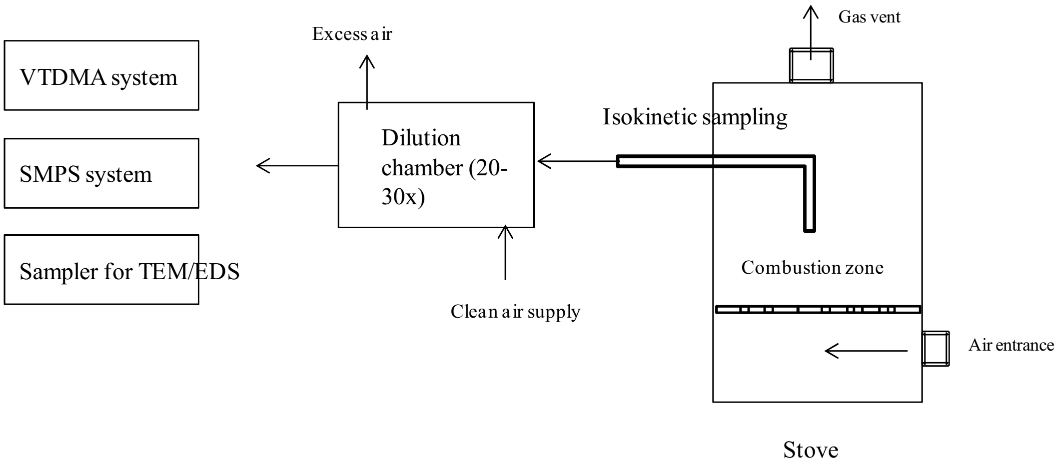


Fig. 1. A schematic of experimental setup.

(TSI 3081 DMA and TSI 3022A CPC) for the range of 20 nm to 600 nm, while the Particle Size Distribution Analyzer (TSI 3603) was used for 200 nm to 10 µm particles. In principle the SMPS measures mobility equivalent diameter while the PSD Analyzer measures aerodynamic equivalent diameter. For plotting both of the measurements in a continuous plot, the aerodynamic equivalent diameters were converted to mobility equivalent diameters by assuming particle density information, which was varied to match two data set (1.0–1.2 g/cm^3).

Volatility analysis of the emitted particles was done using a VTDMA system consisting of two nano-DMAs (TSI 3085), two long-DMAs (to a cover wide size range), a heating tube, and one UCPC (TSI 3776). The working principle of VTDMA system as well as the method of calculating volume fraction of volatile species used in this study was published previously (Park *et al.*, 2009). As (i) the sample was not ambient atmospheric aerosol rather biomass-combustion-emitted particles (carbonaceous) under isokinetic sampling, (ii) sampling was done in a closed system with maintaining specific burning conditions in each case, and (iii) sampling was conducted under the condition of forced air supply, particle loss due to gravity or diffusion were not taken into consideration. Loss due to thermophoresis was neither considered as there was no heating of the generated aerosols in the sampling stream. In volatility analysis, additional heating of the size-selected particles could possibly cause error in measurement due to recondensation or nucleation of the volatile species evaporated from particles, in the cooling section of TDMA system. However, Park *et al.* (2009) had shown such error to be negligible for the VTDMA system used in this study. In volatility analysis, samples have been experimented for the temperature range 20°C to 250°C, as in the heater design the remaining volume beyond 250°C heating would not contain any volatile OC, leaving only the non-volatile core particle. The samples were also analyzed in Energy Dispersive Spectroscopy (EDS, OXFORD INCAx-sight) in order to determine their elemental compositional nature.

RESULTS AND DISCUSSION

Particle Number Emission Factors (PNEF) from Rice Straw Combustion and Global Estimates

The aerosol emission factors in published literature are mostly expressed as mass concentrations. However, considering recent attempts in differentiating among different diameter-sized particles due to their health and other implications, it has become a necessity to express them in terms of number concentrations as well as further differentiation among different diameter size ranges. In calculating our PNEFs for flaming and smoldering burning conditions we used the Eq. (1).

$$\text{PNEF (particles/kg)} = a.C_{av}.\sum(Qt).D_F.A_t / m.A_s \tag{1}$$

where,

C_{av} = average particle number concentration, particles/cc
Q = sample flow rate, L/min.
t = time of each measurement, sec.
D_F = dilution factor (in dilution chamber)
m = burned mass (dry-weight), kg
A_t = cross-sectional area of chimney
A_s = cross-sectional area of sampling tube
a = 16.67 = unit conversion factor

According to the equation, our PNEFs for flaming and smoldering burning conditions for the rice straw are (1.504 ± 0.01) × 10^{11} particles/kg and (6.144 ± 0.05) × 10^{10} particles/kg, respectively. Referring to particle volatility characteristics in Fig. 2, we can take average to estimate the PNEF for open burning condition considering an intermediate burning condition between flaming and smoldering. In that way we can estimate PNEF for open burning condition as 1.059 × 10^{11} particles/kg. There are very little existing data on PNEFs from agricultural residue burning. Zhang *et al.* (2008) reported stand-alone PNEF data for rice straw combustion. However, in Zhang *et al.* (2008), the volume of the aerosol chamber was used instead of 'Qt' which may not represent the total air volume containing particles that were emitted from the exact amount of rice straw burnt, and thereby it could yield in differing results. Zhang *et al.* (2008) reported PNEF of (1.8 ± 0.1) × 10^{13} particles/kg in the non-specific combustion condition occurred with introduction of ambient

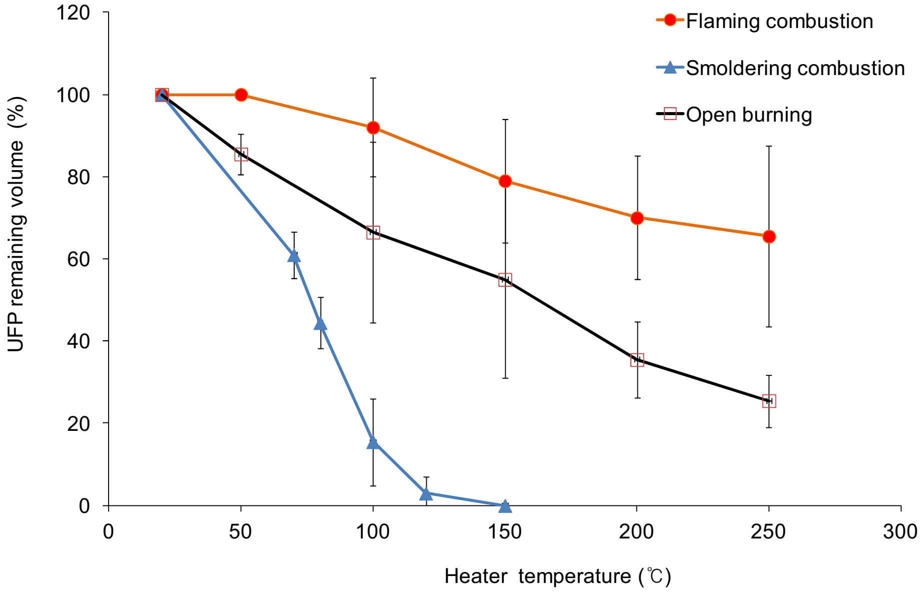


Fig. 2. Average volatility of ultrafine particles (UFP) from rice straw burning.

air. However, in our data we have clearly differentiated PNEFs for flaming and smoldering conditions, as well as for open burning based on volatility characteristics of ultrafine particles.

As it is mentioned in introduction, we present emitted aerosol estimates for different estimation points using the world production of rice and converting it to the respective straw production. We have collected the latest world rough rice production data in 2008 (FAOSTAT, 2011), which is 685.874696 million tons. Among this production Asia contributed 622.608109 million tons, which is 90.77%. Using straw to grain ratio of 0.75 derived in Gadde *et al.* (2007) and equations presented in Gadde *et al.* (2009), we have calculated the global annual total number of aerosols that are likely to be emitted to atmosphere at different estimation points of % of rice straw subject to combustion. Presented in Table 1, we have further divided those estimates for different size ranges of the particles calculated from combined size distributions and converted them into the respective PNEFs. The combined size distributions of particles over the diameter range of (20 nm–10 µm), as emitted from all three types of combustions (flaming, smoldering, and open burning) are presented in Fig. 3.

From Fig. 3 it can be seen that all three burning conditions yielded in unimodal size distributions. Results reported by Hays *et al.* (2005) for another cereal crop and wheat straw (not rice straw according to our best search) also showed unimodal size distributions for almost all combustion conditions for a limited size range (10–400 nm). The y-error bars are not provided in Fig. 3 (which are equilateral) as the size distributions were only used for comparing the relative abundance among different size-fractions (particle diameter, D_p levels), which were further put with regard to the respective PNEFs for quantitative particle emission estimates. It should also be noted here that the number concentrations as presented in Fig. 3 should not be taken to compare among different burning conditions in a quantitative way, as they were not directly related to the quantification of burned fuel amounts. The purpose of size distributions in Fig. 3 is to show the distribution tendency over the particle diameter range for different burning conditions. For the purpose of quantitative inter-comparison between the numbers of flaming and smoldering combustion emitted particles the PNEFs should rather be used, taking amounts of fuel burned into consideration. In Fig. 3 the shift of mode diameter can be seen toward larger diameter end in the order of “open burning < smoldering combustion < flaming combustion”. Such behavior can partially be explained by particle size alteration due to differential melting of particle components and consequential attachment to other particles being affected by differential temperature in the vicinity of burning (measured as flue-gas temperature). The order of increase in the flue-gas temperature was found to be exactly similar to the increase in mode diameters among the three burning conditions. Based on previous study by Gadde *et al.* (2009), we estimated annual global emission of aerosols (E_a) from rice straw combustions.

$$E_a = P_{RR} \times SGR \times Q_{\%SSB} \times PNEF \times f_{Co} \tag{2}$$

where,
E_a = (annual global) emission of aerosols, particles/yr
P_{RR} = (annual global) production of rough rice
SGR = straw to grain ratio, 0.75
$Q_{\%SSB}$ = estimation points of % of rice straw subject to combustion
PNEF = Particle number emission factor
F_{co} = combustion factor, 0.8

By conjointly taking PNEFs and particle size distributions into consideration, Table 1 presents annual global estimates of rice straw combustion-emitted particles for all three burning conditions, which can potentially guide adoption of emission control standards. In the Table 1 particles with < 20 nm diameter could not be considered because particles

Table 1. Global annual estimates of aerosol emissions from rice straw burning.

*$Q_{\%SSB}$	Combustion condition	*E_aTotal (20 nm–10 µm) ≈ $D_p \le 10$ µm	E_a (20–50 nm) ≈ $D_p \le 0.05$ µm	E_a (20–100 nm) ≈ $D_p \le 0.1$ µm	E_a (20–250 nm) ≈ $D_p \le 0.25$ µm	E_a (20 nm–1 µm) ≈ $D_p \le 1$ µm
	Flaming	100%	5.05%	26.92%	84.36%	99.43%
	Smoldering	100%	10.6%	55.23%	94.27%	99.56%
	Open burning	100%	41.2%	81.21%	97.27%	99.85%
15%	Flaming	9.28E+21	4.69E+20	2.50E+21	7.83E+21	9.23E+21
	Smoldering	3.79E+21	4.01E+20	2.09E+21	3.58E+21	3.78E+21
	Open burning	6.54E+21	2.69E+21	5.31E+21	6.36E+21	6.53E+21
35%	Flaming	2.17E+22	1.09E+21	5.83E+21	1.83E+22	2.15E+22
	Smoldering	8.85E+21	9.37E+20	4.89E+21	8.34E+21	8.81E+21
	Open burning	1.53E+22	6.28E+21	1.24E+22	1.48E+22	1.52E+22
55%	Flaming	3.40E+22	1.72E+21	9.16E+21	2.87E+22	3.38E+22
	Smoldering	1.39E+22	1.47E+21	7.68E+21	1.31E+22	1.38E+22
	Open burning	2.40E+22	9.88E+21	1.95E+22	2.33E+22	2.39E+22
75%	Flaming	4.64E+22	2.34E+21	1.25E+22	3.92E+22	4.62E+22
	Smoldering	1.90E+22	2.01E+21	1.05E+22	1.79E+22	1.89E+22
	Open burning	3.27E+22	1.35E+22	2.65E+22	3.18E+22	3.26E+22

*E_a = (annual global) emission of aerosols, particles/yr; *$Q_{\%SSB}$ = estimation points of % of rice straw subject to combustion

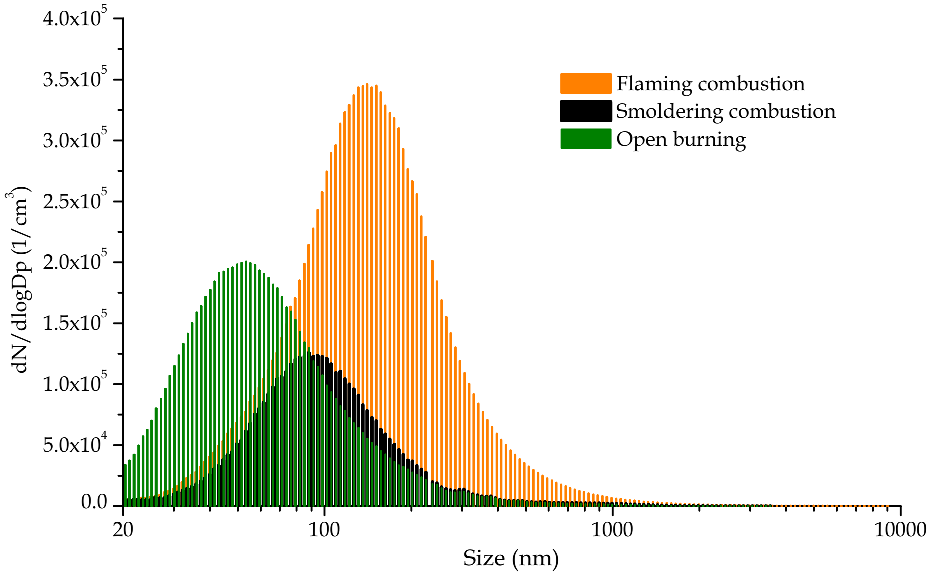


Fig. 3. Size distributions of particles from rice straw burning at different

smaller than 20 nm was not measured in our experimental protocol. Therefore, particles ranging between (20 nm–10 µm) were considered as 'E_a Total' ($D_p \le 10$ µm), and thereby the designation of other respective D_p levels for different size fractions in Table 1. It is noticeable that in 'E_a (20–50 nm)' and 'E_a (20–100 nm)' the percentages of emitted particles greatly vary among the three burning conditions. However, such variation is not very significant when it comes to 'E_a (20–250 nm)' and 'E_a (20 nm–1 µm)', carrying vast majority of particles from the $D_p \le 10$ µm (PN_{10} equivalent) spectrum. At 15% level of $Q_{\%SSB}$, it still produces big enough numbers (E_a–10^{21} particles/yr) compared to 75% (E_a–10^{22} particles/yr). From particle number emission point of view we do not need to have much concern for D_p (0.25–1) µm particles as can be seen from Table 1. Considering smaller-sized particles (i.e., 'E_a (20–250 nm)') for potential health hazard as well as their high fraction (84.36%, 94.27%, and 97.27%) in 'E_a Total', we can advocate for $D_p \le 0.25$ µm ($PN_{0.25}$ equivalent) for adopting standards from this sector. It should also be noted from Table 1 that the resembling E_a values among the three burning conditions in each $Q_{\%SSB}$ group represent particle numbers that are largely contrasting in basic natures and compositions (in terms of containment of BC and diverse OC compounds of emitted ultrafine particles from Fig. 2).

Biomass Burning Management Potential

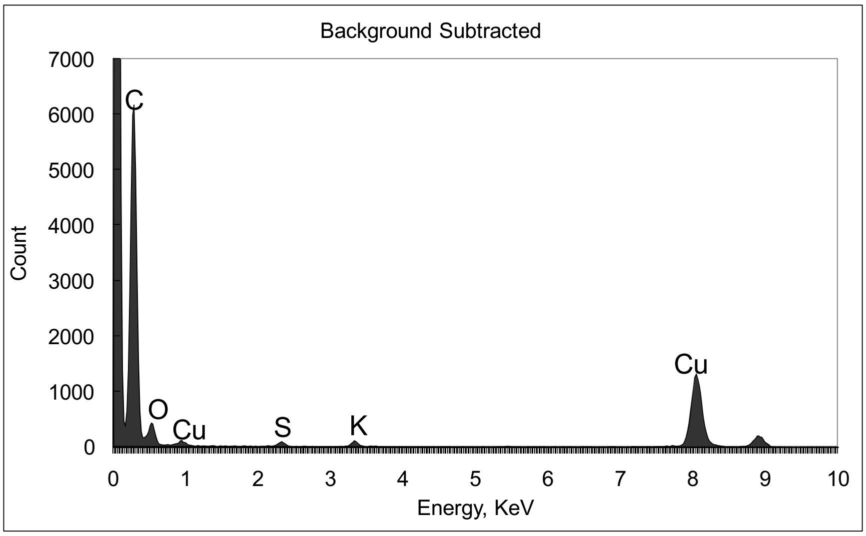
The carbonaceous nature of biomass burning (including rice straw) aerosols included OC and BC being the two component groups therein, and their relative abundance depended on alteration of burning conditions as evident from a growing number of literatures (Rau, 1989, Kleeman *et al*., 1999; Fine *et al*., 2002; Hays *et al*., 2005; Tissari *et al*., 2008). Such literature also suggests that higher-temperature combustion results in refractory black carbons while lower-temperature smoldering combustion resulting particles with organic matter agglomeration (such as tar-balls; (Chakrabarty *et al*., 2010)). Our flaming combustion resembles such higher-temperature firing combustion and our smoldering combustion resembles lower-temperature smoldering combustion, which was also evident from the detected contrasting flue-gas temperatures. Our Energy Dispersive Spectroscopy (EDS) also revealed highest carbon peaks followed by oxygen in all instances, referring to the carbonaceous nature of such particles emitted from rice straw under all three burning conditions as presented in Fig. 4). Particles from the smoldering condition had much stronger K and less C emission line compared to other combustion conditions. Referring to the OC and BC dependence on combustion conditions, increased absorption efficiency can be observed from BC when located inside a scattering particle (Chylek and Hallett, 1992; Jacobson, 2002), and this can cause major uncertainty in radiative forcing estimation, as well as can even change single scattering albedo of the particle in question (Novakov *et al*., 2003; Sato *et al*., 2003).

As shown in Fig. 2, average volatility of ultrafine particles (size-selected at around 50 nm and around 100 nm) emitted from flaming combustion, smoldering combustion, and open burning of rice straw suggested that only the nonvolatile core of the particles left beyond 250°C heating. It is evident from Fig. 2 that in the smoldering combustion ultrafine particles do not contain any non-volatile core (i.e. completely volatile). However, in the flaming combustion and open burning the ultrafine particles are not completely volatilized by 250°C heating, and the remaining volume represents the non-volatile cores which would be comprised of BC and/or non-volatile OC (as per our heater design in VTDMA system) plus other macro- and micro-nutrients present in smaller quantities in the biomass tissues. It is also evident that the volatility characteristics of open burning ultrafine particles resemble to that in between flaming and smoldering particles, thereby suggesting an intermediate and arbitrary ranking of the open burning process between the flaming and smoldering processes. Depending on alteration of conditions (openness of the burning place, stagnancy of air or wind flow resulting renewal of air, overload of fuel, and etc.) the open burning condition might drift more towards either flaming or smoldering conditions. The volatility characteristics of open burning and flaming combustion ultrafine particles presented in Fig. 2 also suggest internal mixing of OC and BC (BC being the usual product in firing/flaming condition shown in a growing number of literatures as indicated in preceding paragraph, while OC was the volatilized fractions within 250°C heating). Such mixing can also alter single scattering albedo, therefore might even change radiative forcing, imparting uncertainty to relevant estimates as suggested in other studies (Novakov *et al*., 2003; Sato *et al*., 2003). However, smoldering combustion ultrafine particles in Fig. 2 clearly do not have such internal mixing, and they are devoid of BC component. The trends in Fig. 2 can also be expressed in terms of volatile organic matter content, implying the highest in smoldering condition, the least in flaming condition, and intermediate proportions in open burning.

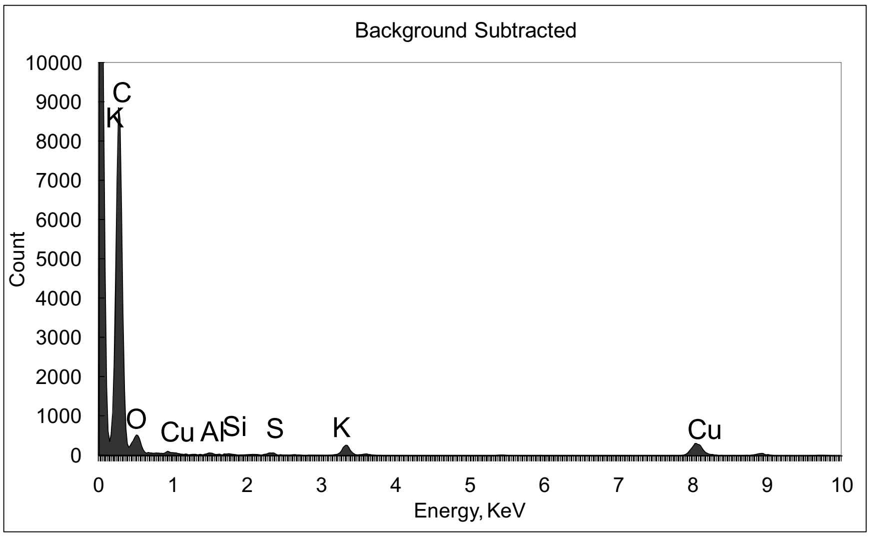
The range between the endpoints of the slopes in volatility of ultrafine particles from smoldering and flaming combustion in Fig. 2 (up to 65.5% contrast in remaining volume) gives us the idea of potential management of such biomass burning through controlling burning conditions towards either ends. Therefore it provides us with clearly distinct choices as well as the scope for optimization within the range for management of rice straw combustion. It is practically less likely that we can phase out biomass burning completely. No matter what are the afflictions associated with such biomass burning either for their negative impacts on global climate or for public health, anthropogenic biomass burning is likely to be continued at some or more extent, be it for the consideration of disease infestation risk or rapid required nutrition for the next crop, or for easier land management options or as crucial fuel for rural cooking stoves or for energy production or even for warmth in winter. Also we have natural biomass burning on which we have less control. Therefore, considering the reality it would prove to be far more important to go for management options rather than trying to eradicate such biomass burnings.

Rice Straw Combustion Aerosols, Radiative Forcing and Public Health

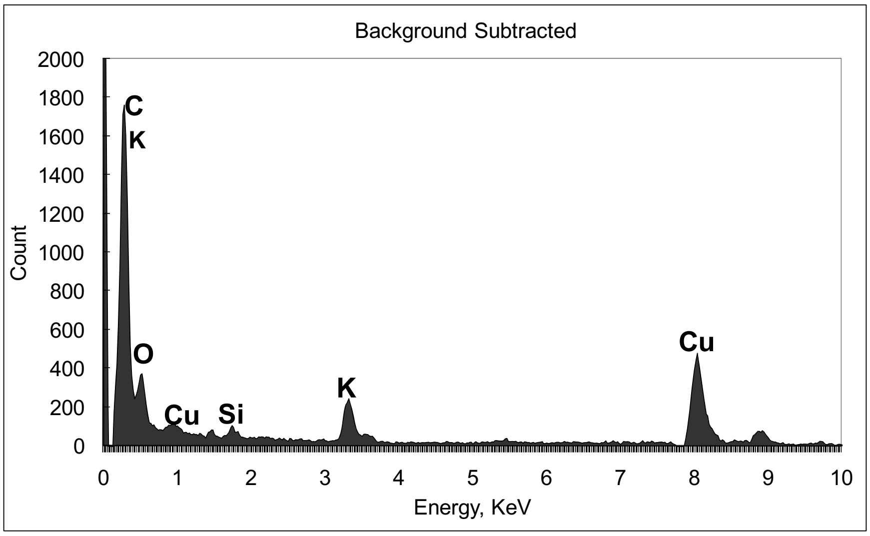
The particle numbers (at least for ‘E_a (20–100 nm)’ or designated $D_p \leq 0.1$ μm) from flaming, smoldering and open burning conditions as presented in Table 1 should be taken in consideration of interpreted OC/BC characteristics of volatility analysis of ultrafine particles (Fig. 2). From literature the current set of knowledge in terms of public health considerations are not quite straight-forward as in case of radiative forcing. In case of radiative forcing it is rather less complicated that most of the absorption is due to the BC while some OC groups also cause some absorption. Among those, aromatic groups such as PAH are highly health hazardous as well as emitted from open burning of rice straw (Korenaga *et al*., 2001). Therefore this OC group has a dual functionality (health hazardous as well as light absorbing). Otherwise suspected organic carcinogens beyond toxic level are found in smoldering combustion of different biomasses (McKenzie *et al*., 1995), as well as some of the dioxins were detected in rice straw and other biomass combustions which are also notably carcinogens (Gullett and Touati, 2003; Lin *et al*., 2007). All these refer to predominant health hazardous aspect of many other OC components. On the contrary, it is also necessary to specify the respective roles of BC and OC in air particulate matter, further resolved in different size-categories, in causing health problems; apart from the general correlation between PM in air and public health hazards found in mounting studies. This is particularly important for any public health concern due to BC components to be precisely identified in addition to their dominant roles in light absorption in atmosphere. Therefore, there cannot be any straight-forward explanation



(a)



(b)



(c)

Fig. 4. Energy Dispersive Spectroscopy (EDS) data for particles produced from (a) flaming combustion, (b) smoldering combustion, and (c) open burning of rice straw

of the numbers (E_a) from flaming, smoldering and open burning conditions as presented in Table 1 in the light of volatility analysis of Fig. 2, unless such complexities are resolved through further research. This is the focal point of this discussion which necessitates mutual cooperation across disciplines, along with the choices that we have for integrated management of such biomass burning at global level.

Realizing the Potential of Resolving the Paradox of Prioritization between OC and BC

So far, there has not been extensive thought as to the management of biomass burning. Some old research in California Rice Research Board (CARRB, 2011) dated as back as 1974 pointed out some burning techniques that would lead to less smoke generation. The techniques mainly included burning of straw containing 12% or less moisture, burning in clear weather with straw been spread and 3 days after harvest, burning between 10 AM and 5 PM, and burning against the wind rather than with the wind. As the aim was to restrict smoke generation, the measures in other words actually restricted smoldering combustion. Although each of those techniques tries to ensure more flaming combustion condition, BC emission would be abundant in such cases instead of OC being generally emitted in smoldering conditions. However, consideration of the role of BC in absorbing light and thereby positive radiative forcing in atmosphere clearly was not among the core considerations.

Therefore, from our data it is clear that there are significant possibilities for biomass burning management simply by advocating maintenance of appropriate burning conditions to meet certain end goals. If it be the case that mutually addressing the issue by both of the air pollution and climate change sciences may arrive at the choice that public health consideration should be given more priority, then in particular ways optimized from the range we can utilize biomass burning management as one of the prudent measures in enhancing public health. In that case we could know of how likely it would be the contribution from biomass burning (black carbon) in the radiative forcing, and therefore inclusion of such consideration in other climate change mitigation policies. Or alternatively if such mutual addressing should arrive on the conclusion that radiative forcing effect should be given more priority in this particular sector, then we can reverse (or alter accordingly as to optimize from the range) the advocated burning conditions in biomass burning management policies so that the resultant components (organic carbon) may lead to efficient global cooling. In that case the public health consideration should be dealt accordingly with quantitative measures to be reflected and addressed in other public health policies. In both cases one big advantage would be the quantification, which is more likely to be dealt with quantitative measures as well as confidence.

However, in the present fashion both air pollution and climate change sciences consider the same practice as important issue for each of them as well as trying to advocate mitigation/remediation measures accordingly. Therefore it might be a waste of good deal of efforts from the same socio-economic system, and perhaps duplication of efforts due to be from both ends for the same extent of concern. Also due to uncertainty in quantification of each kinds of aerosols (as differentiated in volatility characteristics of ultrafine particles in Fig. 2) due to unmanaged burning and changing burning conditions, qualitative rather than quantitative measures would get encouraged with a resultant lesser confidence in their efficiency.

Indulging into expanding actions to solve the existing environmental problems before exploiting the full potentials from the existing measures would only make the situation worse with widening liabilities, also affecting other spheres of social life. Examples for this could be imposing global carbon taxes or considering climate engineering options through injecting large quantities of aerosols into atmosphere, before exploiting the already existing potentials (such as management of biomass burning at global level) simply by resolving the relevant complexities arising from separation of perspectives. We cannot make sustainable growth by not attending and resolving those complexities. Engaging into new and extra efforts would even give rise to newer complexities, thereby making the earlier ones more difficult or might be apparent impossibility to solve. Even the growth of air pollution and climate change sciences independent to each other is also less likely to be sustainable and efficiently meaningful in case they do not resolve mutually inclusive issues that rise from the number of atmospheric aspects that these two disciplines do share. Such approach can also act as an important method in the practice of *sustainability science* (Kates *et al*., 2001; Clark and Dickson, 2003; Clark, 2007), thereby attending many issues with complexities arising from separation of perspectives in the coupled nature-society systems.

CONCLUSIONS

The particle number emission factors vary with varying combustion conditions of rice straw. Yet they vary only from the orders of 10^{21} particles/yr to the orders of 10^{22} particles/yr when it comes to global annual emission, considering the range of 15% to 75% of rice straw subject to combustion globally. However, such accompanying annual particle emission estimates also represent particles which are largely contrasting in their basic nature and composition emitting from different combustion conditions. Therefore, such numbers (annual estimates) also hold differential significance for their implications in global atmosphere. Inferred from prior studies as to the BC and OC nature of the emitted particles, the smoldering combustion emitted ultrafine particles having little BC, flaming combustion and open burning emitted an internal mixture of OC and BC, and the contrasting (as high as 65%, with the arbitrary positioning of open burning in between the flaming and smoldering conditions) volatility characteristics of ultrafine particles further gives the idea of potential management of biomass burning with controllable distinct choices in order to bring about the most optimized implications from the differing perspectives.

From realizing the complexity and limitations in prioritization of BC and OC for radiative forcing and public health concerns it has become incumbent for mutual cooperation of different disciplinary researches (for example climate change science and air pollution science) rather than operating from exclusive separation of perspectives. The concept of exploiting potential from interdisciplinary dimensions can enable more efficient management with least amounts of additional resources utilized, as well as provide further justification of the newly emerging research program *sustainability science*. Such approach can also act as an important method in *sustainability science* in attending a variety complex issues arising from separation of perspectives in the nature-society systems. Finally, particles with $D_p \leq 0.25$ μm ($PN_{0.25}$ equivalent) should be advocated for adopting emission control standards and measures from rice straw combustion in order to arrest their most hazardous implications regarding global ecosystem and public health.

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