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Simulation of Black Carbon Emissions from Gas Flaring Activities in the Niger Delta Region, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

There is no Black Carbon emission inventory for Nigeria and no standard Emission factor with which to measure the volume of emissions. This study aims at providing baseline emission inventory for the volume of Black Carbon released into the environment from gas flaring activities in the National Data Repository (NDR) between 1965 to 2016 (52 years) using Nigeria's associated petroleum gas-related emission factors; modelling of the estimated Black Carbon emissions using logistic growth model. The volume of gas produced and flared within this period was sourced from Nigerian National Petroleum Corporation (NNPC) annual bulletins and other literature. The work shows that: for the period under review, 1.8 trillion cubic meters of gas was produced and 0.91 trillion cubic meters was flared, only 11% of gas produced was flared in 2016. Estimated cumulative Black Carbon emission shows that Black Carbon emission from gas flare is decreasing as the volume of gas flared is decreasing. The model shows that 487050 tons, 1116157 tons; 19438 tons, 44544 tons and 0.10 are the respective carrying capacities, initial Black Carbon volumes and growth rate for the upper and lower Black Carbon emissions. Re-injection and Utilization of flared gas for cooking purposes and placing a heavy penalty on gas flaring activities are among solutions given to reduce gas flaring.

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Keywords: Carbon emissions; gas flaring; energy sources; logistic model.

1. INTRODUCTION

The search for energy continues to generate extensive environmental problems worldwide and as population explosion continues, increase in energy sources become imminent. Energy sources such as crude oil constitute a major source of energy around the world crude oil, fossil oil and natural gas are contributing 31.3%, 28.6% and 21.2% respectively, to world energy, [1] and hence its massive exploration in other parts of the world, Nigeria inclusive. Nigeria is 13th on the list of global top oil producers and 1st in Africa, with a daily production rate of about 2.21million barrels per day, [2] over 90% of Nigeria's crude oil is produced in the Niger Delta region of Nigeria.

Nigeria also has a huge potential for gas, but due to lack of processing and storage infrastructure, a lot of these gas are flared and the gas flaring effects on the environment, ecosystem, socio-economic and health of the residents of the flare area is multifaceted [3,4]. Among the deleterious effects of gas flaring activities is the release of carbonaceous substances such as black or elemental carbon (BC or EC), These sooty substances also called Black carbon [5,6,7], has been underestimated in emission inventories and models, as a result of which models are struggling to predict measurements of BC in regions of intense gas flaring [8]. BC is not the only substance emitted from incomplete combustion, and the climate impacts depend on the full range of co-pollutants emitted from a particular source. However, soot has become the foremost problem of the Niger Delta region in recent years.

Incomplete combustion of fossil fuels, biofuels and biomass are the major causes of Sooty emissions. BC has a diameter of less than 2.5 microns ($PM_{2.5}$), [7] and are the most strongly light-absorbing component of particulate matter (PM). It is the second-largest climate forcer in today's atmosphere [9]. Recently, Niger Delta's atmospheric air has been observed to be laden with sooty materials suspected to be black carbon. This has been blamed on arrays of factors, ranging from gas flaring activities, artisanal refining, asphalt plants and the use of tire fires for abattoir purposes. The need for investigation of black carbon emission from gas flaring activities in Nigeria is thus necessary to determine its contribution to the global pool of black carbon in the Niger Delta region.

Studies have shown that while there are existing models to estimate black carbon emission from different sources, there are inadequate or little existing models to forecast soot emissions from flares, hence for BC emission estimates for inventories and regulatory decisions to be derived (especially in developed countries) BC and other key contaminants such as particulate matters whose diameter is less than 2.5 micro-meter ($PM_{2.5}$), must be reported and are tracked in government inventories [10] (Haung et. al., 2016). McEwen pointed out that emissions are usually estimated using simple emission factors that stipulate a unit of pollutant emitted per unit of fuel consumed. Considering the wide range of variation in flare emissions related to huge changes in climatic conditions, fuel composition, fuel flow rates, flare size and flare design, use of a single factor emission might be misleading.

This research will utilize a combination of two existing mathematical models to estimate black carbon emission from gas flaring in the study area and apply a logistic model to forecast future emission trend. The study will provide a baseline data for subsequent estimations of sooty/BC emissions in Nigeria. The study will show the contribution of the gas flaring activities in our oil and gas sector to the existent, circulating pool of BC predominant in the atmospheric air in Niger Delta. The study will also provide a basis for comparing estimated emission factors to ascertain a better way of emission factor estimation. The study will also serve as reference material for future works in this line of study.

2. RESEARCH METHOD

2.1 Study Area

The Niger Delta region is a great flood plain which covers a 25,640 km^2 of the Nigeria's landmass with an estimated regional population of about 30 million people [11,9]. It comprises of nine states and 185 local government areas. The states include Delta, Rivers, Bayelsa, Imo, Abia, Akwa Ibom, Cross River, Edo and Ondo state. The Niger Delta region remains the sole region for oil and gas generation in Nigeria, which has accounted for over 90% of the country's foreign earnings for more than fifty years now, making it the stronghold of the country's economic and foreign exchange earnings. This region has the biggest wetlands within the nation, the third biggest wetland within the world and the second biggest mangrove forest in the world and it is known for its unique biodiversity and environmental sensitivity [9].

2.2 Data Collection

For this study, secondary data regarding the volume of gas produced, the volume of gas utilized and volume of gas flared were sourced for from the Nigeria National Petroleum Corporation (NNPC) annual bulletins. The data covered the period from 1965 to 2016 (52 years). The amount of gas produced, utilized and flared were given in million standard cubic feet (mcf), they were converted to an international standard unit (SIU) of million cubic meters (mcm). Microsoft Excel (2016 version) was utilized in the analysis of the data.

2.3 Mathematical Models

The mathematical methods employed in this study involved the use of two black carbon (BC) emission models that consisted of:

- Method of Giwa et al. [9]
- Method of McEwen and Johnson [10]

2.3.1 Black Carbon emission estimation by Giwa et al. [9]

Giwa et al. [9], in their work titled Baseline Black carbon emissions for gas flaring in the Niger Delta, accessed the gas production and flared data in Nigeria between 1965 and 2013 from bulletins published in the NNPC website. The method of Black Carbon Emission, as described by Giwa, comprised the use of extreme values of 0.51 kg of BC/10^3m^3 as lower limit (as quoted by McEwen and Johnson, 2012) and 2.5632 kg of BC/10^3m^3 as upper limits. This method however failed to take into cognizance the unique characteristics of Nigeria's natural gas composition, and thus was suspected to yield misleading results if applied to the mathematical expression for computing BC emission volume rate as given by Equation 1.

$$\text{E}Black\ carbon\ Emission\ (E_{BC}) = Emission\ factor\ \left(\frac{kg\ of\ BC}{10^3 m^3}\right) \times Volume\ of\ gas\ flarred\ (m^3) \quad (1)$$

2.3.2 Black carbon Emission estimation by using McEwen [10] method

The first empirical relationship linking BC emission factors and volumetric fuel heating values for a range of conditions as established by McEwen and Johnson, [10] and cited by Haung et al. [12] was used to estimate the emission factor of BC. This method suggests the use of the empirical model in Equation 2 to estimate the emission factor.

$$EF_{flare,BC} = 0.0578 \times HV_{APG} - 2.09\ (correlation: R^2 = 0.85) \quad (2)$$

Where $EF_{flare,BC}$ and HV_{APG} represent the gas flaring BC emission factor and the volumetric weighted heating value of Associated Petroleum Gas (APG), respectively. The Equation (2) shows that $EF_{flare,BC}$ and HV_{APG} have a strong linear relationship. The Net Calorific Value (NCV) or Lower heating value (LHV) and the upper limit of the APG composition, as shown by Haung et al. [12] were used in calculating the emission factor. The emission factor was given in a range. An uncertainty factor of 20% as suggested by Haung et al. [12] was applied to the Emission factor got therefrom, to account for the variability of the APG composition. The lower limit and upper limit were hence got from reducing and adding 20% to the emission factors. The EF is subsequently multiplied by the volume of gas flared to give the emission rate as given by Equation 3.

$$Black\ carbon\ Emission\ (E_{BC}) = (0.0578 \times HVAPG - 2.09 * Volume\ of\ gas\ flared (m3) \quad (3)$$

2.4 Simulating Black Carbon Emission Trends using the Logistic Model

Microsoft Excel (2016 version) was used to plot the cumulative graph of the volumes of black carbon emitted over the 52 years under study (1965-2016). The logistic model was used for simulating the cumulative BC emissions trends over a period of 52 years. The maximum cumulative BC emission rate was predicted and the production rate constants were also estimated by the logistic model given by the expression

$$\frac{dN}{dt} = kN\left(1 - \frac{N}{N_m}\right) \quad (4)$$

The differential equation has the analytic solution as

$$N = \frac{N_m N_o}{(N_m - N_o)e^{-kt} + N_o} \quad (5)$$

This can also be rewritten as

$$N = \frac{N_m}{\left(\frac{N_m - N_o}{N_o}\right)e^{-kt} + 1} \quad (6)$$

Equation (3.6) can be simplified further

$$N = \frac{N_m}{Pe^{-kt}+1} \quad (7)$$

Where:

$$P = (\frac{N_m - N_o}{N_o}) \quad (8)$$

N_m = Maximum cumulative BC emission
N = Cumulative BC at time (t)
N_o= Initial BC emission
K= BC emission rate/ year
T= time (year)

Model Assumptions

For effective modelling, certain assumptions had to be made. For the model in this study, the following assumptions were made:

i. The initial BC emission (N_o) in Nigeria prior to gas flaring in 1965 was assumed to be zero.
ii. All other sources of BC emissions were constant and only BC emission from gas flares varies.

3. RESULTS AND DISCUSSION

3.1 Results

The results include the volume of gas produced and the volume of gas flared between 1965 and 2016. The percentage of the gas produced that was flared was calculated and reported. The range of values for natural gas composition in Nigeria was reported also. The Giwa et al., [9] model which assumed an emission factor and that of McEwen and Johnson [10] which considered unique Nigeria natural gas composition was compared and reported. The calculated emission factors used to deduce the volume of BC emitted into the atmosphere for the duration under review were also reported.

3.1.1 Volume of gas produced in Nigeria from 1965 – 2016

The volume of gas produced in Nigeria within the 52 years (1964-2016) is sourced from the NNPC inventories [14-21] and presented in Fig. 1. The values reported in the annual bulletins which were in mscf has been converted to million cubic meter (mcm). 5 years moving average trend line was also included in the graph to give a clear description of the gas production trends in Nigeria within the period under review.

3.1.2 Volume of gas flared in Nigeria from 1965 – 2016

The volume of gas flared in Nigeria within the 52 years (as reported by NNPC) [13-21] is shown in Fig. 2. 5 years moving average trend line was also included to give a vivid description of the gas flare trend throughout the years under study.

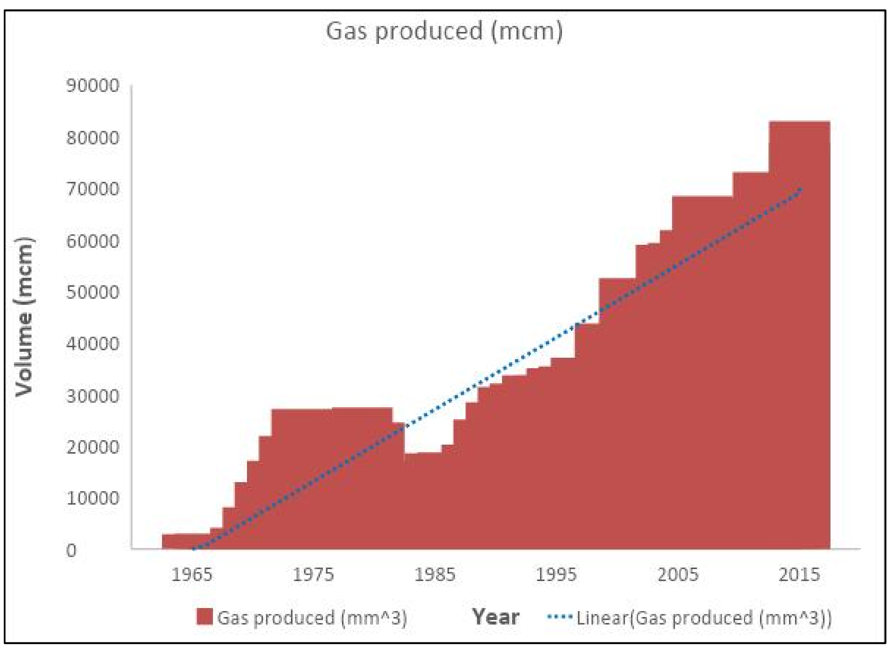

Fig. 1. Volume of gas produced in Nigeria from 1965-2016

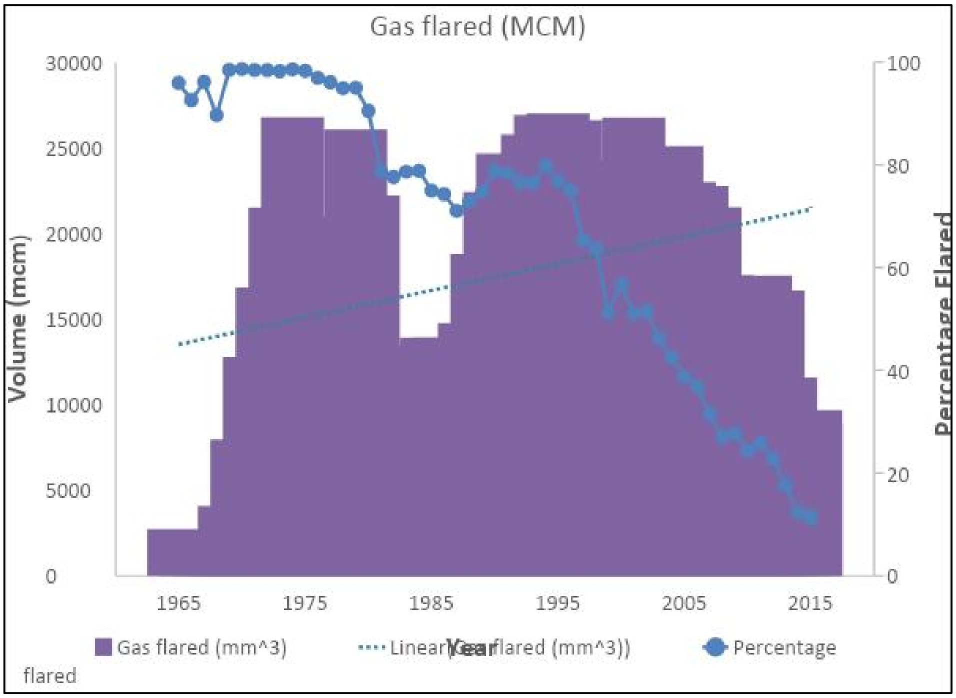

Fig. 2. Volume of gas flared in Nigeria from 1965-2016

3.1.3 Estimated BC emission by method of Giwa et al., 2014

Giwa et al., [9] adopted a value of 0.51 kg as the lower limit of his emission factor, and 2.563 as the upper limit for his emission factor. The values of the estimated BC emissions got using these emission factor values are presented in Fig. 3a and 3b.

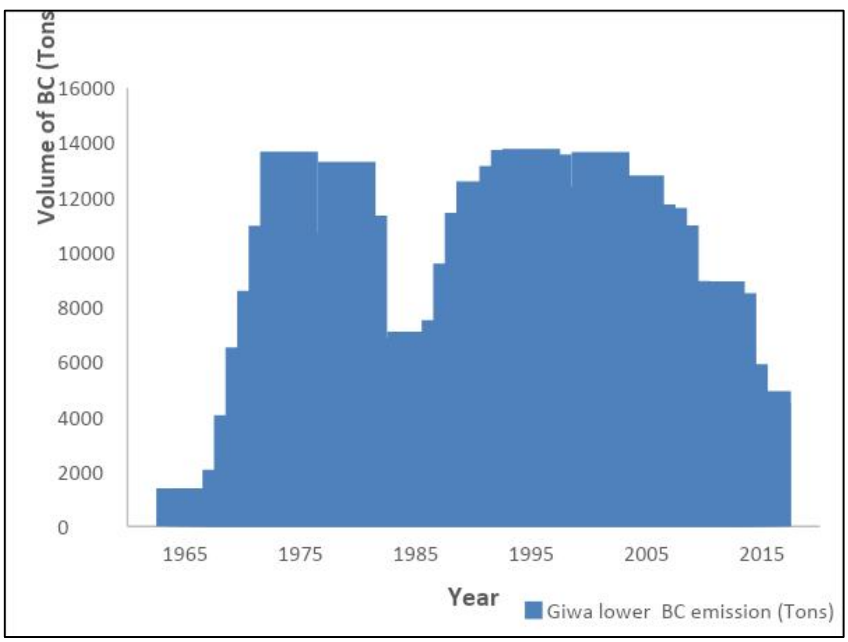

Fig. 3a. Volume of lower BC emitted according to Giwa et al., [9]

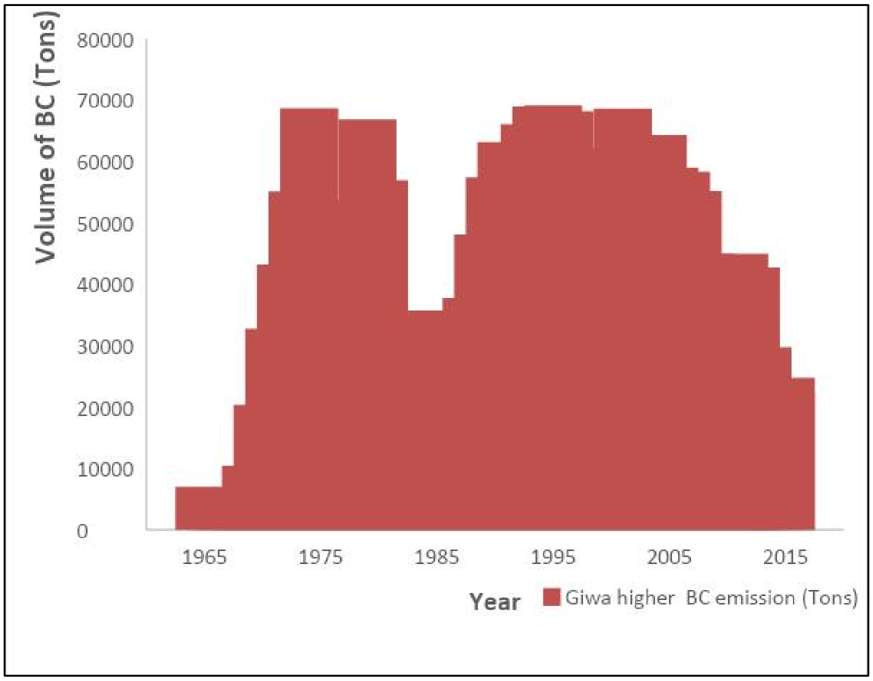

Fig. 3b. Volume of higher BC emitted in Nigeria according to Giwa et al., [9]

3.1.4 Estimated BC emission by the method of McEwen, 2012

The varying compositions of natural gas necessitated the use of a more realistic empirical model which takes into consideration region-based compositions as developed by McEwen and Johnson [10]. The flaring BC was estimated using this method and results are presented in Fig. 4a and 4b.

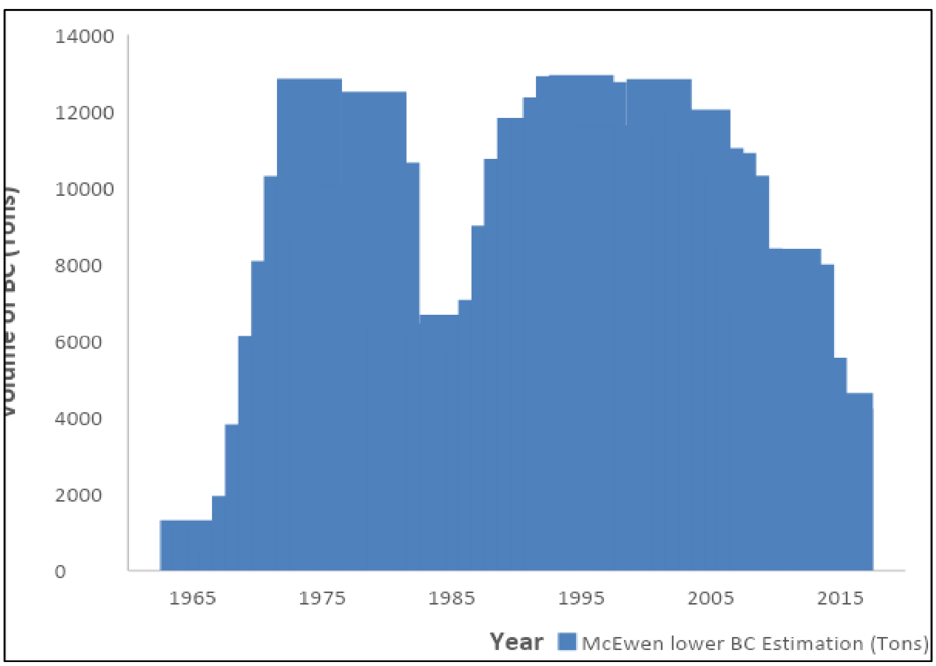

Fig. 4a. Volume of lower BC emitted in Nigeria according to McEwen (2012)

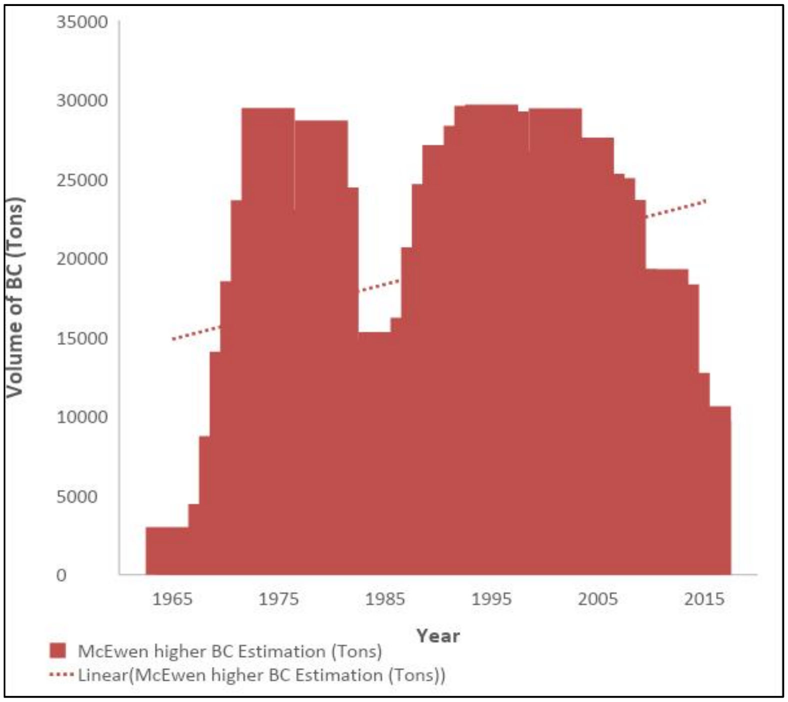

Fig. 4b. Volume of higher BC emitted in Nigeria according to McEwen (2012)

3.1.5 Comparing the two Estimated BC emissions

Fig. 5a and 5b show the comparison between the estimated lower and higher BC emissions of both models. Juxtaposing the models gives a vivid base of comparison of both models hence making obvious the difference between them. While the lower models have little difference, the higher models show a wider difference between the models.

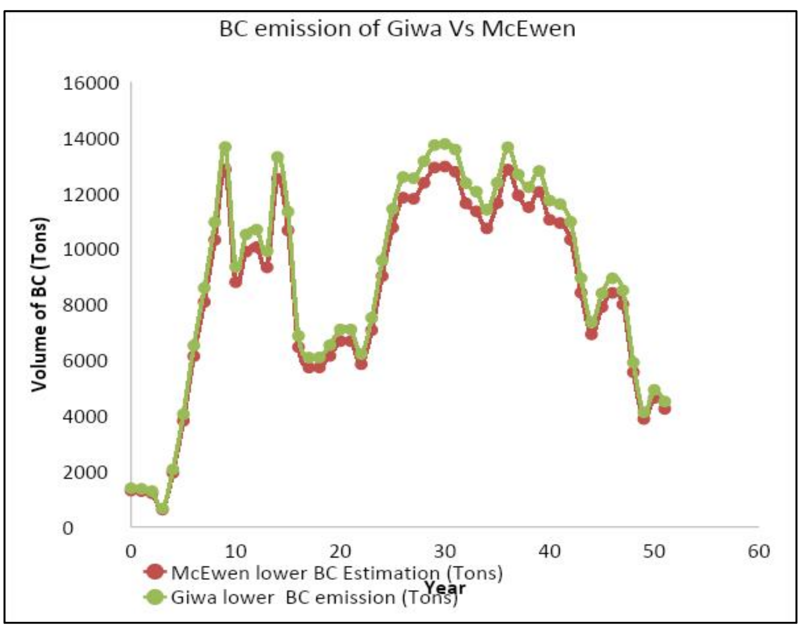

Fig. 5a. Comparison of lower BC emission estimates by Giwa's and McEwen's models

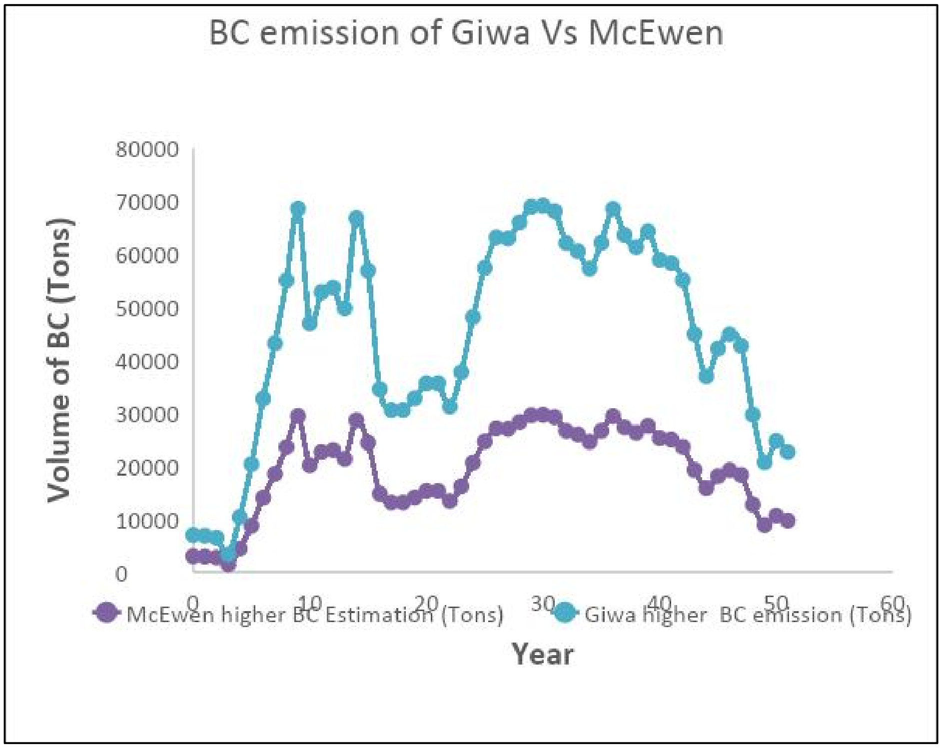

Fig. 5b. Comparison of higher BC emission estimates by Giwa's and McEwen's models

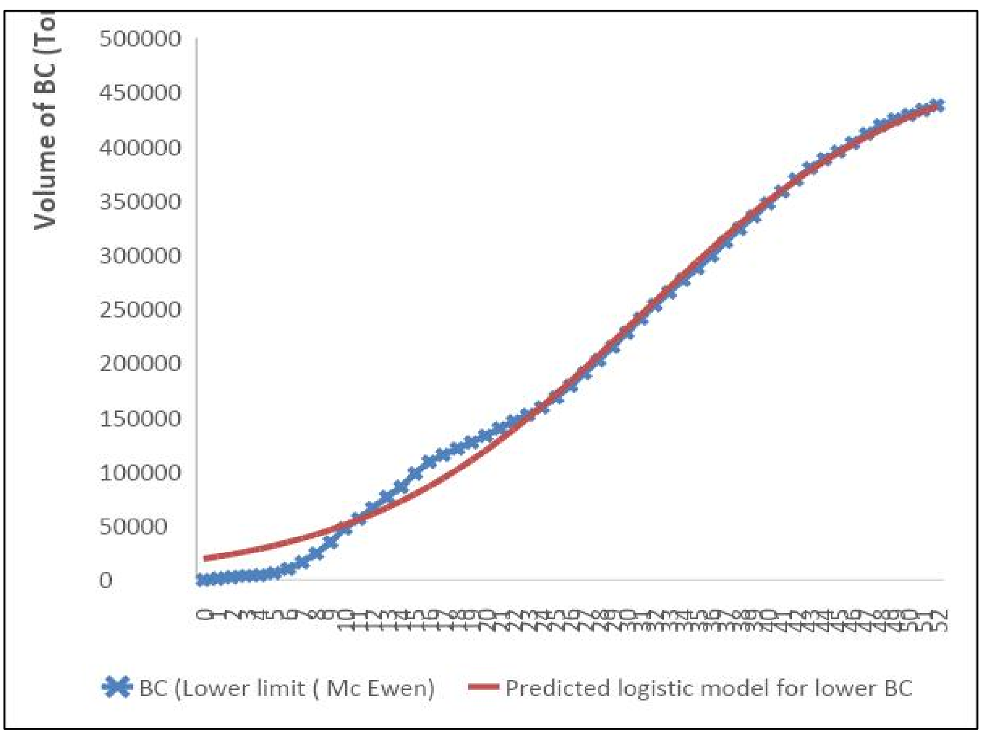

Fig. 6a. Logistic model of lower BC emission estimates by McEwen's model

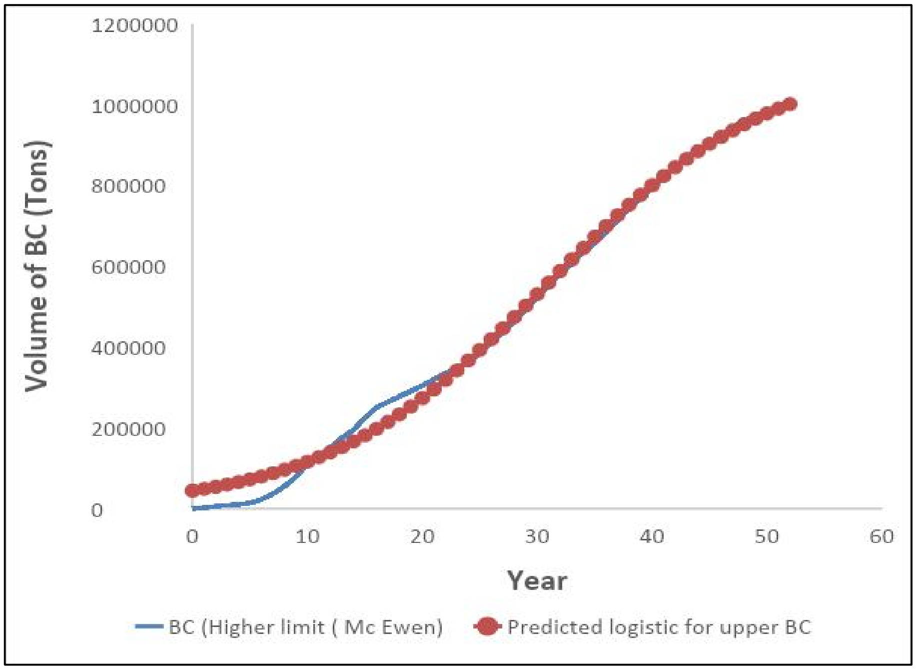

Fig. 6b. Logistic model of higher BC emission estimates by McEwen's model

3.1.6 Modelling BC emissions using the logistic model

The logistic model was used for the McEwen model of BC emissions. The carrying capacities, the emission rate, initial BC emissions at time zero and how long it will take to reach the carrying capacity was predicted and presented in Fig. 6a and 6b.

3.2 Discussion

The graph in Fig. 1 shows that for 52 years of gas production in Nigeria, a total of 1.809 trillion cubic meters. This is an average of 3.478 billion cubic meters per year which brings Nigeria among the top gas producers in the world. The BP (British Petroleum) statistics of 2018 shows that at the end of 2017, Nigeria natural gas proved reserves is 5.2 trillion cubic meters, about 47.2 billion cubic meter equivalent in all. This makes Nigeria the 3rd highest producers of gas in Africa, behind Algeria and Egypt, BP statistics, 2018. The volume of gas flared in Nigeria from 1965 to 2016 is shown in Fig. 4b. The data shows that a total volume of 0.912 trillion cubic meters of gas has been flared in Nigeria between 1965 and 2016. This is enough to meet a large fraction of the energy demand of Africa as a whole. The total value of 0.912 trillion cubic meters is equivalent of 5,734,144 US barrels of oil, according to BP statistics, the price of oil as at the end of 2017 was 54.31 USD, this means that Nigeria would have lost over 311 billion USD in the recent past.

Figs. 3a – 5b show the comparison of the two models. It can be seen that using McEwen's model which considers the Nigerian natural gas composition provides a more accurate value. Absolute error calculation shows that the model Giwa et al., used over estimated by 5.4 percent for the lower BC emission estimation while they had an absolute error of 75 percent for the upper limit BC emission estimation. This confirms the assertion of McEwen and Johnson, 2012 that the use of unfounded constant emission factors across every region leads to wrong estimations of BC emissions.

Logistic growth model was used to simulate the BC emissions in Nigeria from 1965 to 2016. The cumulative data are shown in Fig. 6a and 6b show that it follows a logistic growth curve. Applying the solutions of the logistic model as stated in Equation (6), the $N_{m,}$ carrying capacity of the BC in the environment is shown to be 487050 tons of BC. The initial BC emission in the environment before the commencement of gas flaring in Nigeria, N_o was 19438 tons of BC, this is contrary to the model assumption that initial BC emissions was zero. The BC growth rate per year K is approximately 0.103 for both the Lower limit and upper limit BC emissions modeled. From the model of the BC emission shown in Fig. 6a and 6b, the values for the respective carrying capacities for the lower and upper BC emissions were 487050 tons and 1116157 tons of BC respectively. The initial BC in the environment was 19,438 tons and 44544 tons respectively. This is contrary to our initial assumption that initial BC before gas flare started was zero. This finding also invalidates our second assumption that other sources of BC emissions are constant.

4. CONCLUSION

The study showed that volume of BC emitted into the atmosphere increased progressively in the first forty years of gas flaring with a noteworthy decrease in the amount of BC released in the fifth decade. This study has estimated the total amount of BC released into the Niger Delta area to be over 4.56 x 10^5 tons via the flaring of a total volume of 912.45 bcm of gas worth $311.87 Billion. It was observed that the quantity of BC emitted is decreasing with a decrease in the volume of gas flared.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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