Global Scientific JOURNALS

GSJ: Volume 11, Issue 5, May 2023, Online: ISSN 2320-9186
www.globalscientificjournal.com

EVALUATION OF LOW-COST METAL OXIDE AIR QUALITY GAS SENSOR, DAIRQ THROUGH MEASUREMENT OF CO, NH_3 AND NO_2 ACROSS DAR ES SALAAM CITY

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KeyWords
Air pollutants, Air quality, calibration, low cost sensor, correlation, comparisons,

ABSTRACT
Air pollution affects the quality of life and public health, especially in Urban cities. The carbon monoxide (CO), nitrogen dioxide (NO2) or ammonia (NH3), are among the pollutants found in urban cities and have potential to cause respiratory illnesses or cardiovascular diseases. Metal-oxide gas sensors hold great potential for monitoring air pollutants level as their low cost, ease of operation and compact design can enable dense observational networks. However, several studies have shown that the performance of these sensors can have large discrepancies from those recorded by reference-grade instruments and thus they require frequent calibration. The study focuses on DAirQ metal oxide unit assembled at Dar es Salaam Institute of Technology (DIT) to measure gaseous air pollutants in urban areas. Measured datasets of NH3, CO and NO2 in laboratory and/or field from sites in Dar es Salaam city between October 2021 and February 2022 were used for calibration and performance evaluation of DAirQ units. Calibration model equations extracted from sensor manufacture curves were used in DAirQ sensor through a replication of model on each device. Calibration was carried out using the dataset recorded during collocation deployment of sensors in laboratory and field settings, while sensor performance evaluation was for datasets recorded during field deployment of sensors for separate sites across Dar es Salaam city. The results of linear calibration procedures studied shows significant resemblance of data recorded by these sensors in terms of ranges and magnitude variations to be sufficient for indicative measurements in cities. The dataset from site specific recording across the city showed variations of pollutants among the sites and with time of the day as expected. For individual field observations, some high picks of pollutions above WHO recommended values were observed across the city, especially at rush hours and at night time for sensors located in busy roads and industrial areas, respectively. Over all, the observed indicative measure of air pollutants across the city were sufficient for public awareness and policy making purposes.

1.0 INTRODUCTION

Air pollution affects the quality of life and public health, especially in Urban cities. The carbon monoxide (CO), nitrogen dioxide (NO2) or ammonia (NH3), are among the pollutants found in urban cities and have potential to cause respiratory illnesses or cardiovascular diseases. The 2012 global deaths estimate reviled that 11.6% of all global deaths were due to air pollution as per World Health Organization study [1]. According to 2006 to 2016 studies of inpatient hospital death in various Tanzanian major cities, respiration diseases were found to be the second leading causes of inpatient hospital death after malaria [2]. Of the total Tanzanian death in study period, respiratory diseases claimed about 10.08% (22,316) with other air pollution related death from cardio-circulatory diseases becoming the fifth leading cause with 6.31% (13,981) deaths [2].

The estimates of air pollution related deaths in Tanzania are based on global data and firmly anchored in well-known air pollution science due to absence of monitoring data [2]. However, more specific data is needed for Tanzania in order to classify the main sources of pollution in the country, to quantify their concentration at different areas across the main cities and understand how they vary between day and night. With more systematic assessments of the magnitude of the air quality problem for instance, based on the use of automatic air pollution monitoring systems, better and more comprehensive data can be generated, and consequently, targeted and tailored policy actions can be taken [2].

The state of the art for air pollution monitoring around the World is based on fixed, high quality and expensive sensing infrastructure run by government authorities. These type of monitoring are only affordable in developed countries and unfordable in developing countries where the healthcare system to deal with the impacts of air pollution heath illness are not well developed. With current advancement in sensor technologies, low-cost sensors (LCS) offer alternative solution for air pollution monitoring in developing countries, making the monitoring of air quality more accessible and attainable in developing countries [6], [7]. Currently, low-cost air pollution sensors are being integrated with high quality expensive sensors to create denser networks in developing countries for fine-grained air pollution datasets. Apart from low-cost, the data provided by LCS deployments often lack sufficient accuracy [8]. There are reports about serious inaccuracies of data from these sensors when they are compared from that of high quality and reliable traditional monitoring stations [9]. To deal with the limitations of the data, low-cost sensors are required to be calibrated before, during and after deployment to improve the data accuracy.

This study focuses on DAirQ sensors assembled in Tanzania at Dar es Salaam Institute of Technology (DIT) for monitoring air pollutions. The DAirQ gadgets utilizes MICS 6814 sensor for recording carbon monoxide (CO), ammonia (NH3) and nitrogen dioxide (NO2). The study evaluated the performance of manufacturer-based calibration model developed from sensor characteristics curves using laboratory and field data of the DAirQ sensor measuring NH3, CO and NO2 in urban settings. To collect data for evaluation, six DAirQ sensors assembled with manufacturer-based calibration model were co-located for recording data inside and outside the laboratory and then deployed at sites with different air pollutant concentration profiles in Dar es Salaam city. Datasets recorded from the sensors were used to evaluate sensor performance as well as calibration model transferability to other gadgets.

2.0 METHODOLOGY

This study quantitatively evaluated the performance of the DAirQ units through co-location calibration and field deployment across Dar es Salaam city. Co-location of sensors was performed at DIT station and the later field-deployment involved stations deployed across the city. For each case, air pollutants measured were carbon monoxides (CO), ammonia (NH3) and nitrogen dioxide (NO2) between October 2021 and February 2022[A1].

2.1 The DAirQ Unit

The DAirQ device is constructed utilizing the MiCS[A2] 6814 gas sensors from SGX Sensortech (Figure 1).

Figure 1. DAirQ unit

The MICS-6814 sensor utilized in DAirQ unit is a multi-gas sensor that composes of three sensing layers for measuring three gases namely; carbon monoxide (CO), nitrogen dioxide (NO2) and ammonia (NH3). The principle of operation of the MICS 6814 gas sensor is such that a sensing layer, composed of a metal oxide, generally SnO2, when exposed to air will absorbs chemicasl on its surface. Its electrical conductivity will change locally, leading to a change of its electrical resistance.

2.2 DAirQ Unit Model equation development

In the development of DAirQ device, the manufacturer's calibration curves were the main reference available (Figure 2[A3]).

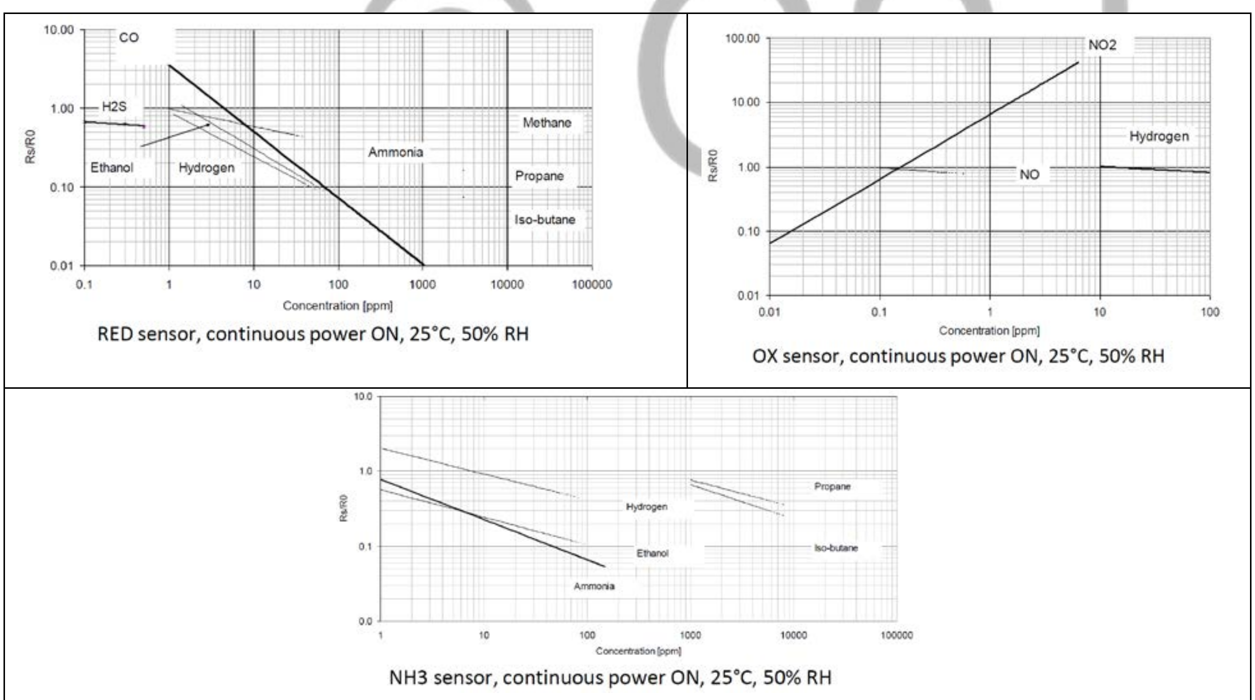

Figure 2: MICS 6814 Sensor Manufacturer's Curves[A4]

Using manufacturer's curve (Figure 2), several data points were collected from the curves and then put into excel sheets to generate trend lines to show the resistance ratio and corresponding concentrations in ppm value for each target gas. The generated equations were implemented in the Arduino software to estimate gas concentration level based on the sensor resistance sensed by DAirQ units.

2.3 Calibration of DAirQ Unit

The calibration of DAirQ device means determining the accuracy of the model equation to convert the measured parameter (resistance) to concentration in parts per million (ppm). That is, to determine whether or not a manufacturer's based calibration model is sufficient, a validation (quality assurance) of the data should be performed. Two methods were carried out, statistical calibration from theoretically calculated model data and deployment of DAirQ device to collect data for analysis.

For data collection with DAirQ device, co-location deployment of six DAirQ devices in W15/3 Laboratory, Electronics and Telecommunication building at Dar es Salaam Institute of Technology (DIT) for three days was carried out from October 14, 2021 to October 16, 2021 (Figure 3).

Figure 3: Collocation of six DAirQ devices inside the W15/3 laboratory

The devices were deployed together in the laboratory to ensure the similar observation conditions among the devices. During the observations, there were no known concentrations of gases in the laboratory but the environmental conditions were varied by burning papers, expelling alcohols, using cleaning detergents, as well as releasing perfumes. The dataset obtained from this experiment was named co-location[A5] dataset1. Further, the six devices were deployed outside W15/3 laboratory for observation of concentration of gases in ambient condition for two days (Figure 4[A6]). For this observation, the concentrations of gases in ambient air was not altered intentionally. The dataset collected for the deployment was named DIT-collocation datasets2.

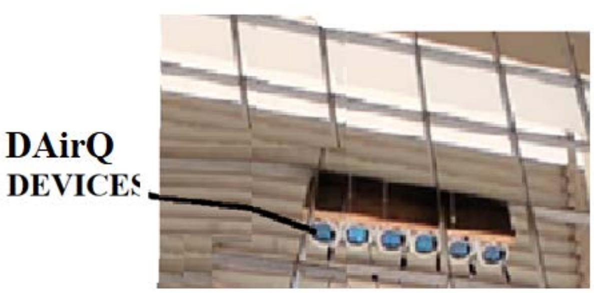

Figure 4: Collocation of DAirQ Devices outside W15/3 Laboratory.

2.4 DAirQ Unit Field Deployment

For performance evaluation of sensors in other environments, field observations using ten replica sensors were performed across

Dar es Salaam city as shown in Figure 5.

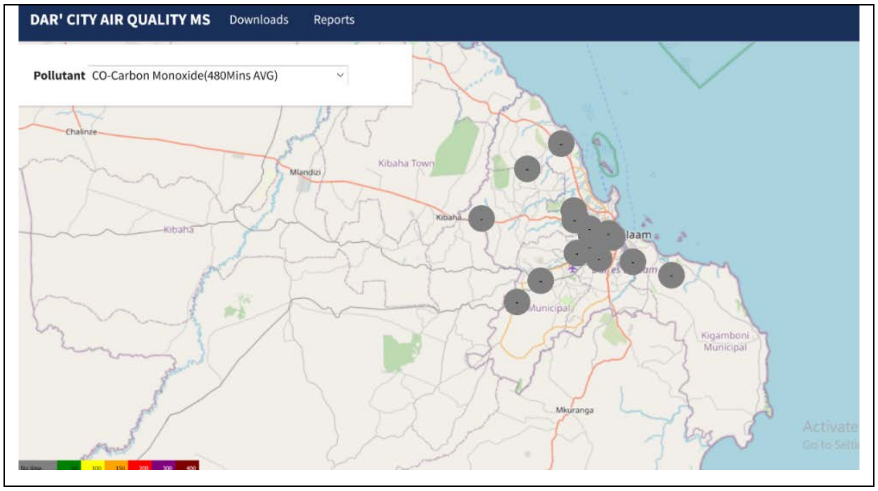

Figure 5: Field deployment of DAirQ sensors.

The characteristics for selected sites included normal office settings, closer to a busy road and closer to an industrial area. For each site, sensors were mounted at a height of at least 3 m high for free air inlet to the devices. All the devices were using mains power supply with rechargeable battery and internet was via a Global System for Mobile (GSM) SIM card for digital cellular communication. The measurement interval was 1 min, and the device could send data to the server after 15 minutes if connection to the server is available otherwise devices had built-in Secure Digital (SD) card for storage of data. This study explores the data recorded between October 2021 and February 2022. The data used for analysis were in hourly mean concentrations.

2.5 Statistical Analysis

All analyses for the data were performed in excel. Scatterplots were generated to examine the fit of the equation for model generated data with that collected with DAirQ units at co-location and later at field sites and thus to establish how well the model equations data represent the true air concentrations at other sites. For further comparison a linear regression model was created for each case to generate calibration equations.

3.0 RESULTS AND DISCUSSION

3.1 DAirQ unit model equations and their evaluation

From data points collected from the manufacturer's curves, the following mathematical relationship between sensor resistance ratio (Rs/Ro) and the gas concentration in ppm were generated for each pollutant gas in excel, as per Equations (1), (2) and (3):

$$Carbon\ monoxide\ (CO\ in\ ppm) = y = 4.4638X^{-1.177} \quad (1)$$

$$Nitrogen\ dioxide\ (NO2\ in\ ppm) = y = 0.1516X^{0.9979} \quad (2)$$

$$Ammonia\ (NH3\ in\ ppm) = y = 0.974X^{-4.33} \quad (3)$$

where: y is the concentration of the gas in ppm and x is the sensor resistance ratio Rs/Ro.

Next from the concentrations data recorded in laboratory, the resistance ratio Rs/Ro was calculated for each gas using the respective equation. From the generated data set, linear regression analysis was applied to estimate the standard error (Std error) and R^2 for each equation to quantify the accuracy of the generated models. Table 1 presents the resulting metrics for each equation.

Table 1: Statistical Metrics for model equations

GSJ: Volume 11, Issue 5, May 2023
ISSN 2320-9186

S/N	Statistical Metrics	CO Equation (1)	NO2 Equation (2)	NH3 Equation (3)
1	R2	1.0000	1.0000	0.9916
2	Std error	0.8227	0.0106	0.0088

3.2 DAirQ unit colocation Evaluation Results

This section presents the DAirQ units co-location results for both inside and outside W15 laboratory at DIT. Results of co-location of DAirQ units inside laboratory on October 14, 2021 and ctober 15, 2021 are shown in Figure 6.

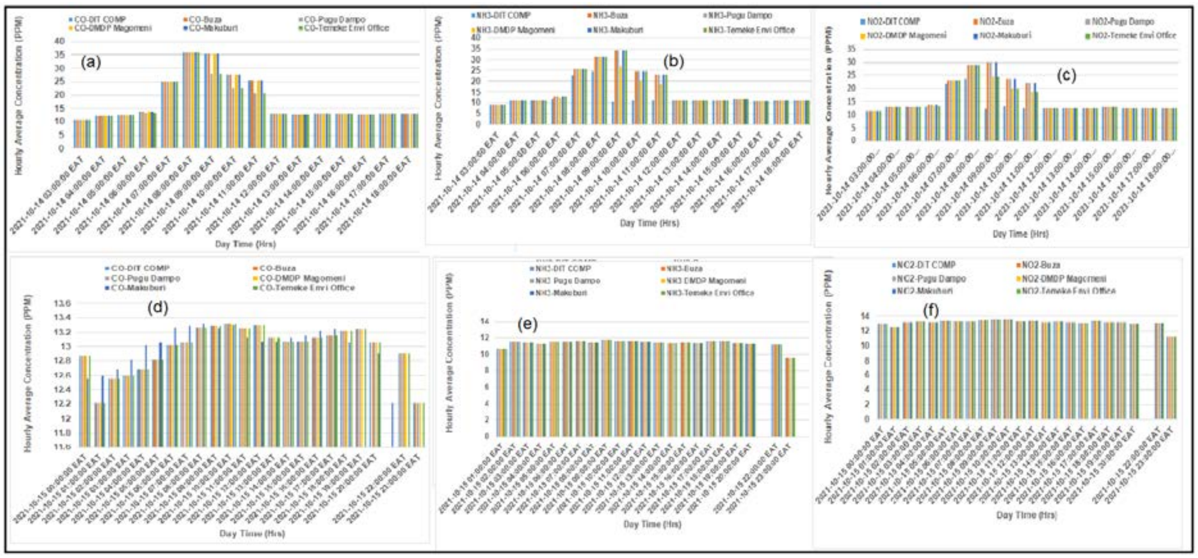

Figure 6: Hourly Average concentration trends for CO, NH_3 and NO_2.recorded with DIT, Pugu Dampo, DMDP Magomeni, Makuburi and Temeke Environmental Office DAirQ unit. (a) CO measurements on 14/10/2021, (b) NH3 concentrations of 14/10/2021, (c) NO2 concentrations of 14/10/2021, (d) CO measurements on 15/10/2021, (e) NH3 concentrations of 15/10/2021, (f) NO2 concentrations of 15/10/2021

For all three pollutant gases, the measured hourly concentration values from the DAirQ units were similar. On 14/10/2021, CO concentrations ranged from 10.8ppm to 35.7ppm, NH3 concentratins ranged from 9.2pp to 34.2ppm, and NO2 concentrations ranged from 11.5 to 30.1ppm. In the observations of all gases, DIT unit showed few cases of under estimation of concentration as compared to other units[A7]. For 15/10/2021, the concentrations ranges were: CO from 12.31 to 13.21ppm, NH_3 from 10.69 to 11.52ppm, NO_2 ranged from 11.27 to 13.54ppm. Measurementsof CO concentrations from Makuburi unit were overestimated by about 0.3ppm as compared to other units on 15/10/2021.

Further, the scatterplots correlating DIT unit hourly concetration data of 14/10/2021 and 15/10/2021 to other units (Buza, DMDP Magomeni, Makuburi, Temeke Environmental Office) are shown in Figure 7.

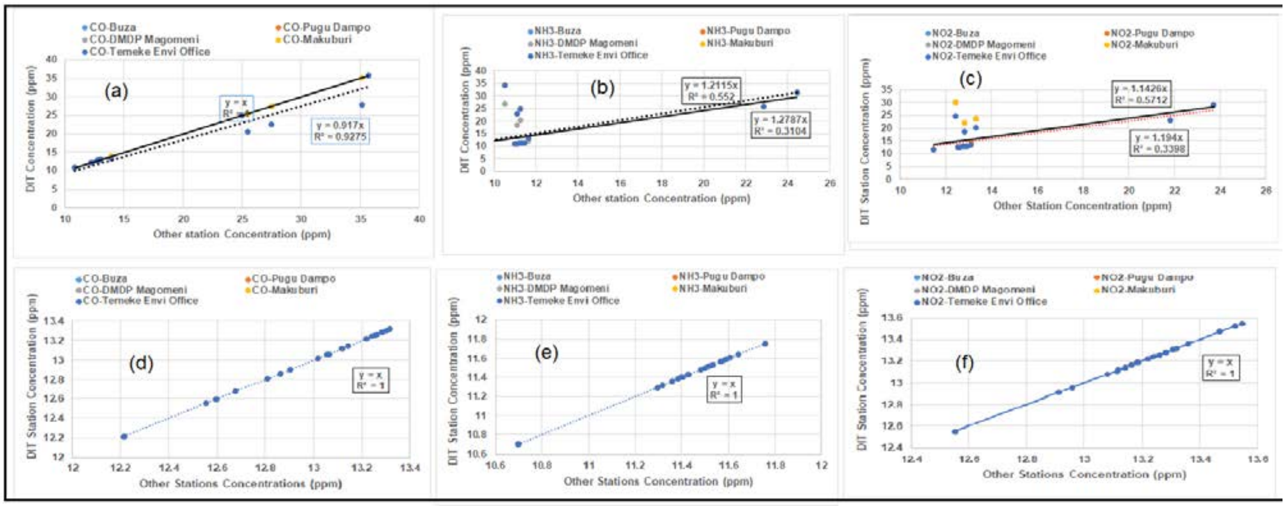

Figure 7: The Scatter plots of hourly concentrations between DIT station and other stations data of 14/10/2021 and 15/10/2021
(a) CO correlation on 14/10/2021, (b) NH3 correlation on 14/10/2021, (c) NO2 correlation on 14/10/2021, (d) CO correlation on 15/10/2021, (e) NH3 correlation on 15/10/2021, (f) NO2 correlation on 15/10/2021.

Table 1: Scatterplot R^2 for correlations of DIT station concentration data to other stations for 14/10/2021 and 15/10/2021.

Station	R^2 - 14/10/2021			R^2- 15/10/2021		
	CO	NH_3	NO_2	CO	NH_3	NO_2
Buza	1	0.552	0.5712	1	1	1
DMDP Magomeni	1	0.552	0.5712	1	1	1
Temeke Environmental Office	0.9275	0.3104	0.5712	1	1	1
Makuburi	1	0.552	0.3398	1	1	1
Pugu Dampo	1	0.552	0.5712	1	1	1

The correlation measure between DIT station CO and other stations ranged from 0.92 to 1, for NH3 the correlation ranged from 0.31 to 0.55, and for NO_2 concentration the correlation ranged from 0.33 to 0.57 for 14/10/2021 concentration data. After running the sensors continously for two days, there were improvemet into the correlation of the measured data such that all the correlation factors R^2 were 1 on 15/10/2021. Gaseous sensors are affected by changes into both temeperature and humidity, requiring to be operated for sometime before they stabilize according to the environments they are being exposed to.

The results for DAirQ unit performance for co-location outside the building on 19/10/2021 and 20/10/2021 are shown in Figure 8.

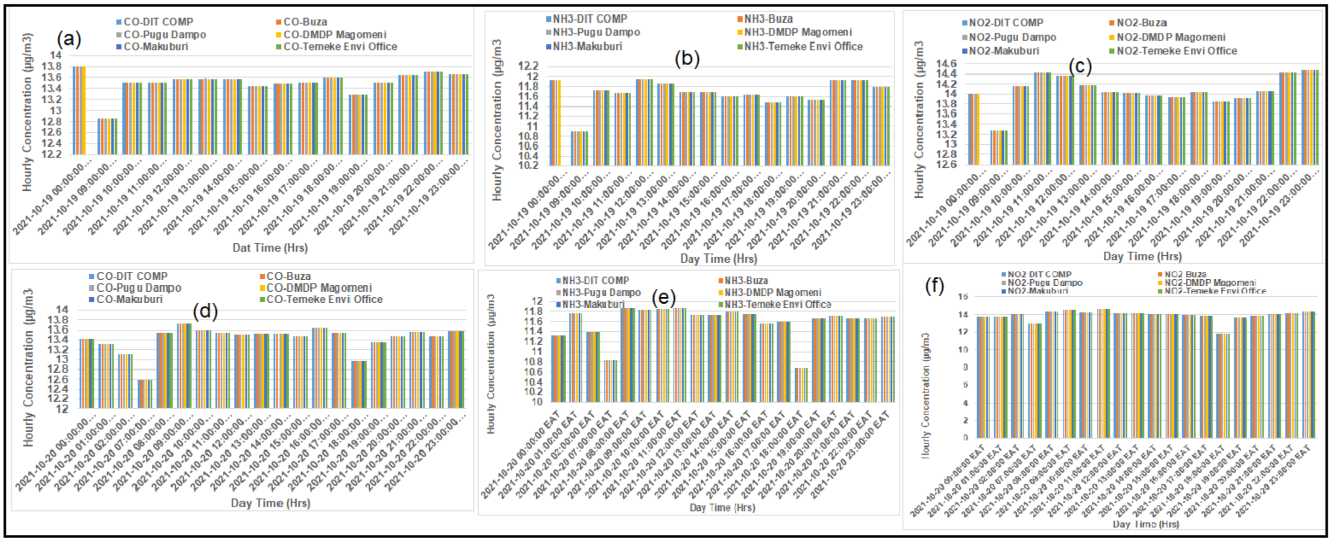

Figure 8: Hourly Average concentration trends for CO, NH_3 and NO_2 on 19/10/2021 and 20/10/2021. (a) CO measurements on 19/10/2021, (b) NH3 concentrations of 19/10/2021, (c) NO2 concentrations of 19/10/2021, (d) CO measurements on 20/10/2021, (e) NH3 concentrations of 20/10/2021, (f) NO2 concentrations of 20/10/2021

Variations of measured concentrations of the three gases, CO, NH3 and NO2 were shown to be of the same value and trends, all decreasing and increasing together. For 19/10/2021, CO concentrations ranged from 12.84 to 13.79ppm, NH3 concentratins ranged from 10.91 to 11.92ppm, and NO2 concentrations ranged from 13.26 to 14.47ppm. For 20/10/2021, the concentrations ranges are: CO from 12.60 to 13.73ppm, NH3 ranged from 10.67 to 11.87ppm, NO2 ranged from 11.87 to 14.57ppm.

The scatterplots for hourly concentrations measured on 19/10/2021 and 20/10/2021 are also shown in Figure 9.

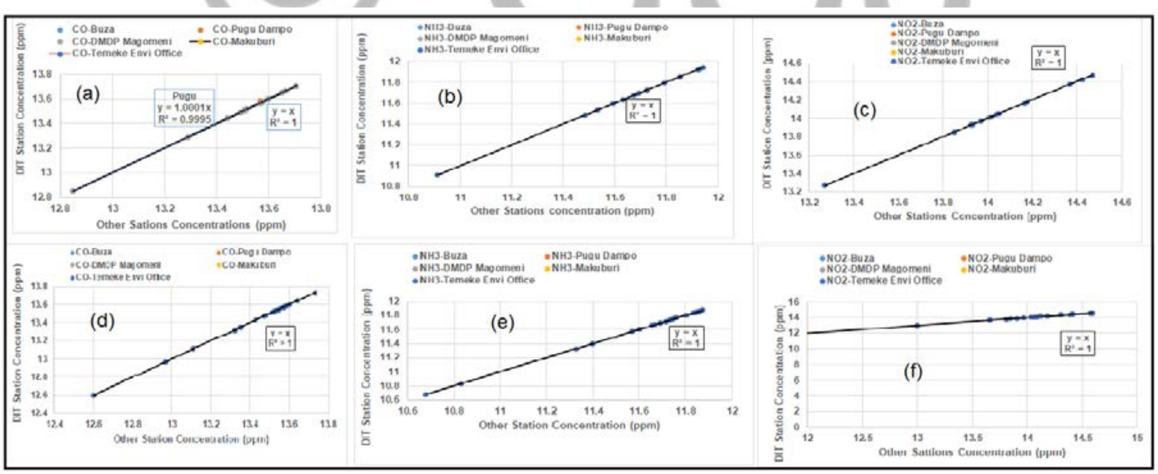

Figure 9: The Scatter plots of hourly concentrations between DIT station and other stations data of 19/10/2021 and 20/10/2021

(a) CO correlation on 19/10/2021, (b) NH_3 correlation on 19/10/2021, (c) NO_2 correlation on 19/10/2021, (d) CO correlation on 20/10/2021, (e) NH_3 correlation on 20/10/2021, (f) NO_2 correlation on 20/10/2021

Table 2: Scatterplot R^2 for correlations of DIT station concentration data to other stations for 19/10/2021 and 20/10/2021.

Station	R^2 - 14/10/2021			R^2- 15/10/2021		
	CO	NH_3	NO_2	CO	NH_3	NO_2
Buza	1	1	1	1	1	1
DMDP Magomeni	1	1	1	1	1	1

Temeke Environmental Office	1	1	1	1	1	1
Makuburi	1	1	1	1	1	1
Pugu Dampo	0.9995	1	1	1	1	1

According to Figure 9 and Table 2, the correlations of measured concentration of DIT unit to that of other units were 1 for all pollutant gases.

3.3 DAirQ unit Field Evaluation Results

Data recorded in field environment on 22/11/2021 and 25/11/2021 are presented Figure 10.

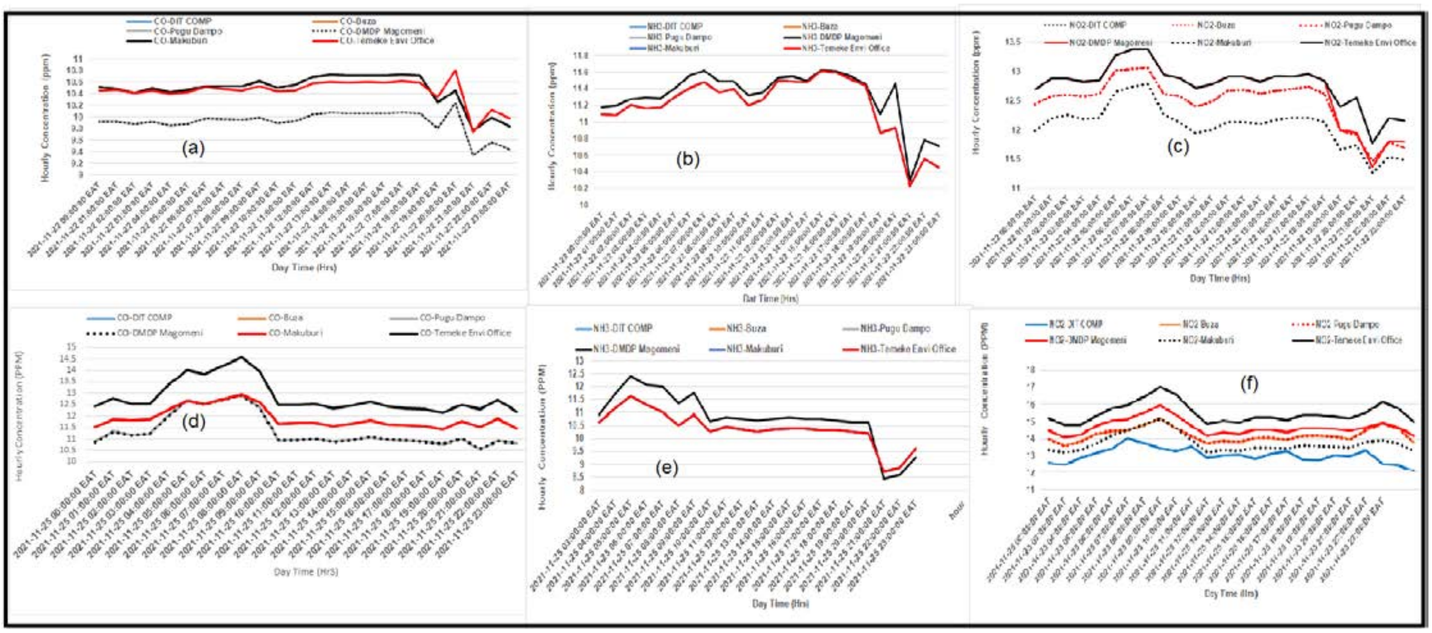

Figure 10: Hourly Average concentration trends for CO, NH3 and NO2 on 25/11/2021

As Figure 10, hourly concentration values recorded on 22/11/2021 were such that the maximum were 14.6ppm for CO, 12.4 ppm[A8][A9] NH3 and 17 ppm NO2. The minimum values were 10.5 ppm CO, 8.4 ppm NH3 and 21.1ppm NO2.

The correlations of recorded data between DIT station and others, is shown in Figure 11.

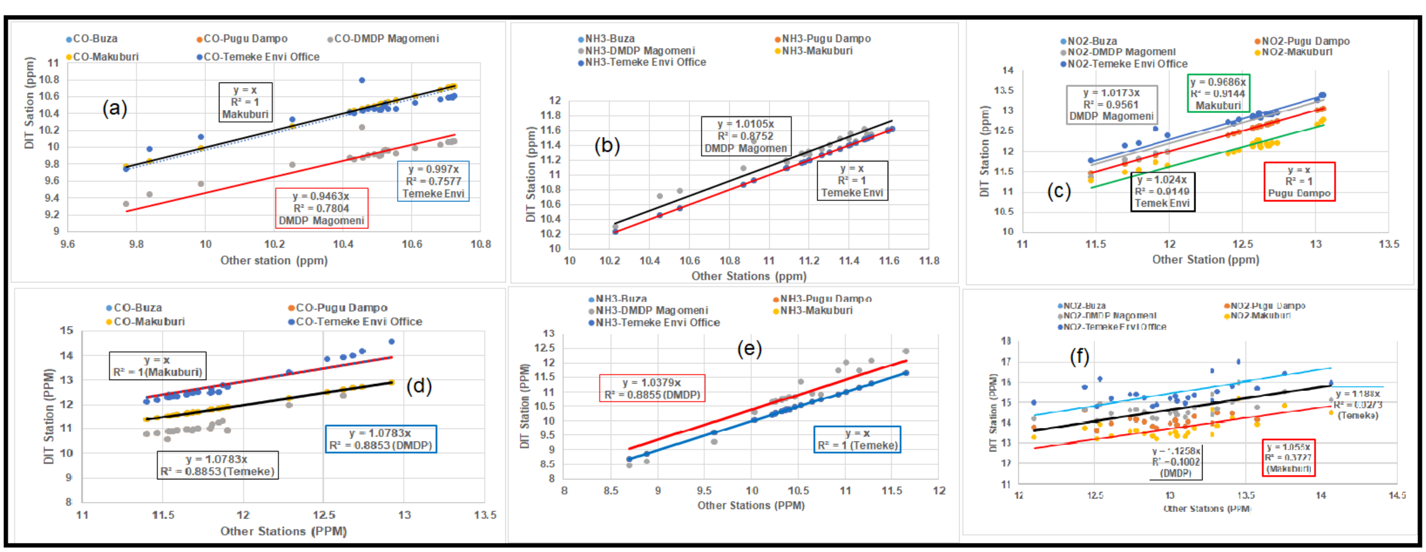

Figure 11: Correlation of DIT data to other stations on 22/11/2021 and 25/11/2021

Table 3: Scatterplot R^2 for correlations of DIT station concentration data to other stations for 22/11/2021 and 25/11/2021.

Station	R^2 - 14/10/2021			R^2- 15/10/2021		
	CO	NH_3	NO_2	CO	NH_3	NO_2
Buza	1	1	1	1	1	0.475
DMDP Magomeni	0.7804	0.8752	0.9561	0.8121	0.8855	0.1002
Temeke Environmental Office	0.7577	1	0.9149	0.8853	1	0.0273
Makuburi	1	1	0.9144	1	1	0.0273
Pugu Dampo	1	1	1	1	1	0.475

The correlation metric, in this case, R^2, was varied according to the Figure 11. For CO, R^2 was 1.0, 0.7804, 0.7577, 1 and 1 Buza, DMDP Magomeni, Temeke Environmental Office and DMDP Magomeni stations, Makuburi and Pugu Dampo, respectively. The R^2 for NH3 was 1, 0.8752, 1, 1, and 1.0 for Buza, DMDP Magomeni, Temeke Environmental, Makuburi and Pugu Dampo, respectively. For NO2, R^2 was 0.475, 0.1002, 0.0273, 0.0273, and 0.475 for Buza, DMDP Magomeni, Temeke Environmental Office and DMDP Magomeni stations, Makuburi and Pugu Dampo [A10][A11], respectively[A12].

4. DISCUSSION AND CONCLUSION

Overall, findings from this study suggest that DAirQ air quality device can adequately capture the air quality information at the site and thus as a low cost sensor is requires further calibration with high quality instruments. The colocation and field deployment comparisons findings were not adequate as sensor did not record high and low range values for full calibrations of the units. Because of unpredictable spatial and temporal variation patterns of air pollution in the city, atmospheric parameters should be considered during calibrations of model equations.

The study has shown that DAirQ air quality unit can reproduce air quality of the site it is exposed to and thus it offers a useful and complementary approach to measuring gaseous pollutants in atmosphere and will contribute to filling critical air pollution data gaps. Further deployment of sensors to cover the whole city evenly and corresponding analysis is till recommended as ongoing efforts to characterize air pollution across the city and increase awareness of the same to the city dwellers and policy makers.

Acknowledgment

The authors wish to thank Dar es Salaam Institute of Technology, Department of Electronics and Telecommunication Engineering for adnistrative support of the research.

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