Further evidence on environmental impacts of carbon monoxide from portable power generator on indoor air quality

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Ismail Babatunde Adefeso¹*, Jacob Ademola Sonibare² and Yusuf Markafi Isa¹

Abstract: The indoor air quality (IAQ) is paramount to the existence of humans considering the amount of time spent indoors. The indoor pollutant levels may be 100 times the levels outdoors. The indoor pollutants need to be considered to enhance better IAQ. This study determined the emission factors of carbon monoxide (CO) emitted from a standby electricity generator (SEG). It evaluated the impacts of CO concentrations on indoor air quality and identified appropriate ways to mitigate the CO concentrations. The indoor CO concentration was determined by simulating a number of scenarios of SEG operated outdoor using a Simulation Tool Kit for Indoor Air Quality and Inhalation Exposure (IAQX) model. Hourly measurements of mean CO concentrations in the ambient environment and wind speed were conducted for four weeks in four field locations. The emission rate of CO from the standby electricity generator was measured. The CO concentration from SEG was $2.4289 \times 10^6$ mg/m$^3$, a very high CO concentration. The CO emission factors...
were obtained as $2.2366 \times 10^3$ kg/m$^3$ of fuel consumed and $9.5411 \times 10^6$ kg/hr of activity. High CO concentrations were obtained in microenvironments from the scenarios $1.28 \times 10^8$ mg/m$^3$, $4.78 \times 10^3$ mg/m$^3$, $4.79 \times 10^4$ mg/m$^3$ and $9.58 \times 10^6$ mg/m$^3$. The results showed that a high air exchange rate allowed CO concentrations to decay fast while low air exchange rates created an accumulation of CO concentrations indoor.

**Subjects:** Environmental Issues; Environment & Health; Chemical Engineering;

**Keywords:** carbon monoxide; indoor air quality; emission factors; indoor activities; standby electricity generator; co-poisoning; indoor air quality model

1. Introduction
Both outdoor and indoor environment activities contribute to and affect the concentration of pollutants, such as carbon monoxide (CO) in indoor air (Baek, 2019; Jones & Molina, 2017). The continuous exchange of atmospheric air between outdoor and indoor environments and the amount of time spent indoor is significant to IAQ. People typically spend a large fraction of their time in various indoor environments such as homes, schools, workplaces, shopping malls and restaurants (Abdel-Salam, 2019; Ana et al., 2019; Andualem et al., 2019; Hines, 1993; Jones & Molina, 2017; Mainka et al., 2018; Ngoma et al., 2018; Ścibor et al., 2019; Wangchuk et al., 2015; Wei et al., 2018; Walkoff, 2018; Yocom, 1982). Generally, people spend about 90% of their time indoors (Baek, 2019; Bourdin et al., 2014; Carslaw, 2007; Chaloulakou et al., 2003). The studies of Abdel-Salam (2019), Ścibor et al. (2019), Marchand et al. (2006), and Lu et al. (2008) reported that urban people spend less than 90% indoors and only a mere 6% outdoors. In developing countries, the majority of those individuals exposed to unsafe concentrations of pollutants indoor are women, who are normally responsible for food preparation and cooking, and the infants and young children who spend time around their mother near the cooking area (Begum et al., 2009; Choo & Jalaludin, 2015; Garland et al., 2017; Kasangana et al., 2018; Kim et al., 2011; Toner et al., 2013; Vanker et al., 2015; Wang et al., 2017; Wei et al., 2018). Similarly, school IAQ is a global concern as children spend the second highest percentage of their time in schools (Mainka et al., 2015) and are especially susceptible to air pollution (Abdel-Salam, 2019; Al-Hemoud et al., 2017; Bragoszewska et al., 2018; Demirel et al., 2014; Guo et al., 2008; Jovanović et al., 2014; Krawczyk et al., 2016; Mainka et al., 2018; Weichenthal et al., 2008; Wichmann et al., 2010). The IAQ status and CO concentration exposure from point sources remain reoccurring challenge in developing countries.

1.1. Carbon monoxide indoor exposure
The indoor air pollutants may be classified base on discomfort, acute illness, carcinogenic, and chronic illnesses (Baek, 2019). Carbon monoxide (CO) is one of the pollutants that cause discomfort and acute illness. CO is a colourless, odourless, tasteless, non-irritating and toxic gas produced primarily during the incomplete combustion of carbonaceous fuels and substances (Baek, 2019; Festy et al., 2003; Hess-Kosa, 2019; Jones & Molina, 2017; Min et al., 2009a). High CO concentrations can cause acute CO intoxication by combining with the haemoglobin to produce carboxy-heimoglobin (COHB), and therefore disrupts sufficient transfer of oxygen from lung to human tissues (Han et al., 2017; Prockop & Chichkova, 2007; Rebolu et al., 2012; Veronesi et al., 2017; Walkoff, 2018). The high CO concentration hinders normal respiratory system function similar to a symptom of COVID-19 (Li et al., 2020). The CO emissions caused more than one-half of the fatal CO-poisonings reported in many countries; fatal cases also were grossly under-reported or miss-diagnosed by medical professionals (Cushen et al., 2019; Eberhardt et al., 2006; Lee et al., 2018; Min et al., 2009b; Veiraiah, 2020; Walkoff, 2018). Lack of consistent supply of electricity in some developing countries led to seeking alternative standby electricity generators. The CO concentration exposure from SEG causes unintentional and suicidal CO-poisonings (Tirosh & Schnell, 2016) and estimation showed that more than half of the 6000 annual deaths
Table 1. Relationship between health effects and exposure to COHb %

| COHb % | Health symptoms associated with COHb level in bloodstream |
|--------|----------------------------------------------------------|
| 80     | Death                                                   |
| 60     | Loss of consciousness; death if exposure is continued   |
| 40     | Collapse on exercise; confusion                         |
| 30     | Headache; fatigue; judgement disturbed                  |
| 20     | Cardiovascular damage; electrocardiographic abnormalities|
| 5      | Decline (linear with increasing COHb level) maximal oxygen uptake of healthy young men undergoing strenuous exercise; decrements in visual perception, manual dexterity, and performance of complex sensor motor tasks |
| 2.5    | Aggravation of cardiovascular disease                   |

Harrop (2002).

from fires in the United States were caused by CO-poisoning. In addition, studies showed that 900 people died of CO-poisoning via using SEG and thousands were injured between 1999 and 2017 (Blässer et al., 2014; Cui et al., 2017; Cushen et al., 2019; Hampson & Dunn, 2015; Sircar et al., 2015; Veiraiah, 2020). The severity of CO-poisoning is dependent on concentration, length of exposure (Table 1), and the general underlying health status of the exposed individual (Veronesi et al., 2017; Ramirez et al., 2014; Sandilands & Bateman, 2016; Cui et al., 2017; Veiraiah, 2020). Because carboxy-heimoglobin concentrations in blood are cumulative over time, prolonged exposure to low concentrations can result in considerable health effects (Table 1) (Min et al., 2009a; Veronesi et al., 2017; Barn et al., 2018, Ramirez et al., 2014; Weaver et al., 2002; Veiraiah, 2020). The CO-poisoning cases are mostly related to emission from SEG, unlike other CO emission sources. The SEG is normally used to complement the epileptic supply of electricity in most developing countries. The users of the SEG often place it near their home or indoors based on concerns about SEG theft and noise to neighbours (Yi et al., 2020; Marcy & Ascone, 2005; Adefeso, 2010). The SEGs are normally used near the living room in the affected locations. Lawrence et al. (2005) reported that the use of SEG in busy roads in India's urban areas (central Indian region) contributed to the CO concentration indoor. U.S. Consumer Product Safety Commission showed that five out of hundred and four deaths caused by generator CO-poisoning were associated with a generator that was placed outside the home near open windows, doors, or vents (Adefeso, 2010; Cui et al., 2017; Hampson & Dunn, 2015; Marcy & Ascone, 2005; Sircar et al., 2015; Veiraiah, 2020). The health effects of CO-poisoning as it enters the blood system are presented in Table 1.

Table 2. Revised cases of indoor CO-poisoning in Nigeria between 2005 and 2019

| Zones in Nigeria | No of casualties 2005/2008* | No of casualties 2008/2019 |
|------------------|-------------------------------|----------------------------|
| South-West       | 35                            | 61                         |
| South-South      | 16                            | 58                         |
| South-East       | 53                            | 72                         |
| North-East       | -                             | -                          |
| North-Central    | 16                            | 9                          |
| North-West       | -                             | -                          |
| Total            | 120                           | 200 + 60                   |

Note * Adefeso et al. (2012).
The effects of exposure to high concentrations of CO had resulted in some deaths in Nigeria where more than 60 people suffocated to death in 2008 alone (Table 2). Adefeso et al. (2012) reported some cases of casualties from all geo-political zones in Nigeria where south-east (SE) with 47 casualties had highest followed by south-west (SW) with 28 though north-east (NE) and north-west (NW) had no reported cases between 2005 and 2008. Table 2 presents also revised cases of CO-poisoning. The casualties from all geo-political zones in Nigeria where south-east (SE) with 72 casualties had highest followed by south-west (SW) with 61 cases, south-south 58 cases though north-east (NE) and north-west (NW) had no reported cases between 2008 and 2019. It showed that the causality from SEG CO-poisoning is still a challenging demand answers.

1.2. Indoor air quality model

Computer modelling techniques have been developed for indoor air quality studies. The study of Chaloulakou et al. (2003) used the mass-balance formulation developed by Hayes (1989) to simulate indoor concentrations of CO in a public school building. INTAIR developed by these authors (Ashmore & Dimitroulopoulou, 2009; Dimitroulopoulou et al., 2001) is a deterministic compartment model that allows indoor concentrations to be simulated into two separate microenvironments. According to the studies of Tong et al. (2017), Vallamsundar et al. (2016), Cushen et al. (2019), and Ocak et al. (2016) reported that indoor concentration is a function of outdoor concentration in the event of an accidental release or chemical attack involving toxic substances. The indoor concentration of pollutants can be related to outdoor concentration using a single model such as IAQX model. According to the study of Adefeso (2010), the IAQX model was modified to produce Equation (1) which was used in this study:

\[
V_i \frac{dC_i}{dt} = \sum_{j=1}^{n_i} R_j + pQ_{ia}C_o + \sum_{k=1}^{n_a} Q_{ik}C_k - \sum_{k=0}^{n_a} Q_{ki}C_i
\]

(1)

Where:

- \(V_i\) = the volume of zone i, (m³);
- \(C_i\) = pollutant concentration in a zone I (mg/m³);
- \(t\) = time, (hr);
- \(n_i\) = number of indoor sources in zone i; \(R_j\) = emission rate for indoor source j in zone i (mg/hr);
- \(p\) = the penetration factor for zone i (unitless);
- \(Q_{ia}\) = infiltration airflow rate from outdoors to zone i (m³/hr);
- \(C_o\) = pollutant concentration in ambient air (mg/m³);
- \(n_a\) = number of air zones;
- \(Q_{ik}\) = airflow rate from zone k to zone i and k ... i (m³/hr);
- \(C_k\) = pollutant concentration in zone k (mg/m³) and \(Q_{ik}\) = airflow rate from zone i to zone k and k ... i (m³/hr).

The continuous occurrence of CO-poisoning and casualties from SEG and other point sources are of serious health concerns. The source of CO-poisoning might have been identified but scientific basis for CO emissions from SEG and other sources linked to suffocation indoor are yet to be understood particularly, in developing countries. The aims of this study were to identify and quantify the CO emissions sources and, to collect wind speed data in an ambient environment. The IAQ Model was used to simulate and to investigate the link between CO emitted from SEG and other sources linked to suffocation. However, the IAQ model was used to investigate the use of SEG in developing countries. The investigation of CO-poisoning on IAQ with the IAQX model is expected to contribute to an understanding of the prevalent impact of CO on IAQ in developing countries. The modelling results were used to recommend an appropriate approach to use SEG around indoor environments.

2. Materials and methods

The study investigated the impacts of one CO pollutant distribution in microenvironments (rooms, kitchen, verandah, and hallway) air and impact on indoor air quality. Some scenarios were considered for the research where natural ventilation parameters, the emission factor of the CO
concentration from an SEG positioned in verandah, hallway, and outdoor position while windows and doors were assumed open. The study simulated CO concentrations with the modified IAQX model to predict the CO concentration in the microenvironment and provided some important insights for operating an SEG safely in homes and commercial activities buildings.

2.1. Sampling location
The research study sampling locations are located in south-west region of Nigeria with longitude: 4° 31’ E and latitude: 7° 33’ N. The selected locations are associated with heavy traffic and traffic congestions at rush hours (6.30–8.30 am and 6.00–8.30 pm) while commercial activities are characterized with frequent use of SEG in daily commercial activities. Hourly measurements of CO concentrations in ambient environment and wind speed were conducted for four weeks in four field locations.

2.2. Sampling procedure
The CO concentration in the ambient environment was measured using an in situ non-integrated single gas CO ToxiRAE II Model PGM-1150 monitor. Wind speed was measured with a Turbo Flow Meter 271 (Davis Instruments). The emission rate of CO from the SEG was measured using an ECLIPSE EGA4 combustion analyzer. The ToxiRAE CO analyzer was used for the ambient measurement of CO concentrations at the selected locations while the ECLIPSE EGA4 combustion analyzer was used for source emission measurement from the SEG. Four locations (A-D) were selected for measurement of CO and wind speed; location D serves as control which was mainly residential area with no commercial activity and very low motor vehicle traffic (Table 3). The locations are associated with heavy traffic and traffic congestions at rush hours (6.30–8.30 am and 6.00–8.30 pm) while commercial activities are characterized by the use of the SEG. Samplings were carried out in these locations at height 1.50 m above ground level. Sampling points were selected for those locations ranging between 1.50 m - 3.00 m from the road while the height at which the winds speed was taking ranges from 1.50 m to 2.00 m from ground level and the monitoring was performed between 6.30–8.30 am and 6.00–8.30 pm during weekdays and weekends, respectively. The traffic density was also monitored through counting per hour number of vehicles and motorcycles. One of the locations serves as control which was mainly residential area with no commercial activity (no SEG) and very low motor vehicle density (Table 3).

The CO concentrations (mg/m³ and ppm), exhaust velocity (m/s), and emission factors (mg/GJ and mg/kW) were determined from the SEG to obtain CO emission factors and CO exhaust flowrate. The CO exhaust emission concentrations and its velocity (to determine exhaust flow rate) from the generator were measured with the ECLIPSE EGA4 combustion analyzer and the turbo flow meter respectively. The heating value of gasoline and other indoor pollutants were obtained from the USEPA database.

2.3. IAQX model simulation
The IAQX Model was used in this study because of user-friendly interface with the building has fixed data (Table 4); can simulate more than one pollutant and volumetric flow rates between indoor and outdoor environments. Thus indoor source terms, outdoor source terms, and outdoor-

| S/N | Location | Motor vehicle count per hour | Motorcycle count per hour |
|-----|----------|------------------------------|--------------------------|
| 1   | A        | 1740                         | 2940                     |
| 2   | B        | 2580                         | 4620                     |
| 3   | C        | 1800                         | 3660                     |
| 4   | D        | 27                           | 88                       |
indoor exchange rate term are considered and they are the main terms in Equation (1) as presented in Equations (2)–(4).

\[ \sum_{j=1}^{n_s} R_j = \text{Indoor source term} \]  

(2) \[ \sum_{j=1}^{n_s} pQ_oC_o = \text{Outdoor source term} \]  

(3) \[ \sum_{k=1}^{n_z} Q_kC_k - \sum_{k=0}^{n_z} Q_kC_i = \text{outdoor – indoor exchange rate term} \]  

(4)

Regarding initial Equation (1), other terms are negligible because CO does not exhibit adsorption/desorption characteristics, absorption characteristics, particulate matters and chemical reaction activities during the simulation of the scenarios in indoor microenvironments.

Scenarios were created with six microenvironments which are a living room/living area, two bedrooms, hallway, verandah, and kitchen (Figure 1 and Table 4). In this study, emissions from the identified sources were considered as input parameters into the modelling tool with all the sources and parameters. The scenarios and the building microenvironment represent an average use of SEG in Nigeria. Some of the scenarios are; scenario 1, the SEG was kept in the verandah for 4 hr in the morning and 8 hr in the night, cooking activities in kitchen windows and doors opened in the morning but doors closed in the night while windows were partially opened but that of Bedroom closed. Scenario 3 showed that SEG was kept in verandah 4 hr in the morning and 8 hr in the night, indoor activities, windows, and doors were opened in the morning but doors closed in the night while windows were opened with high wind speed. Scenarios 4 and 5 kept SEG in the hallway and verandah for 24 hr in the morning with no indoor sources. Windows and doors were opened in the morning but doors were closed in the night with windows partially opened for both scenarios. Scenario 7 kept SEG in the verandah for 4 hr in the morning and 11 hr in the night in the hallway, cooking activities in kitchen windows and doors opened in the morning but doors closed in the night while windows were partially opened. The Bedroom2 doors and windows were closed. Scenario 8 kept SEG in the verandah for 4 hr in the morning and 11 hr in the night in the hallway with very low wind speed, cooking activities in kitchen windows and doors opened in the morning but doors closed in the night while windows were partially opened.

Scenarios 9 and 10 kept SEG in a prescribed location A from the building for 4 hr in the morning and 11 hr in the evening and 24 hr respectively with no indoor sources, windows and doors were opened in the morning but doors were closed in the night but while windows partially opened. Some of the scenarios are presented in Table 5.
3. Results and discussion

3.1. CO concentrations and wind speed

Various combustion activities are responsible for uncontrolled CO emissions. More than 200 different types of SEG were observed during the sampling in all locations except location D. The CO emission concentration obtained from the SEG was very high and the implication of this on IAQ.

Table 5. Possible combinations of indoor and outdoor source in selected scenarios

| S/N | Outdoor source of CO | Indoor source of CO | SEG location |
|-----|----------------------|---------------------|--------------|
| 1   | SEG (4–8 hr)         | CA_b + MsC          | Hallway      |
| 2   | SEG (24 hr)          | MsC                 | Hallway      |
| 3   | SEG (24 hr)          | No source           | Verandah     |
| 4   | SEG (4–8 hr)         | Cab                 | Verandah     |
| 5   | SEG (24 hr)          | No source           | Prescribed location |

CA_b = Cooking activities with LPG, CA_b = Cooking activities with kerosene/charcoals/coal, CA_b+ = Cooking activities with kerosene + (charcoals/coal), MsC = Mosquito coils, Inc = Incenses, Gen = Generator, ACH = Air change per hour.

(4–8 hr) = 4 hr in the morning and 8 hr in the night; (24 hr) = for a whole day.
Source CO concentration from SEG was $2.4289 \times 10^4$ mg/m$^3$, a very high CO concentration with emission factor 2982.20 mg/g of gasoline and other indoor activities that emit CO are presented in Table 6. The CO emission factors for the SEG were $2370 \times 10^3$ kg/m$^3$ of gasoline consumed and $9.5410 \times 10^6$ kg/hr of activity. This is higher than the operational emission factor of $1.00 \times 10^3$ kg/hr reported Wang and Emmerich (2010).

The SEG CO emission is extremely high compared to other studies as a point emission source for CO pollutant (Emmerich & Dols, 2016; Wang & Emmerich, 2010; Wang et al., 2013). With over 200 SEG scatter all over the sampling locations, the CO emission will have great impacts on IAQ - CO-poisoning may be triggered. However, if the good air exchange rate or good ventilation is ensured, it may enhance fast decay of CO concentration level. This is maybe because of the inert characteristics of CO at ambient temperature. The ambient CO concentrations at designated locations were obtained to be in following ranges - A (0.00–109.00 ppm), B (0.00 – 125.00 ppm), C (0.00 – 42.00 ppm) and D (0.00 – 12.00 ppm) while the overall mean CO concentrations were $11.9010 \pm 10.6130$ ppm (Table 7). The CO concentration levels in locations A and B were higher than C and D locations, respectively. This is due to the CO concentration contribution from other outdoor sources (outsource terms in the modified model in Equations (1) and (3)) such as SEGs and a high number of vehicles and motorcycles. However, the location C vehicle and motorcycle count was higher than the location A but CO concentration level was lower than that of location A. The lower value CO concentration was due to a higher wind speed recorded in location C which, was responsible for the reduction in CO concentration observed in location C. The wind speed measured at those designated locations is A (0.00 m/s and 1.80 m/s), B (0.00 m/s and 1.20 m/s), C (0.00 m/s and 3.20 m/s) and D (0.00 m/s and 2.10 m/s). The overall mean wind speed was $0.1742 \pm 0.2911$ m/s (Table 7). The values obtained for CO concentration are also higher than 1.10 ppm reported at 0.60 m/s wind speed (Zuraimi & Tham, 2008). The wind speeds obtained from all the locations affected the CO concentration levels in all the sampling locations either increasing the CO concentration or reducing it. This affects the outdoor-indoor exchange rate as presented in Equation (4). Location B with the lowest wind speed had the highest CO concentration while location C with a relatively high number of vehicles and motorcycles had 42 ppm of CO concentration because of a high wind speed of 3.20 m/s. The location D had the lowest value of CO concentration because of relatively high wind speed, the lowest number of vehicle and motorcycle count. The natural wind speed, number of SEGs, number of vehicles and motorcycle count play important role in ambient CO concentration levels. The mean CO concentration ($11.9010 \pm 10.6130$ ppm) and mean wind speed ($0.1742 \pm 0.2911$ m/s) shall be considered part of the input parameter (Equations (1) and (4)) for simulation of CO concentration level profile in microenvironments. The outdoor-indoor exchange rate term as presented in Equation (4) is a function of the wind speed and its directions.

### 3.2. CO concentrations profile in indoor microenvironments

The IAQ CO concentration level is mostly generated by outdoor activities via various combustion of carbonaceous substances to release oxides of carbon. The indoor contribution of CO
Table 7. Summary of mean and standard deviation (SD) hourly outdoor CO concentrations and wind speeds distribution for the field sampling

| S/N | CO concentration (ppm) | Wind speed (m/s) |
|-----|------------------------|------------------|
|     | Max        | Min | Mean | SD  | Max | Min | Mean | SD  |
| A   |            |     |      |     |     |     |      |     |
|     | weekdays   | 109 | 0    | 13.4318 | 16.3015 | 1.8 | 0    | 0.1136 | 0.2018 |
|     | weekends   | 27  | 0    | 11.2955 | 7.5347  | 0.2 | 0    | 0.0659 | 0.0713 |
|     | Overall    | 109 | 0    | 13.0895 | 11.9181 | 1.8 | 0    | 0.0588 | 0.1366 |
| B   |            |     |      |     |     |     |      |     |
|     | weekdays   | 41  | 0    | 14.1111 | 8.9219  | 1.2 | 0    | 0.0978 | 0.1671 |
|     | weekends   | 21  | 0    | 10.8889 | 6.2057  | 0.3 | 0    | 0.0222 | 0.0599 |
|     | Overall    | 135 | 0    | 12.6756 | 7.5638  | 1.2 | 0    | 0.1204 | 0.1135 |
| C   |            |     |      |     |     |     |      |     |
|     | weekdays   | 49  | 0    | 11.7805 | 7.7830  | 3.2 | 0    | 0.5878 | 0.8222 |
|     | weekends   | 44  | 0    | 7.8444 | 4.9881  | 0.9 | 0    | 0.1533 | 0.1590 |
|     | Overall    | 49  | 0    | 9.6204 | 7.1406  | 3.2 | 0    | 0.2561 | 0.4906 |
| D   |            |     |      |     |     |     |      |     |
|     | weekdays   | 12  | 0    | 0.4167 | 0.2320  | 2.1 | 0    | 0.5800 | 0.0674 |
|     | weekends   | 4   | 0    | 0    | 0     | 0    | 1.8  | 0.8300 | 0.0456 |
|     | Overall    | 12  | 0    | 0.2083 | 0.1171 | 2.1 | 0    | 0.7050 | 0.0421 |
|     | Total*     | 135 | 0    | 11.9018 | 10.6131 | 3.2 | 0    | 0.1742 | 0.2911 |

* The location D was excluded for the calculation of overall averages.
concentration indoor is minimal until SEG is introduced to indoor microenvironments. The modified IAQX model (Equation 1) was used to model the characteristics CO concentration profile in those indoor microenvironments. The results of the simulation CO concentration level show influence of the emission of the SEG on IAQ as shown in Equation 3. The highest CO concentration was obtained in the hallway (Figure 2) - $9.5800 \times 10^4$ mg/m$^3$. The following highest CO concentrations were obtained in rooms from the scenarios as $1.2800 \times 10^4$ mg/m$^3$ in the living room, $4.7800 \times 10^3$ mg/m$^3$ in bedroom2, $4.7900 \times 10^4$ mg/m$^3$ in the bedroom and $9.5800 \times 10^4$ mg/m$^3$ in hallway respectively (scenario 1). The high CO concentrations obtained from the IAQX model for the hallway indicate the contribution of SEG exhaust of CO pollutant to indoor air of microenvironments while the influence of other indoor activities is not significant. Bedroom and kitchen CO concentrations are higher than those of bedroom2 and living because the position C of SEG (Figure 1) is close to the bedroom and kitchen. The position C of SEG as
shown in Figure 1 showed that 80% of COHb (Table 1) in the blood and this is a typical scenario that might be responsible for number of causalities presented in Table 2. Also, it might be linked to the influx of CO concentration flux into the indoor microenvironments and increased the indoor source term (Equations (1) and (2)) concentration contribution to indoor air.

Operating the SEG for 24 hours indicated in Figure 3 where the CO concentration increases exponentially while there were no indoor activities (scenario 2) while in scenario 3 SEG is located in verandah position B (Figure 1). Both follow the same trend of CO concentration profile. The CO concentrations of bedroom and kitchen were also higher than the remaining rooms. It was obvious that the living room and bedroom2 always have the lowest CO concentrations in all cases. This maybe because of proximity of SEG (the indoor-outdoor exchange rate in Equation (4)) and absence of indoor activities but distance plays a major role in the CO concentration profile.

**Figure 4.** CO concentration profile in indoor for different SEG position scenario 5 (refer to Table 4).

**Figure 5.** CO concentration profile in indoors for different SEG position scenario 4 (refer to Table 4).
However, values obtained for scenario 5 (Figure 4) are below <10 ppm (Baek, 2019; Fan & Zhang, 2001; Veiraiah, 2020). The location was situated far away from the building to allow for diffusion and decay of CO concentrations. Scenario 4 (Figure 5) showed that low air exchange rate (the indoor-outdoor exchange rate in Equation (4)) caused accumulation of CO concentration in indoor microenvironments as the concentration could not decay to zero for some time and it does not agree with Milner et al. (2011) which reported that wind speeds affected outdoor CO concentration levels and higher wind speeds resulted in a lower indoor level in absence of indoor sources. It was found that an inverse relationship exists between wind speeds and indoor concentrations (regardless of the wind directions) since low wind speeds (indoor-outdoor exchange rate in Equation (4)) favour accumulation of CO concentration pollutant in microenvironments. The results from the model revealed that the hallway CO concentration was the highest compared to other rooms in the building (Figure 6) and exceeded the indoor air quality standard of <10 ppm as suggested by Baek (2019). The air exchange rate may have an impact on the CO concentration profile, as the strength of dilution or decay of indoor CO concentration level is a function of indoor-outdoor exchange rate as shown in Equations (1) and (4). It was noted that the scenarios which had the highest CO concentrations in microenvironments pose a danger to indoor comfort and health and the possible had been presented in Tables 1 and 2 respectively.

It was unsafe to use the SEG in the hallway overnight because the CO concentration level remained constant. The constant and high CO concentration might be responsible for death from CO-poisoning when using the SEG indoor at position B or C overnight (Table 2). Various sections highlighted and marked in Figures 3–7 (zone A and C in scenario 1 and zone B in scenarios 2 and 3) showed high CO concentrations build-up that pose health risk for humans (Table 1). Scenarios 5 showed that the SEG was kept in a prescribed location A (Figure 1) from the building, operated for 24 hr with active ventilation (windows and doors opened) in the morning but doors closed in the night while windows were partially opened which resulted in low CO concentrations in the microenvironments. The values obtained were below the recommended standard CO concentration (<10 ppm) (Baek, 2019; Veiraiah, 2020; Yi et al., 2020). Scenario 5 or with scenario indicating SEG was used occasionally could be considered the safest way to use SEG in homes and other

**Figure 6.** CO concentration profile in indoors for different SEG position scenario 1 (refer to Table 5).
commercial activities. However, according to Harrop (2002), the value of 10% COHb (Table 1) will give no symptoms of any serious health effects.

Figure 4: Scenario 7 plotted CO conc. profile in microenvironments in mg/m$^3$.

The indoor CO concentration of less than or equal 90 mg/m$^3$ will pose no danger to human health if the concentration does not increase or accumulate over a long time under poor ventilation scenarios. However, inappropriate use of this SEG may account for unintentional deaths among frequent users of SEG (Blässer et al., 2014; Cui et al., 2017; Cushen et al., 2019; Emmerich & Dols, 2016; Hampson & Bodwin, 2013; Hampson & Dunn, 2015; Sircar et al., 2015; Yi
The air exchange rate had an impact on the CO concentration profile as the strength of dilution or decay of indoor CO level is a function of air volumetric flow rate in and out of those microenvironments. Scenarios 4, 5 and 7 depicted the worst scenarios where SEG was wrongly used and run for several hours. Particularly Scenario 7 which had the highest CO concentrations.
indoor because the SEG was kept in the Hallway at the night. The CO concentration level remained constant and the concentration was maintained. This was the reason why some people suffocated to death overnight (Table 2).

Moreover, the CO-poisoning casualties in the country have not reduced as the SEG is only a viable alternative for various small-scale businesses and sources of electricity in most urban locations in Nigeria while the complexity of challenges in energy and electricity demand and supply are so enormous. Scenarios 9 and 10 results showed low CO concentrations in the indoor environment. The values obtained were below the standard (<10 ppm) (Figures 8 and 9) (Choi et al., 2019; Fan & Zhang, 2001) and recommendation of Hess-Kosa (2019). These scenarios are very good ways the SEG can be operated in homes. The challenges of electricity supply are due to lingering infrastructural gaps, centralized and closed grid system (Adhekpuokili, 2018; Bamisile et al., 2020; Edomah, 2019; Edomah et al., 2017; Oyewo et al., 2018; Ugwoke et al., 2020). If the demand for electricity is not fulfilled by the government, the CO-poisoning will persist. The reported casualties’ cases of CO-poisoning are frequent occurrences in Nigeria presented in Table 2, between 2008 and 2019 are well over 260 casualties were reported though most of the CO-poisoning cases were not reported.

4. Conclusions
The CO concentrations emitted by the inappropriate use of SEGs were very high as indicated by the source measurement and a high emission rate of CO concentration. This poses a threat to life if operated indoors or at close proximity (less than the safe distance of 10 m downwind) to buildings. Likewise, explosion of SEG can contribute to casualties of CO-poisoning. Outdoor-indoor relationship concentration was established. Natural ventilation rates affect level of concentrations of CO concentration in microenvironments. Under low or poor ventilation rates, the CO concentrations do not decay to zero value even after many hours the SEG has been shut down while under high ventilation rates, the indoor CO concentrations do decay to zero in few minutes. Operating the SEG indoor resulted in a high accumulation of CO concentrations in microenvironments which could cause death within a short time. The results of this study provide insight for operating SEG safely outdoors (close to residential areas) and establish the impact that may result from inappropriate use of the SEG on indoor air quality. Adherence to the proposed safety distance will effectively decrease the fatality rate of operating the SEG indoor and physical injury that can occur when SEG explodes.

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Author details
Ismael Babatunde Adefeso
E-mail: ismaila@dut.ac.za
ORCID ID: http://orcid.org/0000-0002-4400-7920
Jacob Ademola Sonibare
E-mail: asonibare@yahoo.com
ORCID ID: http://orcid.org/0000-0002-1121-5977
Yusuf Markafi Isa
E-mail: yusufi@dut.ac.za
ORCID ID: http://orcid.org/0000-0001-8272-3402

1 Department of Chemical Engineering, Faculty of Engineering and Built Environment, Durban University of Technology, Steve Biko Campus, Durban 4001, South Africa.
2 Environmental Engineering Research Laboratory, Department of Chemical Engineering, Faculty of Technology, Obafemi Awolowo University, Ile-Ife, Osun, Nigeria.

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