Measurements and Modeling of Emissions from Biomass Combustion Sources in North-central Nigeria.

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Abstract: *This work is aimed at monitoring and analyzing the concentrations of gaseous pollutants such as Carbon (II) oxide, Sulphur (IV) oxide and Hydrogen sulphide and Particulates ($PM_{2.5}$ and PM_{10}) released from biomass combustion sources at specified receptor points downwind. A real time analysis was adopted in monitoring these pollutants by the use of ALTAIR Multi- gas detector and HAT 200 $PM_{2.5}$ and PM_{10} detector. The estimated emission rates of 140mg/s and 84mg/s for CO, 0.744mg/s and 0.714mg/s for SO_2 and 1.556mg/s and 1.176mg/s for H_2S were respectively obtained for charcoal and wood burning sources. This could be attributed to the source geometry and the combustion conditions of these combustion sources. An analysis of the base line monitored concentration depicts wood burning sources as having maximum concentrations of 113.58mg/m^3, 1.01mg/m^3, 1.74mg/m^3, 0.70mg/m^3 and 1.55mg/m^3 for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} respectively while the minimum concentration of 1.20mg/m^3, 0.03mg/m^3, 0.07mg/m^3, 0.11mg/m^3 and 0.24mg/m^3 were monitored for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} respectively from the same sources within their microenvironments (1.0-5.0m). Also, a further consideration of the baseline monitored concentration obtained from charcoal emissions presents the maximum concentrations of 153.92mg/m^3, 0.56mg/m^3, 1.25mg/m^3, 0.05mg/m^3 and 0.11mg/m^3 respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} while the minimum concentrations of 6.24mg/m^3, 0.18mg/m^3, 0.07mg/m^3, 0.03mg/m^3 , and 0.06mg/m^3 respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} were monitored within the microenvironments (1.0-5.0m) of charcoal emission sources. Based on National Ambient Air Quality Standards, it is observed that the safe distance for human health around these biomass combustion sources is any distance greater than 4.0m for CO (1 hour time average, the safe limit is $40mgm^{-3}$), SO_2 (24 hour time average, the safe limit is $0.365mgm^{-3}$) and H_2S (1 hour time average, the safe limit is 0.042mg/m^3). It is then suggested that for minimal deleterious effects on people around these emission sources, duration of activities around them should be reduced and those involved in these activities (e.g cooking) should position themselves at the anti-plume direction.*
Keywords: *Dispersion, pollutants, concentration, biomass, combustion, emissions.*

I. Introduction

The burning of wood, dung, straw and other biomasses produces toxic combustion gases, like for instance carbon monoxide and formaldehyde (Usinger, 1999). These gases pollute the breathing air of those persons near the fire place and when inhaled into the lungs have negative health impacts. Lim et al., 2012 estimated that over 3.5 million premature deaths per year (plus an additional 0.5 million deaths from outdoor air pollution due to household fuel use) results from the use of solid fuel for cooking. These impacts are generally most severe in children, the elderly and people suffering from respiratory or breathing problems (Unger et al., 2010). According to estimates of WHO, 14,000 children, mainly from rural areas, die daily in developing countries on account of respiratory infections (Usinger, 1999). Urban and rural households in developing countries depend mainly on traditional fuels like wood, dung or other biomass for energy. However, the use of traditional fuels in stoves and ovens, especially in those without chimneys, leads to substantial air pollution (Usinger, 1999). Nearly 3 billion people worldwide, and a great majority of households in developing countries such as Nigeria, rely on solid fuels (such as wood, dung, crop residues, coal, and charcoal) with little access to modern fuels for cooking and other household energy needs (Lim et al., 2012; Smith, 2012). In Nigeria, the use of charcoal and wood as alternative sources of energy for cooking is increasingly become popular. However, traditional stoves which are devised in burning charcoal and wood in Nigeria are often inefficient and poorly vented hence resulting in incomplete combustion with attendant highly polluting emissions.

The atmosphere is the medium into which pollutants are released and dispersed. Once emitted into the atmosphere, pollutants move away from the source and disperse into a large volume of air, the concentrations generally decreasing. National Air Quality Management Programme (NAQMP, retrieved on 6th May, 2016) reported that the ability of the atmosphere to disperse pollution varies geographically (from place to place), and temporally (as a function of time). Sometimes the atmosphere promotes dispersion, and in such cases the concentration of pollution is generally decreased. At other times, however, the atmosphere may inhibit dispersion, with the result that pollution will accumulate near the source and concentrations will rise (NAQMP,

2016). This makes concentration of an air pollutant at a particular receptor point along the plume axis a function of atmospheric stability condition (this influences greatly the strength of dispersion at such location), the source type and geometry (this influences the emission rate), and the downwind distance of the receptor from the emission source. All these determine to a great extent the concentration of pollutants at a location.

It is generally observed that pollutants' concentration cannot be measured every where they occur. This may be partly due to the presence of obstacles around pollution sources or plume spreading in directions that are inaccessible for monitoring. This has necessitated the use of model for estimating the concentration of pollution from such sources. Although there are several models for this purpose, the Gaussian Plume model is more appealing for specific application to gaseous pollutants such as; Carbon (II) oxide, Sulphur (IV) oxide, and Hydrogen sulphide. The application of pollution models offers an alternative approach to studying the transport of pollutants from the emission sources to the different receptors. Specifically, air quality models have proven useful for determining the spatio–temporal distribution of air pollutants and for developing emission control policies that allocate limits to air pollutant emissions (Holmes and Morawska, 2006, Zhang et al., 2010,Ma et al.,2013).

In Nigeria, data of spatial and temporal concentration of pollutants from biomass combustion sources are rare. Hence, this has led to much challenge in assessing whether the sources meet the acceptable and safe limit for human and public health. The aim of this paper is to present base line data of concentration of gaseous pollutants and particulates ($PM_{2.5}$ and PM_{10}) at various receptor points downwind biomass combustion sources in North central Nigeria and use these data sets to assess the validity of Gaussian plume model.

II. Methodology

The study area
North Central Nigeria loosely known as Middle Belt; includes Benue State, Kogi State, Kwara State, Nasarawa State, Niger State, Plateau State and the Federal Capital Territory whose respective capitals are; Makurdi, Lokoja, Ilorin, Lafia, Minna, Jos and Abuja as shown in figure 1. The North Central Nigeria is located at an elevation of 115meters above sea level. Its coordinates are $80^{'}0^{0}0^{''}$ N and $8^{0}0^{'}0^{''}$E DMS (in Degree Minutes seconds). Its UTM position is LP88 and its Joint Operation Graphics reference is NC32-14. The sun rises at 08.06 and sets at 20:13 local time. The temperatures are above 18.54^{0}C (65.2 ^{0}F) to 36.9^{0}C (98.4 ^{0}F), and an annual rainfall of about 1,500mm (59.1 in) with a single rainfall maxima in September. However, semi temperate weather conditions prevail on the highlands in central Nigeria above 1,200 meters (3,937 ft) above sea level, namely the Jos Plateau. Temperature in Jos Plateau ranges between 21^{0}C to 25^{0}C which are cool all year round.

In Makurdi particularly, temperature is generally very high during the day, most especially in March and April. It records average maximum and minimum daily temperatures of 35^{0}C and 21^{0}C in summer and 37^{0}C and 16^{0}C in winter, respectively.

Fig. 1: Map of North central Nigeria.

Sampling Procedures.
In this work, real time analysis was adopted to monitor and investigate the spatial and temporal variation of the gaseous pollutants such as Carbon (II) oxide, Sulphur (IV) oxide and Hydrogen sulphide and Particulates ($PM_{2.5}$ and PM_{10}) from some selected biomass combustion sources in three cities in North central

Nigeria as shown in table 1. This was undertaken in Jos, Lafia and Makurdi which are respectively the state capital of Plateau, Nasarawa and Benue states for a period of five (5) months (November to March) at an average monitoring of once a week.

An ALTAIR multi-gas detector and HAT 200 $PM_{2.5}$ and PM_{10} detector were used in measuring the ground level concentration of gaseous pollutants and particulates concentrations respectively along the plume spread of outdoor biomass combustion sources (fire wood burning and charcoal burning use for cooking). The multi gas detector and HAT 200 $PM_{2.5}$ and PM_{10} detector are held at about 1m from the ground level in the direction of plume spread at specified receptor points (i.e 1.0m, 2.0m, 3.0m, 4.0m, and 5.0m) downwind for both emission sources to determine the continuous and temporal variation of plume concentrations within their microenvironments. This is the average breathing zone of an adult who moves round these combustion sources and the cooks who often sits around them.

These receptor points are chosen for the following reasons;

i. The nature of the emission sources; Plume emitted from biomass combustion in stove is naturally of very low buoyancy and are as such are not lofted too high vertically in the atmosphere before dilution and dispersion take place.

ii. Presence of obstacles/obstructions.
    Due to the low level of plume rise and the nature of emission sources (i.e ground level sources), it is very easy for obstruction in form of human, building (even small shades) or vehicle to interrupt data monitoring or cause aerodynamic effects.

Modeling Procedures

The problem of insufficient monitoring stations has generally limited the observational approach in the investigation of how far emissions are transported from point sources in Nigeria. The application of pollution models offers an alternative approach to studying the transport of these pollutants. Gaussian plume model is applied in simulating concentration of pollutants. The Gaussian plume equation for pollutants' concentration along the plume spread is given as [18];

$$C(x,0,0,0) = \frac{Q}{2\pi U \sigma_y \sigma_z} \qquad (1)$$

Where Q is the emission rate in mg/s
U is the mean velocity measured at 1.0m in m/s
σ_y and σ_z are the respective cross wind and vertical dispersion coefficients in meter.

For accurate modeling, emission rates were estimated for both charcoal and wood emissions from their respective average measured concentrations, C (1,0,0,0) of Carbon (II) oxide, Sulphur (IV) oxide and Hydrogen sulphide monitored at 1.0m from the emission sources along the plume centerline. These were inserted into equation (1) for each pollutant to obtain their emission rates. However, this simulation was only carried out for gaseous components of the emissions while the particulates were not modeled.

The modeling was carried out by using the meteorological data obtained under neutral atmospheric stability condition. This meteorological data such as wind speed and wind direction were obtained at the respective Nigeria Meteorological Agencies' stations for Jos, Lafia and Makurdi. Wind speeds were measured at 4.5m from the ground level using anemometer and their respective values at 1.0m, 5.0m and 10.0m were extrapolated by using wind profile law in equation 2.

A typical extrapolation comprises a power law as shown in equation (2) (Darwish and Sayigh, 1988; Lysen, 1988; Gökçek *et al.*, 2007a):

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^a \qquad (2)$$

where 'v' is the wind speed at the required height 'h', 'v_0' is wind speed at the original height 'h_0', and 'a' is the surface roughness coefficient which lies in the range 0.05–0.5 (Akpinar and Akpinar, 2005). Surface roughness coefficient, 'a' can also be determined from the following expression (Ucer and Balo, 2009):

$$a = \frac{[0.37 - 0.088\ln(v_0)]}{\left[1 - 0.088\ln\left(\frac{h_0}{10}\right)\right]} \qquad (3)$$

Ohunakin and Akinnawonu (2012) observed that wind speed increases with height and that the power-law exponent for wind speed typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. Although the power-law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship (Ohunakin and Akinnawonu, 2012).

From the measured wind speed obtained at the anemometer height, the wind speed of 7.99m/s was obtained at 1.0m (which is the height of advection of the plume horizontally from these sources) by applying the wind profile law in equation 2.

III. Results and Discussion

Emission rate of a pollutant affects how much of it can be released into the atmosphere from an emission source. From the monitored data obtained from the biomass combustion sources at 1.0m downwind, table 2 show charcoal burning and wood burning as having estimated emission rates of 140mg/s and 84mg/s respectively for CO, 0.744mg/s and 0.714mg/s respectively for SO_2 and 1.556mg/s and 1.176mg/s respectively for H_2S. This could be attributed to the source geometry of these combustion sources. Considering the type of charcoal stove and the tripod stove configured for wood burning in North central Nigeria, it is obvious that air-fuel mixture ratio has so much effect on the measure of combustion that takes place in a combustion furnace. The air-fuel mixture is higher in the traditional tripod wood stoves than charcoal stoves. This is because the space for air to access the combustion chamber for tripod wood burning stoves is more than that of charcoal burning stoves. Hence, it is easier to achieve a fairly better combustion of fuel (wood) in these tripod wood burning stoves than charcoal stoves. These result in lower emissions of CO and H_2S from wood burning tripod stove than charcoal burning stove. Typically, biomass combustion in open burning and stoves takes place at low temperatures, leading to higher emission of CO (IARC, 2015).

The National Ambient Air Quality Standard by United State of America Environmental Protection Agency is presented in table 3.

The average monitored data from wood burning and charcoal burning sources are presented respectively in table 4 and 5 while their respective modeled data are presented in table 6. The tables generally show concentrations decreasing from emission sources to their respective receptor points. The percentage trend of variation is better depicted by figures 2-7 for CO, SO_2 and H_2S respectively emitted from wood and charcoal at various receptor points downwind the sources. Of these figures, figures 2 and 3 present CO as having the highest dispersion among the gaseous pollutants investigated. The microenvironment around the emission sources experiences the forceful impact of the momentum and buoyant release of pollutants before reasonable dispersion takes place. In this zone (<1.0m from the source), emission rate is prevalent over dispersion rate. However, as the pollutants are being transported farther downwind, dispersion process increases along the microenvironment (assuming the emission rate remains constant from the emission sources), the more the plume spread as a result of dispersion, the greater the volume of air available for dilution of pollutants. The dilution process is a function of the ability of the atmosphere (lower troposphere) to disperse the pollutants downwind the emission sources, hence the average concentration of pollutants from respective sources follow exponentially decreases.

For CO, about 53-60% of its concentration is obtained at 1.0m from the biomass emission sources while about 2-3.5% eventually gets to the receptor point at 5.0m downwind. For SO_2, about 45.5-48% of its concentration is obtained at 1.0m from the biomass emission sources while about 7.25-8.0% eventually gets to the receptor point at 5.0m downwind. However, in the case of H_2S, 35.75% of its concentration is obtained at 1.0m from the sources investigated while 5.25-5.5% gets to the receptor points at 5.0m downwind. This shows that CO has higher dispersion than SO_2 and H_2S among the pollutants investigated.

An analysis of the base line monitored data obtained depicts wood burning sources as having maximum concentrations of 113.58mg/m^3, 1.01mg/m^3, 1.74mg/m^3, 0.70mg/m^3 and 1.55mg/m^3 respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} while the minimum concentration of 1.20mg/m^3, 0.03mg/m^3, 0.07mg/m^3, 0.11mg/m^3 and 0.24mg/m^3 were monitored respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} from the same source within their microenvironments (1.0-5.0m). A further consideration of the baseline monitored data obtained from charcoal emissions presents the maximum concentrations of 153.92mg/m^3, 0.56mg/m^3, 1.25mg/m^3, 0.05mg/m^3 and 0.11mg/m^3 respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} while the minimum concentrations of 6.24mg/m^3, 0.18mg/m^3, 0.07mg/m^3, 0.03mg/m^3, and 0.06mg/m^3 respectively for CO, SO_2, H_2S, $PM_{2.5}$ and PM_{10} were monitored within the microenvironments(1.0-5.0m) of charcoal emission sources.

On their part, the particulates ($PM_{2.5}$ and PM_{10}) show occasional irregularities in variation trends from these sources. These could be as a result of contributions from other sources or the ambient particulates loading from dust that is prevalent in the dry season in North central Nigeria. Comparatively, the average particulates emissions from wood burning are higher than that emitted from charcoal burning. Figure 8 depicts the variation of particulates from wood and charcoal emission at various receptor points downwind. It is observed from this figure that PM_{10} emitted from both charcoal and wood burning is higher than $PM_{2.5}$. This is because the size range of PM_{10} includes the particles between 2.5μm and 10μm in diameter, in addition to particles with diameters smaller than 2.5μm (IARC, 2013a). The ratio of average monthly levels ($PM_{2.5}/PM_{10}$) is estimated to be 0.445-0.524 for wood burning and 0.5-0.833 for charcoal burning.

For in-depth understanding of how the modeled and measured data compare, figures 9, 10 and 11 give the trend of variation of respective pollutant's concentrations under atmospheric neutral stability conditions. These figures depict the measure of validation of Gaussian plume model. From these figures, CO shows a higher validation of the model while H_2S has the least measure of validation. In fact, figure 11 presents H_2S as showing the least correlation between the monitored (measured) and the modeled data. Fischer et al., 1979 assumes that Gaussian plume model can only be effectively applied to pollutants that do not undergo chemical reactions or transformations with distance from the source, no absorption of the pollutants in motion at ground level and no deposition. This is not perfectly the case with SO_2 and H_2S. From literatures, Hydrogen sulfide and oxygen burn with a blue flame to form SO_2 and water at high temperature. This implies that the concentration of emitted SO_2 and H_2S are subject to the occurrence of some chemical reactions and transformations. Also, due to the molecular weight of SO_2 and H_2S that are respectively 34.088g/mol and 64.035g/mol, deposition of these pollutants cannot be totally ruled-out. However, these factors (chemical reactivity and molecular weight) are mild in the case of CO.

Furthermore, to comprehensively determine the correlation of measured (monitored) data (MSD) and modeled data (MDL) from these biomass sources, scatter plots were obtained for all the gaseous pollutants for both charcoal burning and wood burning. These are respectively depicted in figures 12-17. For charcoal burning, the coefficients of regression, R^2 from these plots are 0.996, 0.681 and 0.428 for CO, SO_2 and H_2S respectively while the coefficient of regression, R^2 for wood burning are respectively; 0.807, 0.681 and 0.453 for CO, SO_2 and H_2S. These depict measured (monitored) and modeled CO and SO_2 concentration as correlating closely than H_2S. This study indicates that the models can capture the real-time features governing the dispersal of CO and SO_2 emitted from biomass combustion. However, figures 13 and 17 show a low coefficient of regression (below 50%); R^2 of 0.428 and 0.453 between measured and modeled H_2S concentration for charcoal and wood burning respectively. This implies that the applicability of the model for environmental regulatory purposes will be inefficient and will not present representative data at respective receptor points downwind the sources if used in simulating the concentration of H_2S.

IV. Conclusion

Among the pollutants investigated, dispersion of carbon monoxide is highest. These may be attributed to its comparatively low reactivity and low molecular weight. However, SO_2 which has a higher molecular weight than H_2S presents higher dispersion. This suggests that some portion of H_2S is transformed in the atmosphere under some physical conditions. For example, at a high temperature H_2S is oxidized to SO_2 and water.

Based on National Ambient Air Quality Standards, it is observed that the safe distance for human health around these biomass combustion sources are any distances greater than 4.0m for CO (1 hour time average, the safe limit is 40mgm⁻³), SO_2 (24 hour time average, the safe limit is 0.365mgm⁻³) and H_2S (1 hour time average, the safe limit is 0.042mg/m³). It is then suggested that for minimal deleterious effects on people around these emission sources, duration of activities around them should reduced and those involved in these activities (e.g cooking) should position themselves at the anti-plume direction.

V. Recommendation

Exposure to these sources should be grossly reduced by enacting environmental policies that regulate the duration of exposure to these sources so as to reduce the health impact of these emissions. Since pollutants are generated in combustion chambers of these stoves, modifications to the combustion process itself by ensuring greater air to fuel mixture can be quite effective in reducing their formation. This calls for more research in designing and constructing more environmental friendly stoves that has greater air-fuel mixture ratio for the combustion chamber for both wood and charcoal burning in Nigeria.

Table 1: Monitored Sites Across North Central Nigeria

S/N	Sources	Sites	Locations	Elevations
1	Wood Burning Site, Jos	Faringada Round about, Zaria. Jos.	N09⁰57' 27.6'' E 008⁰51'37.1''	1123.0m
2	Charcoal Burning Site, Jos	Behind Police Training School, Bidabidi, Jos	N09⁰55' 49.1'' E 008⁰52'33.9''	1160.0m
3	Wood Burning Site, Lafia, Nasarawa State	Shabu Lafia, Nasarawa State.	N08⁰33'40.2'' E008⁰32'41.4''	171.00m
4	Wood Burning Site, Makurdi, Benue State	Lafia Garage, North Bank, Makurdi. Benue State	N07⁰46'06.9'' E008⁰33'35.6''	140.00m
5	Charcoal Burning Site, Makurdi, Benue State	Before Dayspring, North Bank, Makurdi. Benue State.	N07⁰45'43.4'' E008⁰33'15.6''	144.00m

Table 2: Emission rate of the pollutants

S/N	Pollutant	Emission rate for charcoal emissions (mg/s)	Emission rate for wood emissions (mg/s)
1	Carbon (II) oxide	140.0	84.0
2	Sulphur (IV) oxide	0.744	0.714
3	Hydrogen sulphide	1.556	1.176

Table 3: National Ambient Air Quality Standards (CARB, 2016)

S/N	POLLUTANTS	AVERAGING TIME	AMBIENT AIR QUALITY STANDARD	STANDARD TYPE
1	Carbon monoxide, CO	8Hr.	$10.00 mg/m^3$	Primary
		1 Hr.	$40 mg/m^3$	Primary
2	Sulphur dioxide, SO_2	1 Hr.	$0.196 mg/m^3$	Primary
		Annual arithmetic mean	$0.08 mg/m^3$	Primary
		24 Hr.	$0.365 mg/m^3$	Primary
		3 Hr.	$1.3 mg/m^3$	Secondary
3	Hydrogen Sulfide	1 Hr.	No National Standards but $0.042 mg/m^3$ for California Standards	
4	Respirable Particulate Matter (PM_{10})	24 Hr.	$0.15 mg/m^3$	Primary
		Annual Arithmetic Mean	_____	
5	Fine Particulate Matter ($PM_{2.5}$)	24Hr.	$0.035 mg/m^3$	Primary
		Annual Arithmetic Mean	$0.012 mg/m^3$	Primary

California Air Resources Board (CARB), 2016

Table 4: Average Concentration of Pollutants emitted from Wood burning

	LAFIA					MAKURDI					JOS				
X(m)	CO	SO_2	H_2S	$PM_{2.5}$	PM_{10}	CO	SO_2	H_2S	$PM_{2.5}$	PM_{10}	CO	SO_2	H_2S	$PM_{2.5}$	PM_{10}
1.00	113.58	1.01	1.04	0.63	1.33	95.99	0.64	0.56	0.47	1.04	74.56	0.56	0.73	0.33	0.74
2.00	75.77	0.55	0.63	0.70	1.55	45.02	0.39	1.74	0.17	0.37	38.57	0.45	0.76	0.22	0.47
3.00	41.49	0.38	0.35	0.44	0.90	26.88	0.30	0.26	0.13	0.27	23.68	0.26	0.52	0.23	0.49
4.00	31.55	0.30	0.14	0.27	0.55	16.09	0.20	0.18	0.20	0.44	12.76	0.21	0.46	0.11	0.24
5.00	20.05	0.19	0.07	0.56	1.15	1.20	0.18	0.07	0.11	0.21	6.42	0.03	0.13	0.12	0.26

**Table 5:** Average Concentration of Pollutants emitted from Charcoal burning

	MAKURDI					JOS				
X(m)	CO	SO_2	H_2S	$PM_{2.5}$	PM_{10}	CO	SO_2	H_2S	$PM_{2.5}$	PM_{10}
1.00	153.92	0.46	1.25	0.05	0.10	113.97	0.56	0.98	0.05	0.11
2.00	81.35	0.35	0.29	0.04	0.09	49.75	0.34	1.14	0.05	0.06
3.00	46.51	0.30	0.22	0.05	0.10	23.31	0.33	0.52	0.03	0.06
4.00	27.67	0.17	0.14	0.05	0.11	11.98	0.21	0.31	0.03	0.06
5.00	12.73	0.18	0.07	0.05	0.10	6.24	0.34	0.12	0.03	0.06

Table 6: Measured and Modeled Concentration of Pollutants from Biomass Emission Sources

x(m)	CHARCOAL						WOOD					
	CO		SO_2		H_2S		CO		SO_2		H_2S	
	MSD	MDL	MSD	MDL	MSD	MDL	MSD	MDL	MSD	MDL	MSD	MDL
1.00	184.33	87.79	0.52	0.47	1.39	0.98	54.38	52.68	0.26	0.45	1.39	0.74
2.00	34.28	21.95	0.39	0.12	1.39	0.24	35.49	13.17	0.23	0.11	1.39	0.18
3.00	6.87	9.76	0.26	0.05	0.98	0.11	21.75	5.85	0.13	0.05	0.70	0.08
4.00	5.73	5.49	0.13	0.03	0.00	0.06	14.31	3.29	0.13	0.03	0.70	0.05
5.00	4.58	3.52	0.00	0.02	0.00	0.04	2.29	2.11	0.09	0.02	0.00	0.03

NOTE:
* MSD- Measured Data
* MDL- Modeled Data

4.0m
8%

5.0m
4%

3.0m
15%

1.0m
48%

2.0m
25%
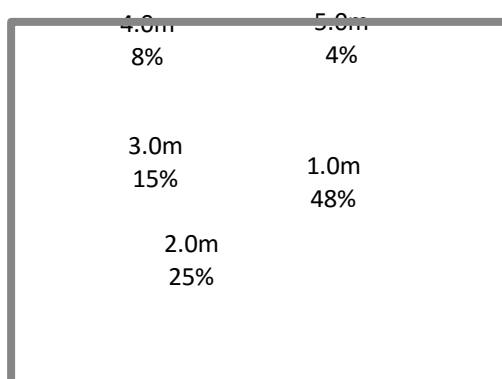
Fig. 2: Percentage Trend of Dispersion of CO at Specified Locations Downwind Wood burning stove.

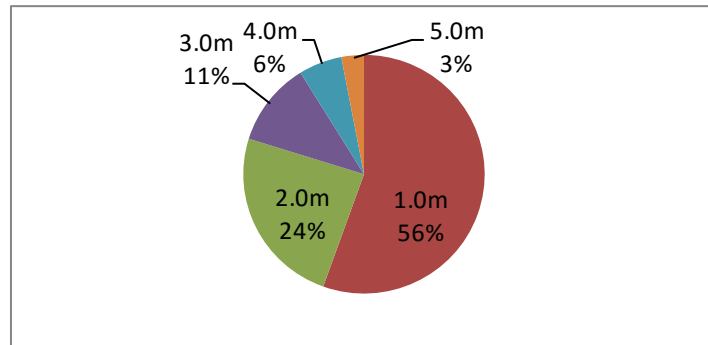**Fig. 3:** Percentage Trend of Dispersion of CO at Specified Locations Downwind Charcoal burning stove.
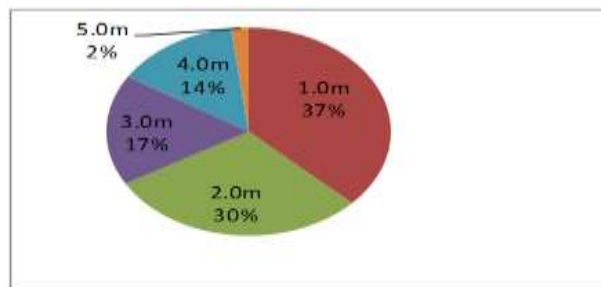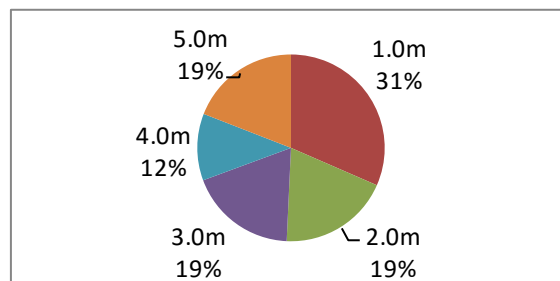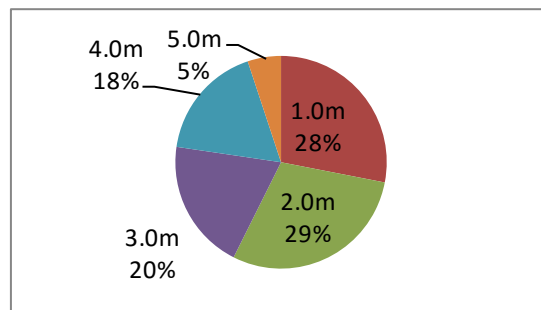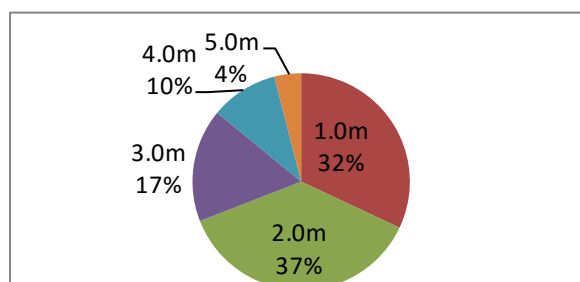

Fig. 4: Percentage Trend of Dispersion of SO_2 at Specified Locations Downwind Wood burning stove.

Fig. 5: Percentage Trend of Dispersion of SO_2 at Specified Locations Downwind Charcoal burning stove.

Fig. 6: Percentage Trend of Dispersion of H_2S at Specified Locations Downwind Wood burning stove.

Fig. 7: Percentage Trend of Dispersion of H₂S at Specified Locations Downwind Charcoal burning stove.
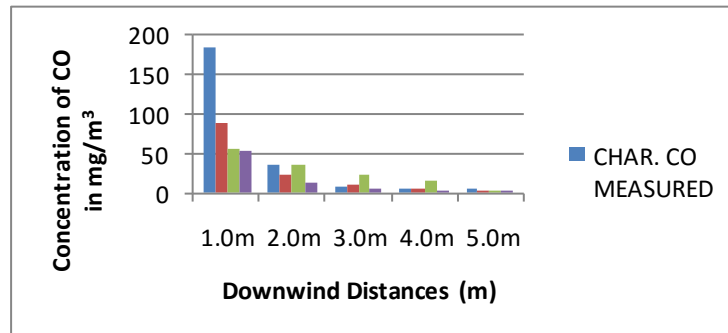
Fig. 8: Measured and Modeled CO Concentration from Biomass Burning**.**
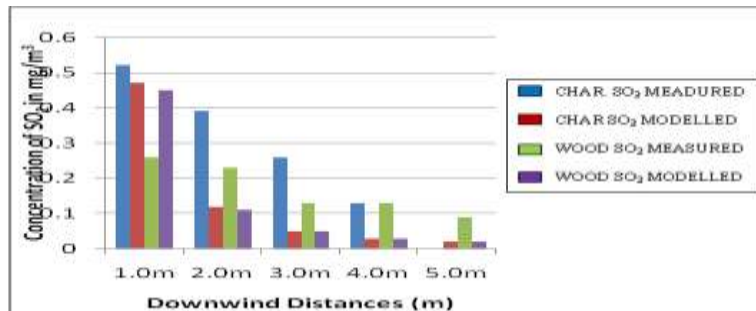
Fig. 9: Measured and Modeled SO₂ Concentration from Biomass Burning
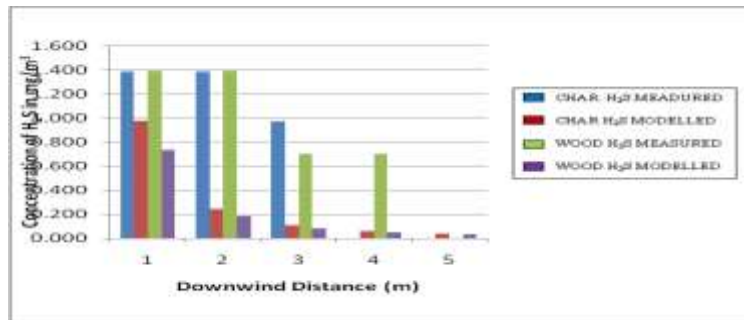
Fig. 10: Measured and Modeled H₂S Concentration from Biomass Burning.
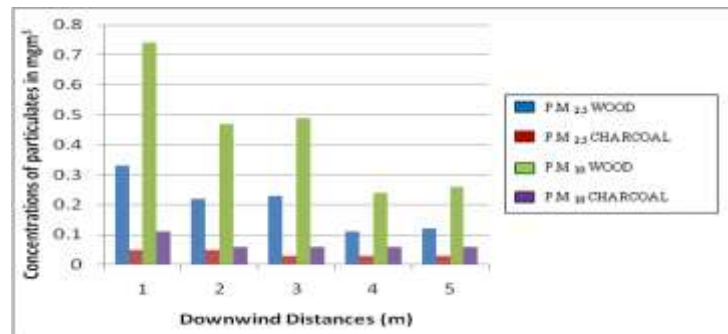
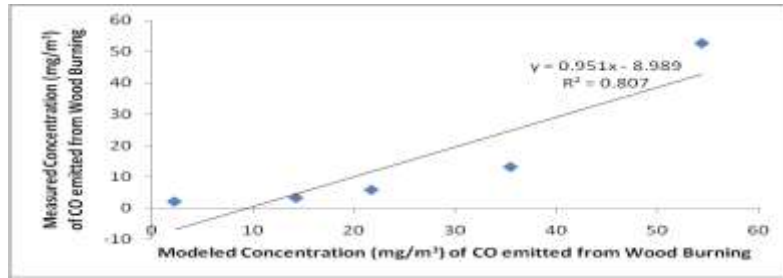**Fig. 11:** Concentration of Particulates from biomass combustion sources at specified Downwind distances

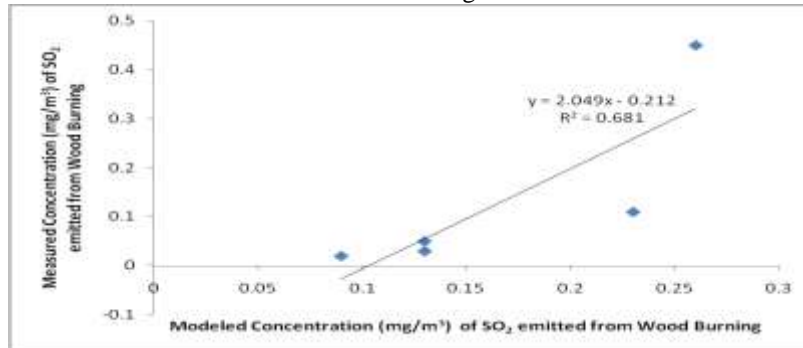**Fig. 12 :** Scatter Plot Measured Concentration Data and Modeled Concentration Data of CO from Charcoal Burning.

Fig. 13: Scatter Plot of Measured Concentration Data and Modeled Concentration Data of SO_2 from Charcoal Burning**.**
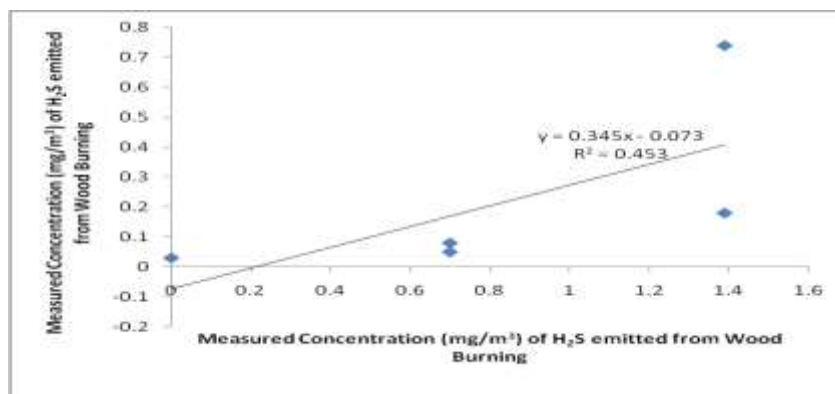

Fig. 14: Scatter Plot of Measured Concentration Data and Modeled Concentration Data of H_2S from Charcoal Burning
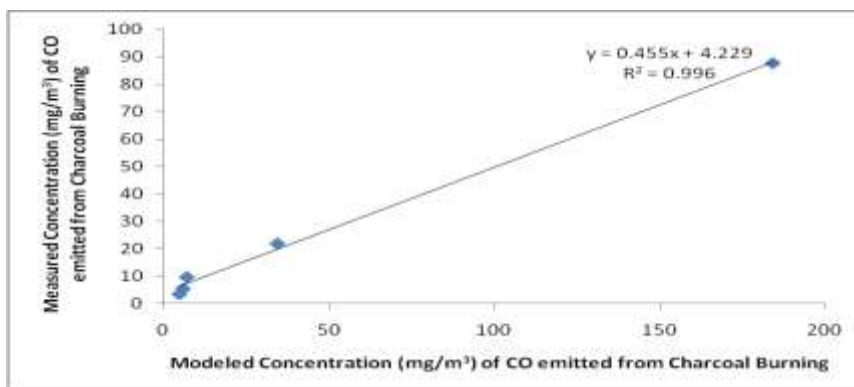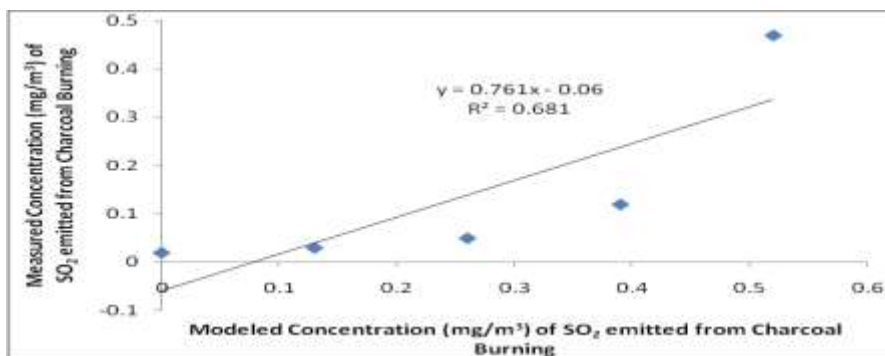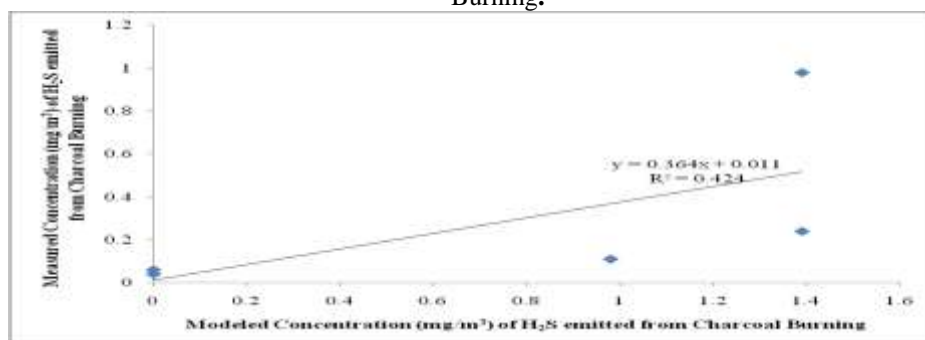

Fig. 15: Scatter Plot of Measured Concentration Data and Modeled Concentration Data of CO from Charcoal Burning

Fig. 16: Scatter Plot of Measured Concentration Data and Modeled Concentration Data of SO_2 from Charcoal Burning**.**

Figure 17: Scatter Plot of Measured Concentration Data and Modeled Concentration Data of H_2S from Wood Burning.

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