















source and open-dumps, respectively [4,10]. Therefore,  $P_{frac}$  = 31.5% of the uncollected MSW (56%).  $\delta$  = combustible amount of the total MSW. Combustible constituents of the MSW ( $\delta$ ) 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 ( $\delta$ ) to be 80.6% (Supplementary file). It compares fairly with 62.6% reported by Kaza et al [19].  $\eta$  = burning/ oxidation efficiency (fraction).  $\eta$  is defined as the portion of waste whose carbon content is oxidized and converted to carbon dioxide.  $\eta$  is closer to 1.0 for waste incinerators (close system). For burning of MSW,  $\eta$  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:

$$Em_i = MSW_B \times EF_i \quad (2)$$

Where,  $Em_i$  = Emission of pollutant  $i$ ;  $EF_i$  = emission factor of pollutant  $i$  (g/kg of dry matter burned or kg-CO<sub>2</sub>/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 <sub>2</sub> )	801.2 kg CO <sub>2</sub> /ton MSW *
Methane (CH <sub>4</sub> )	162.5 kg CO <sub>2</sub> /ton MSW *
N <sub>2</sub> O	44.7 kg CO <sub>2</sub> /ton MSW *
NH <sub>3</sub>	0.94 g/kg
Black carbon (BC)	5.5 g/kg
Organic carbon (OC)	5.27 g/kg
Sulphur dioxide (SO <sub>2</sub> )	0.5 g/kg
Nitrogen oxides (NO <sub>x</sub> )	3 g/kg
Carbon monoxide (CO)	42 g/kg
Non-methane volatile organic compounds (NMVOC)	15 g/kg
Particulate matter 10 (PM <sub>10</sub> )	30 g/kg
Particulate matter 2.5 (PM <sub>2.5</sub> )	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



$\eta=0.58$  [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<sub>2</sub> emissions from fossil-carbon materials were taken into account. The fraction of CO<sub>2</sub> 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].

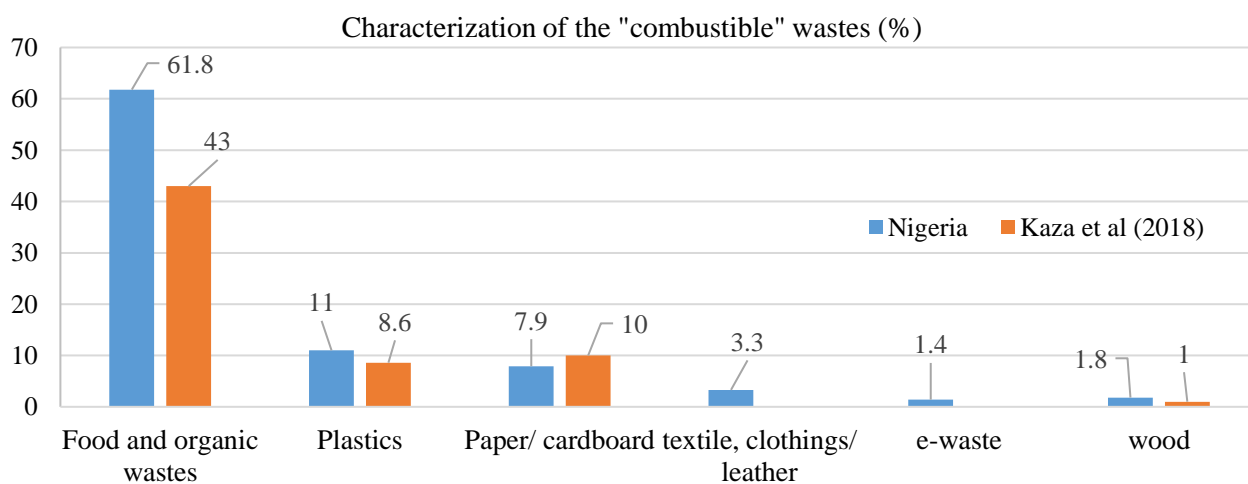
## 4. Result and discussion

### 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 ( $\delta$ )-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 ( $\eta=0.58$ ). 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  $\frac{1}{7}$ 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.

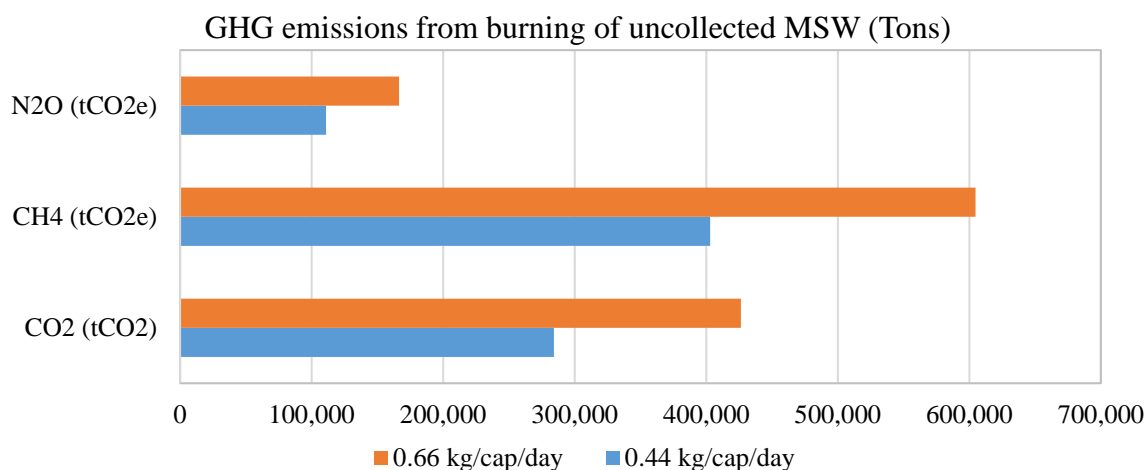
Depending on the way they are disposed, different kinds of MSW have different environmental and health impacts. Also, sustainable management methods for different waste varies. For example, recycling of organic waste is not possible and plastic cannot be composted [15]. Plastic wastes accounts for 11% 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 IPCC national guidelines for GHG inventories, only combustion of carbon of fossil-source were reported for CO<sub>2</sub> 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<sub>2</sub>; 403–604.6 kiloton of CO<sub>2</sub>-eq/year for methane (CH<sub>4</sub>) and between 110.9–166.3 kiloton of CO<sub>2</sub>-eq/year for nitrous oxide (N<sub>2</sub>O). 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<sub>4</sub> is the largest emissions per annum, followed by CO<sub>2</sub> emissions, and then N<sub>2</sub>O. The total emissions for the three GHGs from burning of the MSW ranges between 798 to 1,197 kilotons of CO<sub>2</sub>-eq (Kt

CO<sub>2</sub>-eq) per year. Put differently, our obtained GHG emissions (in Kt CO<sub>2</sub>-eq) is about 0.002–0.003% of the total GHG emissions (311,450 kt of CO<sub>2</sub>-eq) reported for Nigeria in 2018 [46]. The IPCC shows that usage of default EF for N<sub>2</sub>O 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.

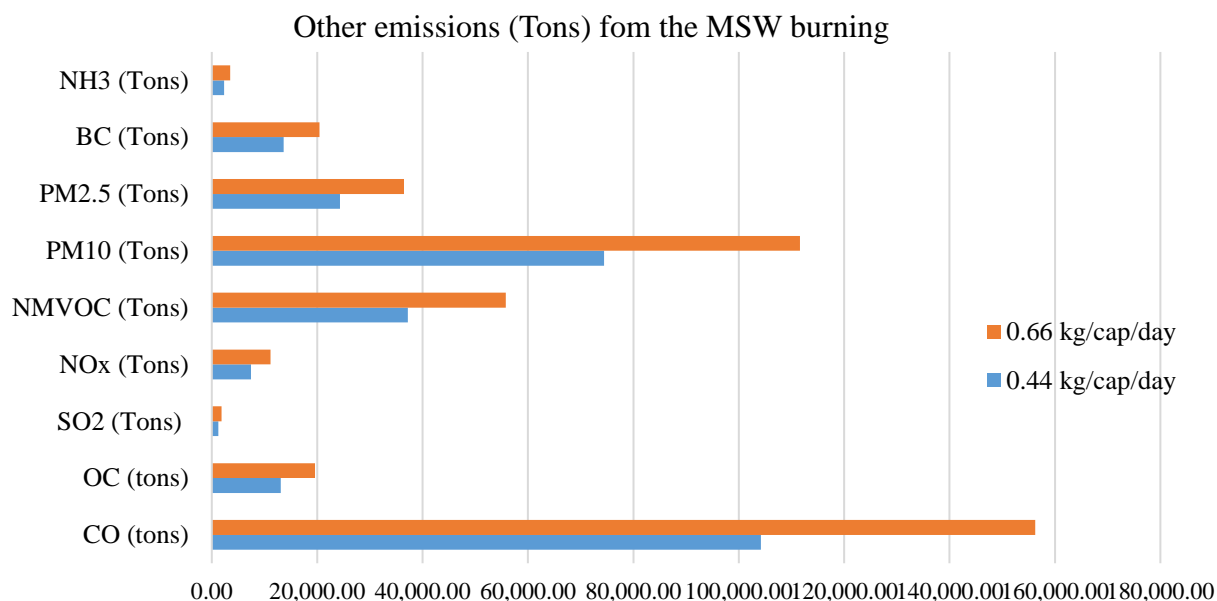
Dividing the emissions by the total urban population of Nigeria (for year 2020), per capita CO<sub>2</sub> from burning of the uncollected MSW ranges from 0.002 to 0.004 tCO<sub>2</sub>, which is far below the 0.67 tCO<sub>2</sub> (per capita annual CO<sub>2</sub> emission profile), reported by the World 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<sub>2</sub>-eq and 300 kgCO<sub>2</sub>-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<sub>2</sub>-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<sub>10</sub> (74.4–111.6 kt); NMVOC ranging from 37.2 to 55.8 Kt; PM<sub>2.5</sub> (24.3–36.4 Kt), BC (13.6–20.5 Kt), OC (13.0–19.6 Kt);, followed by NO<sub>x</sub> ranging from 7.4 to 11.1 Kt, then NH<sub>3</sub> (2.3–3.5 Kt) and the least SO<sub>2</sub>, which is between 1.2–1.8 Kt. The distribution shows the following in order of magnitude of emissions: CO > PM<sub>10</sub> > NMVOC > PM<sub>2.5</sub> > BC > OC > NO<sub>x</sub> > NH<sub>3</sub> > SO<sub>2</sub>. 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<sub>2</sub>, NO<sub>x</sub> and NH<sub>3</sub>. Ipeaiyeda and Falusi [20] recorded the magnitude of emissions as follows NH<sub>3</sub> > NO<sub>x</sub> > SO<sub>2</sub>. However, ours is consistent with Fakinle et al [21] which showed the distribution CO > PM<sub>10</sub> > NO<sub>x</sub> > SO<sub>2</sub>. It is also consistent with Okedere et al [5] which shows CO > NMVOC > PM > NO<sub>x</sub> > SO<sub>2</sub>. 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 NO<sub>x</sub>, 11.9 Kt was reported in [21]. Further, [21] reported 1.98 Kt/ annum for SO<sub>2</sub>; 166.6 Kt/ annum for CO and 31.7 Kt/ annum for PM<sub>10</sub>. 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 ( $\eta=0.58$ ), 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<sub>10</sub> and PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> were- respiratory diseases (773,000), lung cancers (180,000) and cardiovascular diseases (2 million). Reduction in long-term exposure to PM<sub>2.5</sub> has been linked with a rise in average life expectancy [48]. Estimate shows ambient PM<sub>2.5</sub> 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<sub>2</sub>. Thus, warming the atmosphere. It is the second largest contributor to climate change after CO<sub>2</sub>. However, its residence time is only few days to weeks, unlike CO<sub>2</sub> 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<sub>2</sub>O 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<sub>3</sub> in the lower atmosphere have harmful effects on human health, plants and outdoor materials [47].

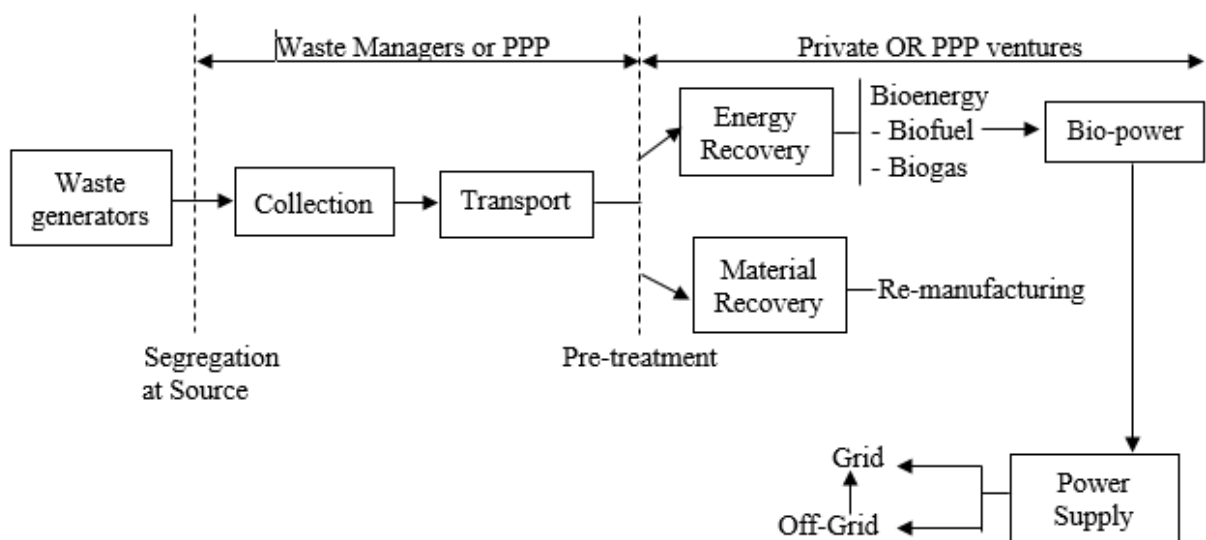
From the above, there is a need to strongly enforce regulation against burning of MSW in Nigerian cities, for public health safety and quality environment. This cannot happen without availability of sustainable alternatives.

#### 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 2<sup>nd</sup> generation biofuels production in Nigeria, which does not add to the issue of 1<sup>st</sup> 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<sup>3</sup> 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<sub>2</sub>-eq per year. Further other emissions such as black carbon, organic carbon, NMVOC, PM<sub>10</sub> and PM<sub>2.5</sub> 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.

## References

1. Ogwueleka TC (2009) Municipal solid waste characteristics and management in Nigeria. *J Environ Health Sci Eng* 6: 173–180.
2. Ayantoyinbo BB, Adepoju OO (2018) Analysis of solid waste management logistics and its attendant challenges in Lagos metropolis. *Logistics* 2: 11. <https://doi.org/10.3390/logistics2020011>
3. Aluko OO, Obafemi TH, Obiajunwa PO, et al (2021) Solid waste management and health hazards associated with residence around open dumpsites in heterogeneous urban settlements in Southwest Nigeria. *Int J Environ Health Res* 2021: 1–16. <https://doi.org/10.1080/09603123.2021.1879738>

4. Adekola PO, Iyalomhe FO, Paczoski A, et al, (2021) Public perception and awareness of waste management from Benin City. *Sci Rep Nat* 11: 1–14. <https://doi.org/10.1038/s41598-020-79688-y>
5. Okedere OB, Olalekan AP, Fakinle BS, et al, (2019) Urban air pollution from the open burning of municipal solid waste. *Environ Qual Manage* 28: 67–74. <https://doi.org/10.1002/tqem.21633>
6. Das B, Bhawe PV, Byanju RM, et al. (2018) Estimating emissions from open burning of municipal solid waste in municipalities of Nepal. *Waste Manage* 79: 481–490. DOI: 10.1016/j.wasman.2018.08.013
7. dos Muchangos LS, Tokai A (2020) Greenhouse gas emission analysis of upgrading from an open dump to a semi-aerobic landfill in Mozambique—the case of Hulene dumpsite. *Sci Afr* 10: e00638. <https://doi.org/10.1016/j.sciaf.2020.e00638>
8. Kristanto GA, Koven W (2019) Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia. *City Environ Interact* 4: 100027. <https://doi.org/10.1016/j.cacint.2020.100027>
9. Olukanni DO, Mnenga MU (2015) Municipal solid waste generation and characterization: A case study of Ota, Nigeria. *Int J Environ Sci Toxicol* 391: 1–8.
10. Adeniran AA, Adewole AA, Olofa SA (2014) Impact of solid waste management on Ado Ekiti property values. *Civil and Environ Res* 6: 29–35.
11. Okedere OB, Elehinafe FB, Oyelami S, et al, (2021) Drivers of anthropogenic air emissions in Nigeria-A review. *Heliyon* 7: e06398. <https://doi.org/10.1016/j.heliyon.2021.e06398>
12. Shrestha R.M, Oanh NTH, Shrestha RP, et al (2013) Atmospheric Brown Clouds (ABC) Emission Inventory Manual, United Nations Environment Programme, Nairobi, Kenya.
13. IPCC, Intergovernmental Panel on Climate Change (2006a). 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Incineration and open burning of waste. [https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5\\_Volume5/V5\\_5\\_Ch5\\_IOB.pdf](https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_5_Ch5_IOB.pdf)
14. Cogut A (2016). Open burning of waste: A global health disaster. R20 Regions of Climate Action, 1–63.
15. Chen DM, Bodirsky BL, Krueger T, et al, (2020) The world’s growing municipal solid waste: trends and impacts. *Environ Res Lett* 15: 074021. <https://doi.org/10.1088/1748-9326/ab8659>
16. IPCC, 2006b, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories: Emissions from waste incineration, 455–468. [https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5\\_3\\_Waste\\_Incineration.pdf](https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf)
17. Verma R, Vinoda KS, Papireddy M, et al, (2016) Toxic pollutants from plastic waste- A review. *Procedia Environ Sci* 35: 701–708.
18. Valavanidid A, Iliopoulos N, Gotsis G, et al, (2008) Persistent free radicals, heavy metals and PAHs generated in particulate soot emissions and residual ash from controlled combustion of common type of plastics. *J Hazard Mat* 156: 277–284.
19. Kaza S, Yao L, Bhada-Tata P, et al, (2018) What a waste 2.0. A global snapshot of solid waste management to 2050. Urban Development Series. International Bank for Reconstruction and Development/ The World Bank, Washington, DC: World Bank. <https://doi.org/10.1596/978-1-4648-1329-0>.
20. Ipeaiyeda AR, Falusi BA (2018) Monitoring of SO<sub>2</sub>, NO<sub>x</sub> and NH<sub>3</sub> Emission from Burning of Solid Wastes at Awotan and Lapite Dumpsites, Ibadan, Nigeria. *S Afr J Chem* 71: 166–173. <https://doi.org/10.17159/0379-4350/2018/v71a22>

21. Fakinle BS, Odekanle EL, Olalekan AP, et al (2020) Air pollutant emissions by anthropogenic combustion processes in Lagos, Nigeria. *Cogent Eng* 7: 1808285. <https://doi.org/10.1080/23311916.2020.1808285>
22. Dunne D, The carbon Brief Profile: Nigeria, 2020. Available <https://www.carbonbrief.org/the-carbon-brief-profile-nigeria>
23. Edenhofer O, Seyboth K (2013) Intergovernmental Panel on Climate Change (Eds) Encyclopedia of Energy, Natural Resource, and Environmental Economics. DOI: 10.1016/B978-0-12-375067-9.00128-5
24. Magazzino C, Mele M, Schneider N, et al, (2021) Waste generation, wealth and GHG emissions from the waste sector: Is Denmark on the path towards circular economy? *Sci Total Environ* 755: 142510.
25. Nnaji CC (2015) Status of municipal solid waste generation and disposal in Nigeria. *Manage Environ Qual* 26: 53–71.
26. Aliu IR, Adeyemi OE, Adebayo A (2014). Municipal household solid waste collection strategies in an African megacity: Analysis of public private partnership performance in Lagos. *Waste Manage Res* 32: 67–78. <https://doi.org/10.1177/0734242X14544354>
27. Ibikunle RA, Titiladunayo IF, Akinnuli BO, et al (2019) Estimation of power generation from municipal solid wastes: A case study of Ilorin metropolis, Nigeria. *Energy Rep* 5: 126–135. <https://doi.org/10.1016/j.egy.2019.01.005>
28. Ezeudu OB, Agunwamba JC, Ugochukwu UC, et al, (2020) Temporal assessment of municipal solid waste management in Nigeria: Prospects for circular economy adoption. *Rev Environ Health* 20200084.
29. Magazzino C, Mele M, Schneider N (2020) The relationship between municipal solid waste and greenhouse gas emissions: Evidence from Switzerland. *Waste Manage* 113: 508–520. <https://doi.org/10.1016/j.wasman.2020.05.033>
30. Somorin TO, Adesola S, Kolawole A (2017) State-level assessment of the waste-to-energy potential (via incineration) of municipal solid wastes in Nigeria. *J Clean Prod* 164: 804–815. <https://doi.org/10.1016/j.jclepro.2017.06.228>
31. Bichi MH, Amatobi DA (2013) Characterization of household solid waste generated in Sabon-Gari area of Kano in Northern Nigeria. *Am J Res Commun* 1: 165–171.
32. Nwude MO, Igboro SB, Otun JA, et al, (2014) Solid waste generation and characterization in Kaduna metropolis, Nigeria. *Acad J Sci Eng* 6: 31–39.
33. Ayuba KA, Manaf LA, Sabrina AH, et al, (2013) Current status of municipal solid waste management practice in FCT Abuja. *Res J Environ Earth Sci* 5: 295–304.
34. Iyamu HO, Anda M, Ho G (2017) Socio-technical systems analysis of waste to energy from municipal solid waste in developing economies: A case for Nigeria. *Renew Energy Environ Sustain* 2: 1–9. <https://doi.org/10.1051/rees/2017027>.
35. Amarachukwu E, Evuti AM, Salam KA, et al. (2020) Determination of waste generation, composition and optimized collection route for University of Abuja main campus using “MyRouteOnline” software. *Sci Afr* 10: e00569. <https://doi.org/10.1016/j.sciaf.2020.e00569>
36. Ferronato N, Torretta V, (2019) Waste Mismanagement in Developing Countries: A Review of Global Issues. *Int J Environ Res Public Health* 16: 1060. <https://doi.org/10.3390/ijerph16061060>
37. The World Bank, Population growth (annual %)-Nigeria, 2021. Available from: <https://data.worldbank.org/indicator/SP.POP.GROW?locations=NG>

38. Knoema, Nigeria–urban population as a share of total population. World Data Atlas>Nigeria>Demographics, 2021. Available from: <https://knoema.com/atlas/Nigeria/Urban-population>
39. The World Bank, GDP per capita, (Current US\$)–Sub-Saharan Africa, 2021. Available from: <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=ZG>
40. UNDP, United Nations Development Programme, National human development Report, 2018. Achieving human development in North East Nigeria. Available from: [http://hdr.undp.org/sites/all/themes/hdr\\_theme/country-notes/NGA.pdf](http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/NGA.pdf)
41. Okafor CC, Madu CN, Ajaero CC, et al, (2021) Sustainable management of textile and clothing. *Clean Tech Recycl* 1: 70–87.
42. Orhorhoro EK, Oghoghorie O (2019) Review on solid waste generation and management in Sub-Saharan Africa: A case study of Nigeria. *J Appl Sci. Environ Manage* 23. DOI: 10.4314/jasem.v23i9.19
43. Adeniran AE, Nubi AT, Adelojo AO (2017) Solid waste generation and characterization in the University of Lagos for a sustainable waste management. *Waste Manage* 67: 3–10. <http://dx.doi.org/10.1016/j.wasman.2017.05.002>
44. Ibikunle RA, Titiladunayo IF, Dahunsi SO, et al (2021) characterization and projection of dry season municipal solid waste for energy production in Ilorin metropolis, Nigeria. *Waste Manage Res: The J Sustain Circ Econ* 39: 1048–1057. <https://doi.org/10.1177%2F0734242X20985599>
45. Popoola O E, Popoola A O, Purchase D (2019). Level of awareness and concentrations of heavy metals in the blood of electronic waste scavengers in Nigeria. *J Health Pollut* 9: 1–10.
46. The World Bank, Total greenhouse gas emissions (kt of CO<sub>2</sub> equivalent)–Nigeria, 2020. <https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE?locations=NG>
47. Dave PN, Sahu LK, Tripathi N, et al (2020) Emissions of non-methane volatile organic compounds from a landfill site in a major city of India: Impact on local air quality. *Heliyon* 6: e04537. <https://www.sciencedirect.com/science/article/pii/S2405844020313815>
48. Fuzzi S, Baltensperger U, Carslaw K, et al. (2015) Particulate matter, air quality and climate: lessons learned and future needs. *Atmos Chem Phys* 15: 8219–8299. <https://doi.org/10.5194/acp-15-8217-2015>
49. Okafor C, Madu C, Ajaero C, et al, (2021) Situating circular economy and energy transition in an emerging economy. *AIMS Energy* 9: 651–675. <https://doi.org/10.3934/energy.2021031>
50. Kuo J, Dow J (2017) Biogas production from anaerobic digestion of food waste; and relevant air quality implications, *J Air Waste Manage Assoc* 67: 1000–1011, <https://doi.org/10.1080/10962247.2017.1316326>



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