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Research article

Estimating emissions from open-burning of uncollected municipal solid waste in Nigeria

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Abstract: Open-burning of municipal solid waste (MSW) is very common in Nigeria. Hence, this work estimated the emissions (greenhouse gases and others) from open-burning of uncollected MSW in Nigeria. The parameters (secondary data) used for the estimations were obtained from pertinent literature of MSW generation rate in Nigeria, level of uncollected MSW subjected to burning in Nigeria, oxidation/ burning efficiency and others, 80.6% of wastes generated in Nigeria are combustibles. The National Bureau of Statistics showed that 52% of Nigerians lives in urban areas in the year 2020. With an annual mean growth rate of 2.62% between 2006–2020 (World Bank data), the urban population of Nigeria was estimated at 104,885,855 in 2020. The estimation for the year 2020 shows that the MSW generated by the urban population of Nigeria ranges from 16.8–25.3 million tons. With burning/ oxidation efficiency (η) of 0.58, between 2.4–3.7 million tons of the uncollected wastes are open-burned. This represents 14.7% of the total MSW generated in Nigeria for the year. IPCC guidelines show that only fossil-carbon wastes are climate-relevant for CO_2 emissions. Our estimation shows that 14.3% of the MSW generated in Nigeria contain fossil carbon. The total emissions for the three GHGs–carbon dioxide, methane and nitrogen oxides were between 798 to 1,197 kilotons of CO_2-eq per year. Other emissions associated with open-burning of MSW was also estimated using their default emission factor. The findings suggest the urgent need for the country to transition to proper

waste management system, which will include improved collection and disposal to sanitary landfills, to protect public health and the environment.

Keywords: open-burning; municipal solid waste; greenhouse gas; emissions; waste collection; waste management; Nigeria

1. Introduction

Climate change has become a topical global issue, and the phenomenon is highly correlated with greenhouse gas (GHG) emissions. These GHG and other non-GHG emissions have environmental, socioeconomic and health implications. Therefore, proper management of municipal solid waste (MSW) has become a major concern in Nigeria [1–5]. Open-burning of MSW is a poorly characterized and an underestimated source of air pollution in developing countries [6–8]. In Nigeria and other developing countries, MSW are deliberately burned either at generation-source, at an open dump or in uncontrolled, un-engineered dumpsites [1,2,9–13]. Many urban households in Nigeria prefer burning their wastes, while municipal waste managers incinerate because it is a fast, easy and cheap way to reduce the volume and size of waste at dumpsites or landfills [1,3,9,14], so as to create space for new batches. There are existing laws against open-burning in many states of the country. Yet, the practice is very common, which indicates poor enforcement or lack of better alternatives. Other causes are poor financial resources of local and state governments, unavailability of other appropriate options to dispose or manage the waste [3]. MSW management is a very challenging environmental issues facing Nigeria. MSW is a category of waste generated from households. It comprises commercial and industrial wastes, depending on the reporting standard [15].

Open-burning (different from controlled burning) is combustion at low temperatures (between 250 and 700 ^oC) in oxygen-deprived setting, without temperature and burning-time control. There is lack of air pollution control measures, and it results to incomplete combustion [8,14]. The practice has been linked to public health, environmental, and social issues. For example, open-burning of wastes leads to 270,000 premature deaths per annum, across the globe [7]. Its emissions include GHGs such as carbon dioxide (CO_2), methane (CH_4), oxides of nitrogen (NOx) and nitrogen oxide (N_2O) [8,13,16]. Also, burning of wastes releases highly noxious smoke, foul odor, CO_2, particulate matter, heavy metals (such as cadmium, chromium, copper, zinc, etc.), known carcinogens such as benzene, dioxins, furans and PAHs, etc. [1,14,15,17,18]. This is very serious since waste generation levels of countries such as Nigeria (experiencing increasing economic and population growth) are expected to triple in the next 30 years [19].

Generally, waste collection is more developed in urban areas than the rural areas of Nigeria. The average waste collection rate for lower middle-income countries (LMICs) is 33%. The waste collection rate for sub-Saharan Africa countries is about 44% [19]. The other 56% are disposed to open dumpsites (usually open-burned) or open-burned by the generators. While many studies have been done on waste generation, characterization, and methane emissions from anaerobic decomposition in Nigeria; there has not been much attention to estimating emissions from open-burning of wastes [5]. This has created a gap in literature as regards to the extent of air pollution that the disposal method (open-burning) generates. Okedere et al [5] used secondary data to estimate emissions from open-burning of MSW from 13 cities in Nigeria; Ipeaiyedea and Falusi [20] focused only on two dumpsites at Lagos and Ibadan, while Fakinle et al [21] used secondary data to estimate emissions from solid waste combustion in Lagos from 2007–2016. The studies highlighted that MSW open-burning is a leading source of emissions in Nigeria metropolises. However, our study attempts to estimate for the emissions from burning MSW for the entire urban Nigeria population for the year, 2020. To the best of our knowledge and relevant search, no such works have been conducted. The need for the study is critical considering the huge amount of solid wastes generated within the urban areas of Nigeria and the abysmally poor collection and disposal methods. Thus, the importance of this study. It is expected that waste managers and policymakers will find useful the data generated by the study, so as to create policies and action plans for effective and adequate waste management and future emissions control strategy.

In this paper, simplistic estimation was conducted on emissions from open-burning of uncollected MSW. secondary data were used, and were assumed for the entire country. The study is very relevant considering that climate change is a critical concern facing the globe today. The effect is predicted to be more severe for developing countries such as Nigeria that lacks technical and adaptation capacity [7,22]. Data on waste management are still at infant stage in Nigeria and while it is assumed that 44% of the wastes generated in the country are collected, there is no readily available data on their treatment method. Thus, it becomes difficult to carry out estimation for open-burning of collected wastes in Nigeria. Disposal methods for uncollected wastes are generally, carelessly disposed to the environment (land and water) and open-burning [4,19].

This study adopted the IPCC guidelines [12,13,16] in the estimation Intergovernmental Panel on Climate Change (IPCC) is viewed as the leading global entity for the assessment of climate change [23] (and invariably their forcing factors–greenhouse gas emissions). Accordingly, they have developed a comprehensive method to standardize the calculation or estimation of GHG emissions at countrywide level. Their guidelines are also used to inventories for the major emissions defined in the Kyoto protocol in a particular system such as regional, national and others [13,16]. Most studies on the estimation of emissions from open-burning of wastes or waste management in general employs the IPCC methodologies, for example [6–8]. Limitations were acknowledged in this estimation. This study assumes default oxidation or burning efficiency, given by the IPCC [12,13,16] and also respective default emission factors of the pollutants [8,12]. It was also assumed that open burning takes place throughout the year. Similarly, the rate of burning for the various waste materials were assumed uniform. Level of waste recovery (for recycling or reprocessing) was assumed negligible in the estimation. In the first section, general introduction and brief literature review was discussed; while the second section explains the methodology adopted. The third section presents and discusses the results.

2. Brief literature review

MSW is one of the most pressing problems connected with economic growth and urban population. When it is not treated, it creates damaging and toxic constituents, which spreads into the environment [24]. MSW generation are expected to increase in developing countries such as Nigeria, where income level and population (both influencing consumption pattern) are rising steadily [1,19,24–27]. Other factors such as urbanization is also influencing the trend. In Nigeria (and most other places), solid wastes are related more with urban areas since waste generation is normally lower in rural areas. On the average, rural dwellers earn lower income, and consumes lesser finished consumer goods [28]. Economic (and population) growth increases waste generation and the pollution emissions they produce in the process of disposal [29]. Although it is widely accepted that Nigeria's waste generation ranges between 0.44 to 0.66 kg/capita/day, there is marked variation across the different geographical locations and between urban and rural areas [1]. For example, the following were reported in some Nigerian cities 0.13 kg/capita/day for Oyo State; 0.25 kg/capita/day for Borno state, 0.60 kg/capita/day for Rivers state [30]; 0.71 kg/capita/day at Ekiti State [25]; 0.58 kg/capita/day at Ogun State [9]; 0.30 kg/capita/day for Kano State [31]; 0.31 kg/capita/day for Kaduna metropolis [32]; 0.95 kg/capita/day for Lagos[26]. Food waste averages 50% of all MSW in Nigeria [25]. For the entire Nigeria, waste generation ranges between 0.44–0.66 kg/capita/day [1], which encompasses World Bank statistic (0.53 kg/capita/day) for Lower-middle income countries for the period, 2016–2030 [19]. Per capita MSW generation in Nigeria is substantially lower than those of developed or high-income countries, but the expected growth in Nigeria (and other developing countries) will increase the generation rate. For example, adopting Toda and Yamamoto approach and Granger tests, there is a bidirectional causal association between per capita GDP and MSW generation [29]. This is consistent with economic conception that increased wealth produces higher demand for consumer goods and, consequently, more waste [19,28]. Conversely, the provision of proper MSW management services by the municipalities is not increasing correspondingly in the country [3,4,25.33].

MSW management consists of collection, storage, transport, treatment, reprocessing, and disposal [4,28,33,34]. The practice is very poor in Nigeria, because waste management (which are mostly run by state governments) is poorly funded in Nigeria. Transportation alone accounts for about 33% of waste management [2], while the entire activities related to collection accounts for between 60–80% of waste management costs [35]. Literature shows that the state agencies responsible for waste management do not have adequate trucks/ vehicles and equipment for waste transportation. Those available are poorly maintained or are non-functional [28] for example, Ibikunle et al [27] reported that only 43% of collection vehicles are functional or available in Ilorin, Nigeria. In a study, inadequate funding accounts for 28% of the challenges faced by waste management agencies in Nigeria, followed by inadequate vehicles (22%), lack of proper maintenance (21%), distance between the waste disposal sites from residential areas (12%), inadequate workers (9%) and inaccessibility to the residential areas due to lack of urban planning (8%) [2]. The result suggests that collection-related issues accounts for about 72% of the problems facing waste management. Non-transportation of waste from designated or sanctioned waste bins have led to overflow of wastes into the streets, rivers; constituting aesthetic nuisance and adverse public health effects [28].

Without transportation, waste collection cannot be achieved. Poor waste collection creates a major barrier to advanced waste management value chains such as recycling, waste-to-energy schemes and others. To counter these barriers most state governments in Nigeria have partnered with private enterprises to provide adequate and efficient waste management. Though the populace is satisfied by the improvements private partnership brings to waste management, poverty and unwillingness-to-pay has weakened or affected the model seriously in most states of the country [26]. Accordingly, many of the PPP have been cancelled entirely or services rendered reduced significantly. Because of the poor waste management system in Nigeria, most of the urban populace are left with no other option than to use a cheaper way of disposing their wastes which includes open-burning. The burning is carried out in drums, containers, fields, large or empty plots and illegal dumps [5]. Figure 1 shows waste disposal method in Nigeria, as sourced from [4,10,19].

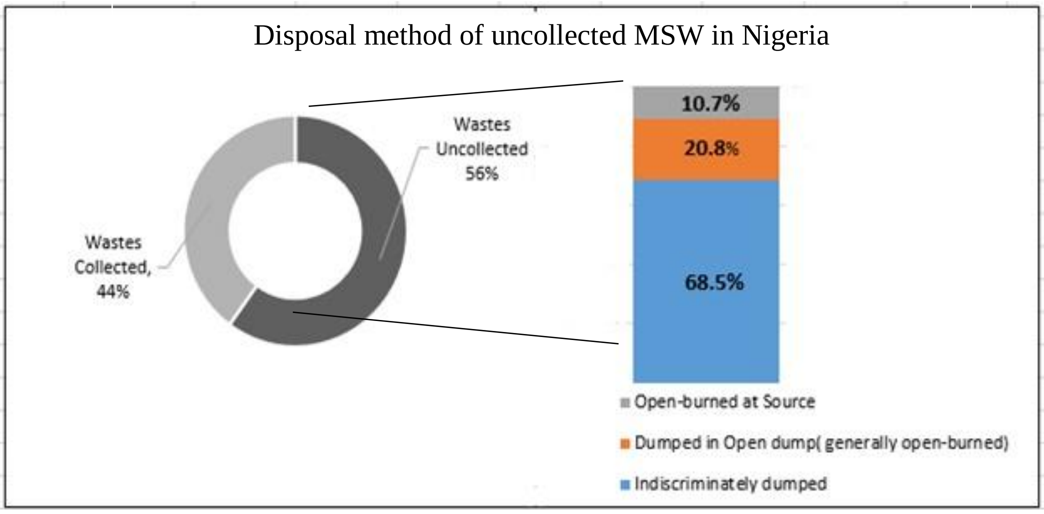

Figure 1. Disposal method of uncollected MSW in Nigeria.

The figure above suggests that 17.6% of the entire wastes generated in urban areas of Nigeria are open-burned either at source or at open dumpsite, while 38.4% are carelessly disposed. The practice of open-burning MSW is not limited only to households, municipal waste managers also frequently burn their wastes at the landfills (or at best sanctioned dumpsites) [3]. Change in consumption pattern has increased and diversified the composition of waste generated in Nigeria. While organic or decomposable wastes still accounts for most of the waste generated in Nigeria, the composition are changing. Unlike organic wastes, inorganic wastes pose more serious environmental and health risks such as heavy metal pollution of aquatic and terrestrial habitats. Burning of such wastes (plastics, e-wastes, etc.) also releases toxins such as polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs) [36]. Thus, measures must be put in place to reduce or enforce the ban on waste burning in Nigeria, so as to safeguard the environment and the health of the people. That calls for proper and adequate waste management system. Considering that waste generation are bound to increase because of income and population growth; the finite nature of earth's resources; a growing concept towards mitigating the trend is circular economy [24,28], which is regenerative in nature and decouples economic growth from waste generation.

Studies have been carried out on emissions from burning of MSW in Nigeria. [5,20,21]. Ipeaiyeda and Falusi [20] analyzed for only SO2, NOx and NH_3, using air measurement near a dumpsite at Awotan and Lapite dumpsites in Ibadan metropolis, Nigeria. Fakinle et al [21] estimated anthropogenic emissions (including open-burning of MSW) for Lagos using secondary data and emission factors. They estimated levels of emission of PM_{10}, carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NOx) and volatile organic compound (VOC). Okedere et al [5] using secondary data on MSW generation and emission factors, estimated emissions of thirteen (13) cities in Nigeria. Both studies [5, 21] assumed that 100% of the generated MSW are subject to burning. However, many studies show that a greater level of uncollected wastes in Nigeria are dumped in environment such as on land and into water bodies [10,28]. Hence, it is assumed that there is a different "treatment" method for collected and uncollected wastes. Thus, we can safely reason that amount of MSW open-burned in Nigeria is lesser than 100%. Besides, not all waste open-burned are completely burnt. This is related to factors such as amount of combustible wastes, compaction, oxidation or efficiency factor [12,13,16]. Thus, the need to conduct Nigeria-wide (urban areas) estimations using IPCC guidelines.

3. Methodology

3.1. The study area

The study area, Nigeria, is located in West Africa. The country lies between Latitudes 4.32°N and 14°N and longitudes 3°E and 15°E. It has a total land area of 910,770km^2, while water bodies are 13,000km^2. There are thirty-six (36) states and a Federal Capital Territory (FCT, Abuja) in Nigeria. The National Population Commission (NPC) census of 2006 recorded the country's population as 140,431,790. The country's population great an average of 2.62% between 2006–2020 [37]. Nigeria has a population density of 226 persons per kilometers-squared in 2020 and is the seventh-most populous country in the world. In the year 2020, 52% and 48% of Nigerian population live in urban and rural areas, respectively [38]. In the same year, per capita GDP of the country is $2,097, which is higher than the average for sub-Saharan Africa ($1,483.7) [39]. Waste generation in Nigeria ranges between 0.44–0.66 kg/capita/day [1], but there is variation across different locations of the country (see Figure 2).

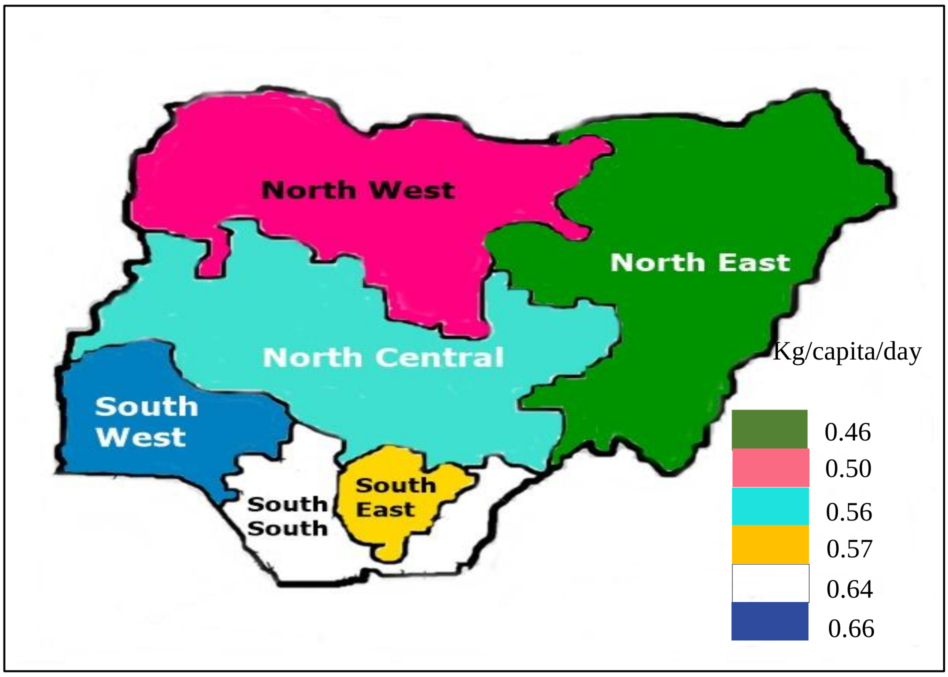

Figure 2. Waste generation across geographical zones of Nigeria.

Our disaggregated data shows the waste generation rate in southern part of the country is 0.62 kg/capita/day, while it is 0.58 kg/capita/day in the northern part (Supplementary file). South-West Nigeria has the highest per capita waste generation, while the least, is the North-East. The regional variation may be related to economic indicators. The southern regions of the country are more economically advanced than the northern regions. For example, 65.3% and 32.6% of the population in northern and southern regions, respectively, lives below the poverty level [40]. Nigeria has a tropical climate with varying wet (rainy) and dry season across the geographical regions. Humidity is usually high in the North and decreases during the harmattan period. Usually, open-burning of solid waste occurs at two levels–at generators and disposal sites (dumpsites or landfills) [1,8,12,16,41]. It is common for rainfall and wind to transport wastes across the environment. Similarly, particulates and other noxious emissions produced during open-burning spreads, together with its associated health risks. Globally, Nigeria is the 17th largest GHG emitter and second in Africa (after South Africa). Climate change will have impact Nigeria greatly. For example, lower precipitation will affect food supply since the country depends heavily on rain-fed agriculture [22]., This poses socioeconomic and political risks.

3.2. Estimation methods

The study adopted the IPCC guidelines [12,13,16]. The importance of IPCC guidelines in emissions model is clearly seen in similar works [5,21] done in Nigeria, which assumed that all MSW generated in Nigeria are open-burned. Though they applied emission factors, there was no specification of the amounts that were combustibles, the level of oxidation or burning efficiency, amount collected or subjected to the burning as not all generated MSW are burned. Thus, the result can become an over-estimation. IPCC guidelines [12,13,16] requires that the above parameters must be included for national estimation. Data were sourced from literature, and the estimation was conducted for the year 2020. The year 2020 estimation ofn the population data of Nigeria was conducted using the figure given Nigerian National Population Commission Census of 2006 (last census conducted in Nigeria). There is no available data on the amount of waste open-burned at dumpsites/ landfills in Nigeria. However, the level of open-burning of uncollected MSW were sourced from Adekola et al [4] and Adeniran et al10]. Therefore, the study focused on open-burning of uncollected MSW. The generally accepted MSW generation rate 0.44–0.66 kg/capita/day [1] was adopted, and encompasses the 0.53 kg/capita/day for sub-Saharan Africa [19] for the period between 2016–2030. In open-burning of MSW, the important GHG to account for are CO_2 (normally the most substantial), methane (CH_4) and nitrous oxide (N_2O). In this study, these were reported using the Global Warming Potential (GWP), which quantifies the effect over time (usually 100 years) of a polltant amount, compared to the same amount of CO_2 expressed in CO_2-equivalent (CO2-eq) [7,8,12,13,16]. The adopted default emission factors (for the other two GHG–CH_4 and N_2O) were expressed in kg CO_2-eq.

3.2.1. Amount of waste open-burned

The adapted IPCC Guidelines for GHG inventories [12,13,16], is expressed as:

$$MSW_B = PC \times MSW_P \times P_{frac} \times \delta \times \eta \times 365 \quad (1)$$

Where, MSW_B = amount of MSW open-burned (kg/year); PC = urban population (capita). PC = 104,885,855. The estimated total population of Nigeria in year 2020 is 201,703,566, projected with an annual growth of 2.62% [37] from 140,431,790 given by 2006 National Population Commission census. 52% of Nigerians lives in urban areas [38]. MSW_P = per capita MSW generation factor (kg/capita/day); and MSW_P = 0.44–0.66 kg/capita/day [1]. According to [13], P_{frac} is population whose waste is not collected by municipal waste managers but rather are burned at source and open-dumps. Only 44% of wastes generated in Nigeria (and sub-Saharan Africa) are collected by municipal managers, while, 56% are uncollected [19]. 20.8% and 10.7% of the uncollected MSW are burned at source and open-dumps, respectively [4,10]. Therefore, P_{frac}= 31.5% of the uncollected MSW (56%). δ = combustible amount of the total MSW. Combustible constituents of the MSW (δ) include food residue, paper, plastic bottles, textile and clothing, wood, vegetation (green, grass/ garden trimmings), cartons used for packaging, plastic and polyethylene bags [27]. The following studies reported combustible amount of the MSW as 89.2% [31]; 91% (Edo State) and 87% (Lagos) [42]; 81% [43]; 73.4% [1]; 72.1–81.1% [32], 70% [27]. Accordingly, we calculated the average composition of combustible wastes in Nigeria (δ) to be 80.6% (Supplementary file). It compares fairly with 62.6% reported by Kaza et al [19]. η = burning/ oxidation efficiency (fraction). η is defined as the portion of waste whose carbon content is oxidized and converted to carbon dioxide. η is closer to 1.0 for waste incinerators (close system). For burning of MSW, η is lower, and 0.58 is recommended by the Intergovernmental Panel on Climate Change [8,12,13,17].

3.2.2 Emissions produced by open-burning of wastes

Emissions were estimated using the IPCC Guidelines for GHG inventories and [12]. The study adopted default unit emission factor for each pollutant, which expresses the emission per amount of MSW burned as follows:

$$Em_i = MSW_B \times EF_i \tag{2}$$

Where, $Em_i =$ Emission of pollutant i; $EF_i =$ emission factor of pollutant i (g/kg of dry matter burned or kg-CO_2/ton MSW); and MSW_B = amount of MSW burned (kg/year). The EFs are given in Table 1 below:

Table 1. Emission factors for Burning of MSW

Species	Emission factor
Carbon dioxide (CO_2)	801.2 kg CO_2/ton MSW *
Methane (CH_4)	162.5 kg CO_2/ton MSW *
N_2O	44.7 kg CO_2/ton MSW *
NH_3	0.94 g/kg
Black carbon (BC)	5.5 g/kg
Organic carbon (OC)	5.27 g/kg
Sulphur dioxide (SO_2)	0.5 g/kg
Nitrogen oxides (NOx)	3 g/kg
Carbon monoxide (CO)	42 g/kg
Non-methane volatile organic compounds (NMVOC)	15 g/kg
Particulate matter 10 (PM_{10})	30 g/kg
Particulate matter 2.5 ($PM_{2.5}$)	9.8 g/kg

Limitations: In the estimation, limitations were acknowledged. Because of the way burning of MSW is carried out in Nigeria, there is no available reliable data [8,12,14,15]. Methods for collecting of data relevant to solid waste management are at infant stage in Nigeria and have extensive gaps [4,19,30]. The study is therefore limited to estimating emissions produced from only open-burning of uncollected MSW. The paper assumes the IPCC oxidation/ burning efficiency of 58% or

η=0.58 [12,13,16]. Open-burning of wastes is associated with daily MSW generation (kg/cap/day), and is likely to occur seven days a week, with burning events occurring less frequently during the rainy season and more regularly in the dry season [12]. The study assumed uniformity, that is, burning occurs throughout the year (365 days). The study assumes the rate of burning for the different MSW materials are homogenous. Emissions from burning of MSW depend in part on factors, such as local weather conditions (for example, ambient temperature, humidity), waste composition (organic and inorganic) and their moisture contents, etc. [1,12,44]. Since default emission factors were used, the local weather conditions were assumed negligible [8,13,16]. Only the climate-relevant CO_2 emissions from fossil-carbon materials were taken into account. The fraction of CO_2 considered to be from fossil sources are regarded as climate-relevant. Generally, three waste types consist of non-biogenic (fossil) carbon–plastics, textiles and a mixed group of rubber and leather [13,16]. In our study, fossil (non-biogenic) carbon is about 14.3% (plastics and textile/clothing and leather) of the combustible MSW (see Figure 3 and supplementary file). The waste generation was assumed for one-year period, January 1 to December, 30, 2020. Thus, our estimate did not include wastes generated before or after the date. Finally, in the estimations, the rate of waste recycling was assumed to be negligible [7].

4. Result and discussion

4.1. Waste generation and disposal method

With per capita waste generation ranging between 0.44 to 0.66 kg/capita/day [1], the total MSW waste generated by the entire urban population of Nigeria ranges between 16.8 to 25.2 million tons for the year 2020. The waste collected for disposal to dumpsites (or landfills) ranges between 7.4–11.1 million tons, at the 44% collection rate. Fifty-six percent (56%) of the entire wastes generated are not collected, meaning that about 9.4–14.1 million tons of MSW are carelessly disposed to the environment annually. 31.5% of the uncollected wastes (or 17.64% of the entire generated MSW) are open-burned annually. Therefore, between 2.97–4.5 million tons of wastes are subjected to open-burning every year in Nigeria, while between 6.5–9.7 million tons of uncollected MSW are carelessly disposed of in the environment–aquatic and land per annum. This means more wastes are disposed carelessly to Nigerian environments than those disposed to dumpsites/ landfills. This careless disposal method is linked with many ecological problems-flooding (because of blocked drainage), diseases outbreak, leaching of heavy metals and other toxic compounds into groundwater supplies and surface water, emissions of foul odor, fumes, and others [1,4,33]. The method therefore poses major challenges to Nigeria, considering that population and consumption are growing, and are leading to higher level of waste generation [25]. Per capita waste generation is greatly associated with economic activity expressed in GDP per capita [15]. Because of the 2016–2017 recession and COVID-19 pandemic, we can assume that per-capita waste generation may not have increased in the last five years. However, population-effect must have increased the total MSW generated in the country. It is expected that consumption (per-capita) will increase in the nearest future, as the economy grows.

Compared to other lower-middle income countries in other regions of the globe, MSW collection efficiency in Nigeria is very poor. For example, South Asia, which have similar waste generation like of that of Nigeria (0.74 kg/cap/day) have relatively better improved waste collection system. Major cities in India have higher MSW collection efficiency. For example, it ranges from 75% for New Delhi to 100% for Greater Mumbai; while Nigeria's major cities shows the following–Lagos (10%), Ibadan

(40%) [19]. These collection efficiency in major Nigeria cities are substantially lower than the average for lower-middle income countries (LMICs) (71%). Similar to Nigeria, the wastes are mainly disposed to the open or un-engineered dumpsites. But, the extensive development of sanitary landfills is growing in India. Waste management is labor-and capital intensive, and involves transportation, treatment facilities, disposal, construction and maintenance of sanitary landfills, with their leachate and emissions control [9,35]. MSW management constitutes about 20% of the local governments' budget for LMICS, while it is 20–50% for Nigeria [26,33,35,42]. In middle-and higher-income countries, it is 10% and 4%, respectively [19]. Between 70 and 85% of the total cost for solid waste management is spent in collection, and the rest on disposal [1,35]. Inadequate funding (for vehicles, personnel and transportation) constitute 67% of the reasons for the poor collection efficiency in Nigeria [2]. For example, out of 2000 tons of waste generated in Kano city, only 800 tons (40%) were evacuated by municipal authority [31]. Another major factor that causes the lower collection efficiency is the distance between neighbourhoods and disposal sites, which ranges between 10 to 40 kilometers [19]. Additionally, the waste collection is mostly carried out once a week or even more (especially weekends) [9]. Thus, greater number of the populace prefers to dump their wastes in rivers, drainages or vacant plot. Our calculated amount of combustible wastes (δ)-80.6% - is to the same as 80.5% reported by Kaza et al [19] for lower-middle income countries such as Nigeria. From figure 3 below, "food and green" accounts for the highest composition (61.8%) of MSW in Nigeria (Supplementary file), which is similar to that reported for Indonesia - 72% [8].

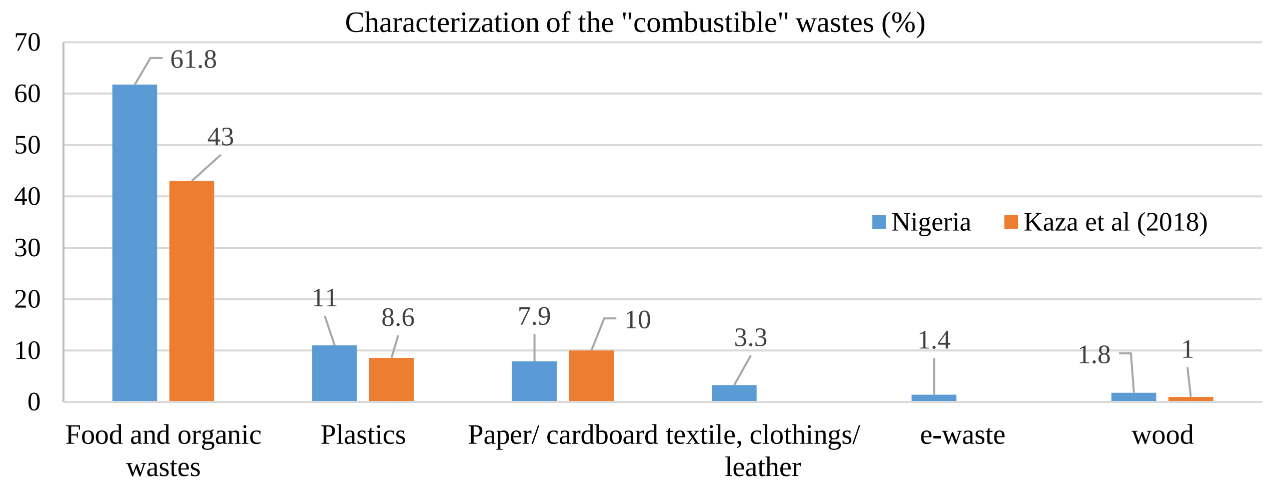

Figure 3. Characterization of the "combustible" wastes.

* Textiles and e-waste were not shown for [19], as their categories were not specified. It may have been combined with "Others" making it difficult to determine their percentages

Similarly, our calculated paper and textile composition, 7.9% and 3.3%, respectively compares well with Indonesia's 7.07% and 2.4%, respectively [8]. Our data suggests Nigeria's plastic composition is substantially higher than that of Indonesia (3.5%) [8]. "Wood" wastes in Nigeria were also slightly higher than those obtained in Kaza et al [19]. Changes in consumption pattern in Nigeria is occurring, as Nigerians shifts towards finished goods such as packaged food, electronics and others. Even so, organic wastes are higher in lower-income countries than higher income countries. This is because consumed goods in higher-income countries are more of paper and plastics than in lower-income countries. For example, figure 3 shows 74.8% of the wastes in Nigeria are putrescible (food and green wastes, paper/ cardboard, textiles and wood), and this is consistent with the range of 50–70% obtained in [34] for the entire country. Our result is also consistent with [8] for Indonesia. Due to the high organic and moisture content of wastes generated in lower-middle income countries such as Nigeria, the burning method is mostly an incomplete combustion.

4.2. Open-burning of the wastes

Even though between 2.9 to 4.5 million tons/ year of the wastes are subjected to open-burning, it is not all of the wastes that eventually burns. Between 2,480,481,846 to 3,720,722,769kg (2.4–3.7 million tons) of the MSW generated actually burns every year, in Nigeria. The difference between the amount subjected to burning and the amount that actually burns is explained by oxidation/ burning efficiency or incomplete combustion (η=0.58). Often, especially when a significant amount of wastes in open dumps is burned, a great amount is left un-burnt. The fraction that is compacted usually burns [12]. But waste compaction does not take place at source and open-dumps [33]. Therefore, we can safely argue that a substantial amount of urban wastes in Nigeria dumpsites are not completely burned or oxidized, because of the higher moisture content. The amount of MSW burn in Nigeria represents a 14.7% of the total MSW generated per annum. Put differently, almost $^1/_7$th of MSW generated in Nigeria is open-burned. Estimate shows 41% (620 million tons) of the wastes generated globally are burned openly, mostly occurring in developing countries [14]. Our estimate differs from Fakinle et al [5] and Okedere et al [21], which assumes that 100% of MSW generated in the respective urban areas they studied are burned. Okedere et al [21] estimated that 2,2120,248 tons per year (2.2 million tons) produced in thirteen (13) Nigerian cities (with population of 13,125,541) are open-burned. The level of wastes burned obtained in Fakinle et al [21] is higher than our estimate. Our study focused only on uncollected MSW. Uncollected MSW are usually burned and or disposed carelessly in the environment. Additionally, it is not every waste type that burns. Thus, the level of MSW actually burns in Nigeria must be lesser than 100% adopted by Okeder et al [5] and Fakinle et al [21].

Our estimated MSW burned represents between 0.3%–0.6% of the total wastes burned globally. With the high growth in population, urbanization and economic development, occurring in Nigeria and developing countries, waste generation is increasing at a rapid rate (estimated to grow by 40% by 2050) for incremental incomes than in higher-income countries [19]. This shows the importance and urgency of addressing proper waste management, in connection with climate change and public health programs. There is more attention on waste collection than waste treatment methods in Nigeria [5,10,20,19]. But both are equally important. Improved collection without corresponding proper disposal method, will lead to a significant point-source pollution (air, water and soil) and adverse public health issues.

Depending on the way they are disposed, different kinds of MSW have different environmental and health impacts. Also, sustainable management methods for different waste varies. For example, recycling of organic waste is not possible and plastic cannot be composted [15]. Plastic wastes accounts for 11% of the MSW generated in Nigeria (shown in Figure 3). The burning of plastic wastes such as PVCs releases toxic gases like dioxins, furans, mercury, carbon black and aromatics (example, pyrene and chrysene), and polychlorinated biphenyls (PCBs) into the environment. Additionally, burning of PVCs releases toxic halogens and contribute to climate change. Dioxins settles on crops and in aquatic environment, and via that way, enter the food chain and human body. 90% of human ingestion of dioxin and furan is from food. Dioxins, a toxic persistent organic compound and its deadly constituent 2,3,7,8 tetrachlorodibenzo-p-dioxin (TCDD) causes cancer and neurological impairment, and also affects reproductive and respiratory systems. Accordingly, burning of plastic wastes increases the risk of cardiovascular disease, exacerbates respiratory illnesses (for example, asthma and emphysema), destroys the nervous systems and others. Incomplete oxidation of polyethylene (PE), polypropylene and polystyrene emit high level of carbon monoxide. Further, the harmful emissions may consist of bromide and colorants containing heavy metals like chromium, cadmium, lead, copper, cobalt, selenium, etc. Smoke and ash filtrate from plastic combustion has a high health and environmental effects as they contain VOCs, particulate matter, PAHs and polychlorinated dibenzofurans (PCDFs). Benzene is a known carcinogen [17,18]. High level of lead (Pb) and manganese (Mn) beyond their respective normal range, was reported in those exposed to open-burning of burning e-wastes. It indicates their high risk of developing neuro-generative disorders [45]. Accordingly, those living near or around dumpsites/ landfills in Nigeria are at high-risk of developing ill-health conditions [17,18,33].

4.3. Emissions from the open-burning

4.3.1. Greenhouse gas (GHG) emissions

Following the IPPC national guidelines for GHG inventories, only combustion of carbon of fossil-source were reported for CO_2 emissions in our study. 14.3% of the MSW burned is fossil carbon. Figure 4 shows calculated GHG emissions from burning of the uncollected waste.

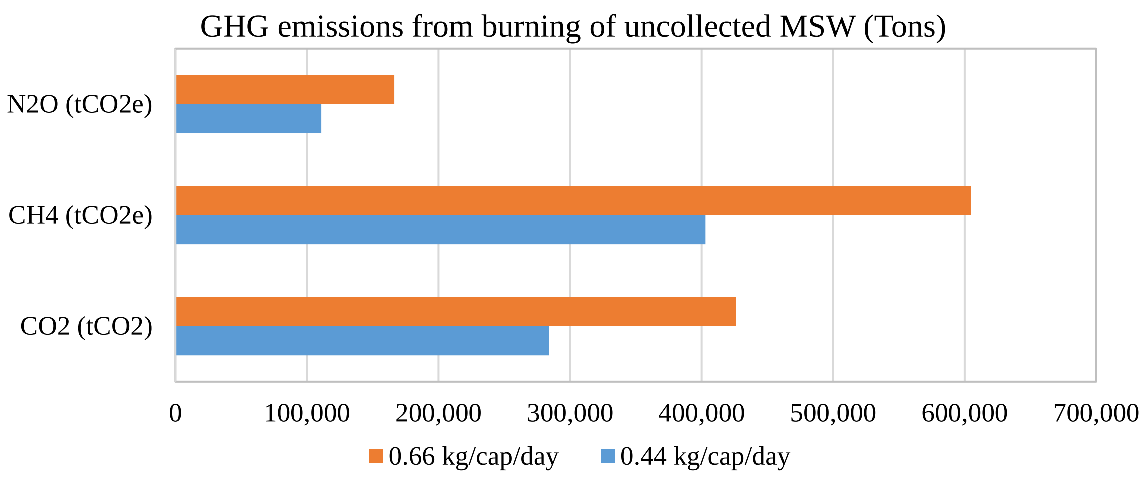

Figure 4. GHG emissions from burning of uncollected MSW in 2020.

The contributions to GHG emissions established in our study is as follows: between 284.2–426.3 kilotons of CO_2; 403–604.6 kiloton of CO_2-eq/year for methane (CH_4) and between 110.9–166.3 kiloton of CO_2-eq/year for nitrous oxide (N_2O). Substantial quantity of carbon in the waste is not oxidized, therefore methane is more substantial in open-burning [3,10]. The estimation show overall, CH_4 is the largest emissions per annum, followed by CO_2 emissions, and then N_2O. The total emissions for the three GHGs from burning of the MSW ranges between 798 to 1,197 kilotons of CO_2-eq (Kt

CO_2-eq) per year. Put differently, our obtained GHG emissions (in Kt CO_2-eq) is about 0.002–0.003% of the total GHG emissions (311,450 kt of CO_2-eq) reported for Nigeria in 2018 [46]. The IPCC shows that usage of default EF for N_2O emissions from open-burning of MSW have a fairly high degree of improbability [13]. Thus, the need for Nigeria to develop country-specific EF, including for other emissions.

Dividing the emissions by the total urban population of Nigeria (for year 2020), per capita CO_2 from burning of the uncollected MSW ranges from 0.002 to 0.004 tCO_2, which is far below the 0.67 tCO_2 (per capita annual CO_2 emission profile), reported by the World Bank [46] for Nigeria. The emissions from burning of the MSW may be higher than our estimate. For example, though 44% collection rate is assumed for Nigeria (and sub-Sahara Africa) [19], most of the collected wastes are disposed to open-dumpsites/ landfills which are usually burn. Further, the uncertainties of data obtainable in Nigeria supports the assumption that actual collection efficiency may be lower than the 44%. A good example is Lagos, the most cosmopolitan city in Nigeria, which has collection efficiency of only 10% [19].

Climate change will impact developing countries, which generally lack adaptation and mitigation capacities. Nigeria accounts for 0.97% of the total global GHG emissions. In Nigeria, waste management accounts for 9% of the emissions, while energy and agriculture sector were 60 and 25%, respectively. In its Nationally Determined Contribution (NDC), Nigeria pledged to reduce emissions by 20% below business-as-usual (BAU) scenario by 2030 [46]. Addressing the issue of proper waste management will assist in reducing emissions. However, burning of MSW cannot be eradicated without improvement in waste collection and disposal methods. The current practice of open-dumping has a very high emissions compared to that of sanitary landfill. For example, in [7], it was 1000 $kgCO_2$-eq and 300 $kgCO_2$-eq for open-dumping and sanitary landfill, respectively. Adoption of sanitary landfill (with emissions control) will lead to meaningful reduction and other benefits such as methane recovery and utilization.

In another African country, open-burning of MSW produces 20% (568 Gg CO_2-eq) of the total emissions produced from waste management in Mozambique which are mostly open-dumped. Conversely, transition to semi-aerobic landfill method will reduce their emissions by 40% [7]. The current situation of open-burning is related to poor collection rate and improper disposal method currently obtained in the country. Thus, it is time to re-assess the entire waste management system in Nigeria. For example, in [7], emissions from open-burning accounted for only 22%, while it is 78% for decomposition in dumpsites in Mozambique.

4.3.2. Other emissions

The other emissions which are associated with open-burning of MSW were also estimated, and presented in Figure 5.

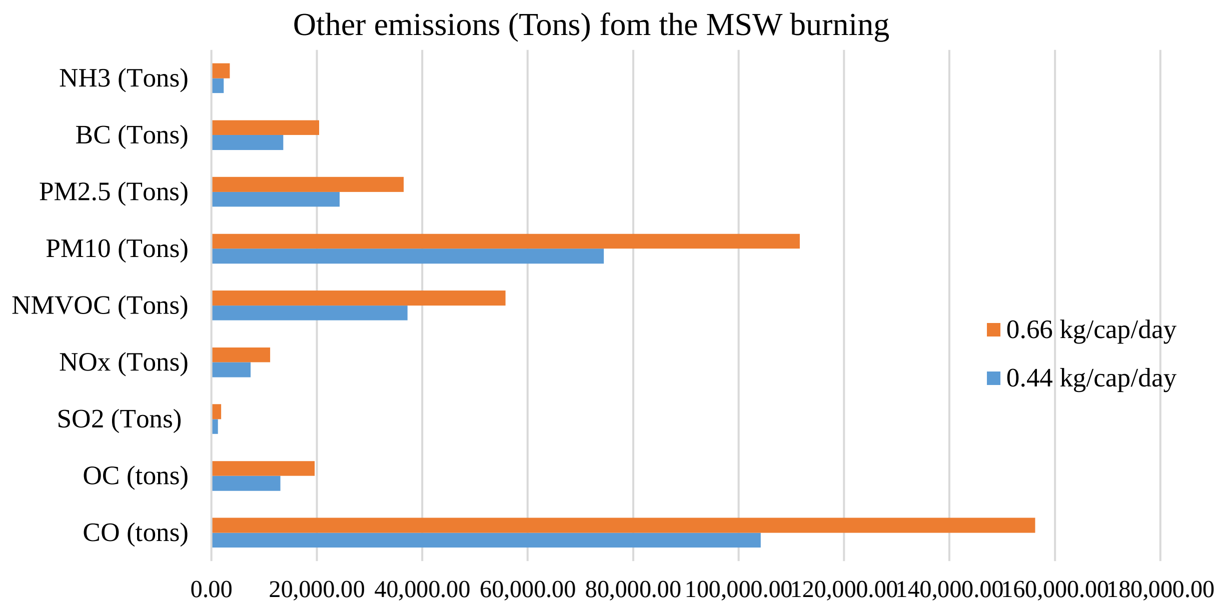

Figure 5. Other emissions from Open-burning of uncollected MSW (tons) in Nigeria.

Carbon monoxide (CO) accounted for the largest, ranging between 104.1–156.2 kilotons (Kt), secondly PM_{10} (74.4–111.6 kt); NMVOC ranging from 37.2 to 55.8 Kt; $PM_{2.5}$ (24.3–36.4 Kt), BC (13.6–20.5 Kt), OC (13.0–19.6 Kt);, followed by NOx ranging from 7.4 to 11.1 Kt, then NH_3 (2.3–3.5 Kt) and the least SO_2, which is between 1.2–1.8 Kt. The distribution shows the following in order of magnitude of emissions: CO > PM_{10} > NMVOC > $PM_{2.5}$ > BC > OC > NOx > NH_3 > SO_2. The magnitude is a function of emission factors. Our result quite differed from the trend observed in Ipeaiyeda and Falusi [20] which analyzed only for SO_2, NOx and NH_3. Ipeaiyeda and Falusi [20] recorded the magnitude of emissions as follows NH_3 > NOx > SO_2. However, ours is consistent with Fakinle et al [21] which showed the distribution CO > PM_{10} > NOx > SO_2. It is also consistent with Okedere et al [5] which shows CO > NMVOC > PM > NOx > SO_2. The difference with Ipeaiyeda and Falusi (2018) may be explained by methodology. Fakinle et al [21], Okedere et al [5] and ours used emission factors (EF) in the calculation while Ipeaiyeda and Falusi [20] used air measurement.

While our study reported 7.4–11.1 Kt / annum for NOx, 11.9 Kt was reported in [21]. Further, [21] reported 1.98 Kt/ annum for SO2; 166.6 Kt/ annum for CO and 31.7 Kt/ annum for PM_{10}. Accordingly, estimated level of emissions from solid waste burning reported by Fakinle et al [21] for Lagos alone was seen to be higher than that for the entire Nigeria reported in our work. While our study made use of urban population of Nigeria (104,885,855); Fakinle et al [21] made use of only Lagos population. The difference is explained by methodology adopted by both works. Fakinle et al [21] made use of only activity rate multiplied by emission factor of respective pollutants, where activity rate is 0.5 kg/cap/day. However, our study factored in oxidization/ burning efficiency (η= 0.58), which greatly reduced the amount of MSW that actually burned and their emissions. Further, our study recognized that not every waste generated by Nigerian urban population is subjected to burning. We established that only 17.4% of the entire generated MSW are subjected to burning. These explains the higher results obtained by Fakinle et al [21]. Our estimation was conducted according to IPCC [13,16] guidelines for national inventories. Okedere et al [5] adopted the same methodology seen in [21]. The results obtained in Okedere et al [5] for only 13 urban areas of Nigeria was higher than ours conducted for the entire urban population of Nigeria. Both studies assumed that 100% of the wastes generated in their study locations are burned. Conversely that is not the reality. Granted, waste management (including collection) is very poor in Nigeria. But the amount of wastes subjected to burning is only 31.5% of the uncollected wastes [4,7,19]. It is therefore over-generalization to assume that all MSW generated in Nigeria are burned. Still, both studies [5,21] shows that MSW burning is a serious contributor to emissions in urban areas of Nigeria, and thus poses serious challenges.

These pollutants constitute environment and public health issues. The prevalence of CO is related to the incomplete combustion. These emissions have both health implications, while some have climatic effects. Emission from waste disposal (burning and decomposition) is a substantial source of non-methane volatile organic compounds (NMVOCs). NMVOCs are a wide group of organic chemicals, that are in some circumstances, clearly harmful to health. Additionally, they usually function as precursors to the formation of ozone and particulate matter. The few harmful ones (for example, benzene, 1,3-butadiene) are lung irritants or cancer-causing agents. They are produced both by fossil and biogenic carbon (including plants and soil) [47]. According to World Health Organization, globally, 3.7 million per premature deaths per annum is related to outdoor air pollution. Humans are at risk of the effects of PM because their size allows them to penetrate internal spaces. Also, their half-life in the atmosphere is longer because of their tiny sizes, allowing its spatial- temporal spread. The constituents of PM_{10} and $PM_{2.5}$ can be organic (PAH, dioxins, benzene, 1-3 butadiene) in the case of plastics or inorganic (metals, carbon, etc.). They can be soot, smoke, fly ash, heavy dust, etc. Long-term chronic effects of exposures to $PM_{2.5}$ include nasopharyngitis, cardiovascular diseases, respiratory and impairment of the immune system and infant mortality. They destroy forests and crops, causes water acidity and modifies nutrient balance of aquatic ecosystems. The health symptoms of CO poisoning include headache, faintness, weakness, vomiting and unconsciousness. CO has greater affinity for hemoglobin than oxygen. CO poisoning leads to hypoxia and ischemia. Further, CO alters the climate-relevant GHG, leading to increased soil and marine temperatures, and intense weather conditions/ storms. In a single year (2005), premature deaths from exposure to $PM_{2.5}$ were- respiratory diseases (773,000), lung cancers (180,000) and cardiovascular diseases (2 million). Reduction in long-term exposure to PM2.5 has been linked with a rise in average life expectancy [48]. Estimate shows ambient $PM_{2.5}$ pollutions is responsible for about 23.8 premature deaths for every 100,000 Nigerians. This is much higher than the average rate for the West African region [11].

BC, a solid matter of carbon, is the most potent light absorbing (radiative forcing) constituent of PM, and also reduces the radiation flux of the earth's surface. It absorbs one million more radiations than CO_2. Thus, warming the atmosphere. It is the second largest contributor to climate change after CO_2. However, its residence time is only few days to weeks, unlike CO_2 that can remain in the atmosphere for up to a thousand years. Similar to all atmospheric particles, BC influences reflectivity, stability and period of clouds and changes precipitation. BC from open-burning produces a sharp surface cooling resulting in atmospheric movement responses and climate changes on a regional level. N_2O infiltrates deep into the lungs causing respiratory illnesses, coughing, wheezing, dyspnea, bronchospasm and at high concentrations, pulmonary edema [48]. NMVOCs (or VOCs) reacts with NO in the presence of sunlight to form tropospheric ozone. Higher level of O_3 in the lower atmosphere have harmful effects on human health, plants and outdoor materials [47].

From the above, there is a need to strongly enforce regulation against burning of MSW in Nigerian cities, for public health safety and quality environment. This cannot happen without availability of sustainable alternatives.

4.4. Policy implications

Various strategies for GHG abatement in the waste management sector exists. They include energy recovery and material circularity. For energy recovery, it includes landfill extension and energy recovery method for waste disposal (landfill gas recovery) for combined heat and power generation; food waste treatment which includes thermal treatment, composting and anaerobic digestion [24]. These will support Nigerian Biofuel Policy 2007 through 2nd generation biofuels production in Nigeria, which does not add to the issue of 1st generation biofuels (food versus energy conflict). However, these depend on putting proper waste management system in place. Collection, transportation and proper disposal (in sanitary landfill) of MSW entails enormous financial requirement, which most municipalities in Nigeria find difficult to shoulder adequately [1,4,10,11,27,30,43]. Hence, it is important that states and municipalities in Nigeria considers employing the emissions trading scheme, for example, the Clean Development Mechanism (CDM). It supports lower-middle income countries accommodating CDM ventures to realize sustainable development, and at the same time offers opportunities for high-income countries to accomplish their emission reduction targets. It helps local and state governments to secure more investments and other socioeconomic and ecological advantages that otherwise would not be pursued for lack of financial and technical capabilities [7]. Another model is private-public partnership, which should encompass waste management and value-chains of re-manufacturing and energy resources. One of the principal limitations which deters private sector participation in social services (waste management) in Nigeria is the unwillingness of the populace and their inability to pay [26]. Therefore, the need to transform wastes into a valuable resource which can pay for its management. The model includes circular economy, and waste-to-energy and-material resources [49]. It will not only improve economic development–improved energy supply, job creations, revenue for governments, technology transfer-, but will ensure quality environment (reduction in waste going to dumpsites/ landfills and open-burning with their attendant emissions) [5,28,49].

One proposal is to convert dumpsites/ landfills to a bio-reactor. It will offer waste stabilization, energy production, in addition to beneficial end-products- fertilizers and soil conditioners [8]. For example, Nigeria's estimated yearly electricity generation potential from MSW is around 26,744 GWh/year [18]. At 156 kWh, this is 8.5 times the current consumption of electricity from the national grid. About 89% of the states in Nigeria have enough waste generation capacity to satisfy the requirement of 50 MW stipulated by Nigeria regulatory requirement [30]. There are huge opportunities for utilization of biomass for energy production (bioenergy) in Nigeria. It may be bio-power and/ or biofuels. For example, with the national value of 0.44 kg/capita/day, 206 million Nigerians will generate about 90.6 million kg of wastes each day. Further, with a higher organic composition, the country produced about 62 million kg of organic wastes per day in 2020 [49]. Anaerobic digestion can yield about 90.6 m^3 of methane for each ton of raw food waste [50]. Material recovery is also important to improving waste management (reduction in wastes entering landfills and open-burned) [1,28]. Efficient and sanitary mechanism should be put in place to support developed and efficient recovery of valuable end-of-life materials, and this entails circular economy.

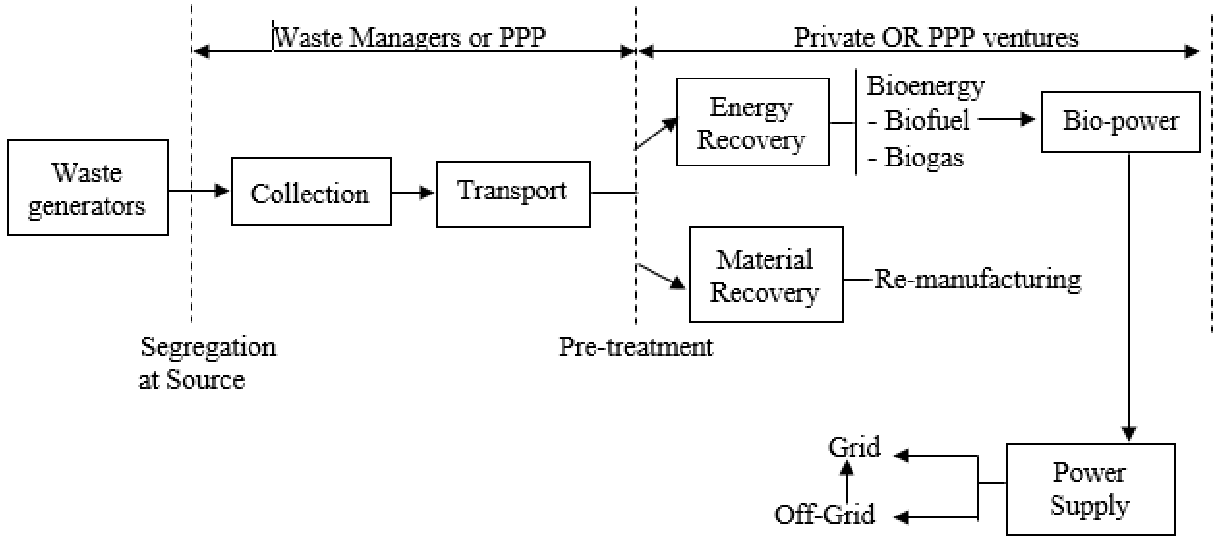

Figure 6. Waste-to-energy and material support linkages.

Waste managers (either municipal or public-private partnership) should be responsible for collection and transportation to pre-treatment sites, and from thereon, private or PPP ventures should be responsible. The PPP ventures may fund the activities of waste transport. Thereby, the waste managers are saved the financial implication of landfilling, or as the case in Nigeria, dumping. The model will offer immense financial benefits, considering that waste management agency in Nigeria are heavily under-funded. The adoption will transform liability (cost) into a revenue, as biofuel or bioenergy companies' shoulder or partially subsidized the financial implications of municipal waste management (collection, transportation, etc.). The importance of private enterprises cannot be over-emphasized. They have the technical proficiency and are not limited by bureaucratic barriers, they are innovative and market-centered, and have the capacity to attract local and foreign investments. The issue of proper waste management system–separation at source, efficient collection and transportation and recycling/ reprocessing–must be addressed adequately, if it will be turned into scalable energy production or material recovery strategies.

5. Conclusion

Economic growth (implied in purchasing power) and population increase has led to huge increase in the amount of MSW generated in Nigerian cities. MSW management is a very serious problem in Nigeria where institutional and policy support have been lacking for years. Accordingly, many Nigerians dispose their wastes carelessly, and this include open-burning. Open-dumping and open-burning of solid wastes is a major disposal method adopted across Nigeria. The method has negative implication on the environment and public health. We estimated the level of emissions–greenhouse gases and non-GHG produced by the burning of wastes by urban population of Nigeria. Factors critical to the estimation were waste generation rate (kg/cap/day), MSW collection efficiency, combustible portion of the MSW and oxidation/ burning efficiency. At the accepted waste collection efficiency of 44% for Nigeria, we estimate that 14.1 million tons of MSW are carelessly disposed to the environment annually. Our estimation shows 14.7% of the total generated MSW in Nigeria is open-burned. However, not all the amount subjected to burning actually burns out. This is related to burning efficiency, which in our study adopted $\eta = 0.58$, after IPCC 2006 guidelines for areas such as Nigeria, with high organic wastes and low level of waste compaction. Our estimated level of MSW burned in Nigeria represents between 0.66–1.1% of the total MSW open-burn globally. The total emissions for the three GHGs–carbon dioxide, methane and nitrous oxides were between 798 to 1,197 kiloton of CO_2-eq per year. Further other emissions such as black carbon, organic carbon, NMVOC, PM_{10} and $PM_{2.5}$ which have adverse health effects are emitted by the method. Thus, the need to phase out waste open dumping and burning, with upgraded waste disposal method, to foster beneficial environmental impacts, support in achieving the country's Nationally Determined Contribution (NDC) and protect the health of the people. Extensive and updated country-specific data should be generated across all the aspect of waste management in Nigeria. This will enable accuracy of estimation to a higher extent of the environmental implications of the value-chain.

6. Further research

Acknowledging the limitations of this study (a simple estimate), there is need for further research to assess the accurate estimate of emissions produced by open-burning of MSW (both collected and uncollected) in Nigeria. Taking into consideration Nigeria's waste characteristics, technical, weather and other factors; the research should concentrate on determining burning/ oxidation efficiency and default emissions for the respective pollutants associated with open-burning; specific to Nigeria. Also, other factors associated with the practice–seasonality, settlement patterns should be inculcated. Further, disaggregated waste method disposal across the states or region of the country should be studied in detail. These are necessary since waste management has been identified as one area that contributes to greenhouse gas emissions, and invariably climate change.

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Conflict of interest

All the authors declare no conflicts of interest in this paper.

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