J. Earth Syst. Sci. (2020)129 91
https://doi.org/10.1007/s12040-020-1339-7

Assessing the emissions of CO, SO_2, and NO_X and predicting potential zones of CO concentration from sugarcane factories in Egypt

Mohamed Abdelkareem[1,2,*], Yao Tan[3,4], Raafat M El Attar[1] and Abdelmonsef Hassan[1]

[1] *Geology Department, South Valley University, Qena 83523, Egypt.*
[2] *Remote Sensing Lab, South Valley University, Qena 83523, Egypt.*
[3] *School of Business Administration, Baise University, 12 Zhongshaner Rd, Baise 533000, Guangxi, People's Republic of China.*
[4] *Hubei Academy of Social Science, 165 Donghu Rd, Wuhan 430077, Hubei, People's Republic of China.*
**Corresponding author. e-mail: mohamed.abdelkareem@sci.svu.edu.eg mismail@bu.edu*

MS received 4 February 2019; revised 19 November 2019; accepted 26 November 2019

Air pollution causes significant environmental and health problems around the world. The present study assesses the emission of CO, SO_2, and NO_X from six sugarcane factories (SCFs) in Egypt, which are using two dominant fuels, bagasse and natural gas. The detected CO emission and concentrations levels from the stacks of SCFs that used bagasse were higher (1751–3030 mg/Nm^3) than those using a mixture of bagasse and natural gas (555 mg/Nm^3), as well as natural gas only (169.2–246.5 mg/Nm^3). The emission of CO is higher than permissible levels, but SO_2 (2.5–26.5 mg/Nm^3) and NO_X (25.5–149.75 mg/Nm^3) emissions in all kinds of fuels are within the permissible levels. Dispersion of CO in the ambient from stack emission from Kom Ombo SCF is simulated using the Ministry of Economic, Trade, and Industry Low-Rise Industrial Source dispersion (METI-LIS) model. The results predicted the higher risk zone (>10 ppmv) extends $\sim$1 km around the KSCF and occupies the near middle part of the plume, but the lower zone (<0.1 ppmv) occupies the outer zone and extends for several kilometers. Measurements in the ambient air validated the predicted model, which revealed that people living in areas about 1 km south and west downwind of the KSCF are exposed to higher levels of CO concentration. Usage of bagasse in SCFs needs to be replaced by natural gas for the reduction in emission of pollutants. Moreover, pollutants emitted from the SCFs should be monitored periodically to control the emission for healthy environment.

Keywords. Air pollution; bagasse fuel; co-emissions; sugarcane factories; Egypt.

1. Introduction

Industrial emission causes significant pollution by releasing pollutants into the environment. In developing countries, the production of sugar from sugarcane causes water, air, and land pollution (spillages and stillage), along with noise, dire odors (stench as a result of by-products like molasses), soil degradation, and biodiversity threats (Zimwara *et al.* 2013). One thousand one hundred million tons (per year) of sugar can be produced from sugarcane, mostly from 80 developing countries (UN Bioenergy Primer 2000). The production of 1 kg of sugar yields about 0.3 kg of molasses and 1.25 kg of fibrous residual (bagasse), which is utilized to produce steam and electric power

Published online: 11 March 2020

generation in sugar mills worldwide, particularly in many developing countries (Botha and Blottnitz 2006).

Bagasse contains cellulose (27–54%), hemi-cellulose (22–39%), lignin (14–24%), and inorganic matter (3–5%) (Aiman and Stonington 1993). Recently, bagasse has become an important biomass fuel for energy in the sugarcane processing industry in developing countries. Based on its moisture content, bagasse provides different energy values; for example, 0% and 48% moisture content providing 19,250 and 9950 kJ/kg, respectively (Nemerow 1995). Moreover, Cheesman (2004) revealed that when the moisture content reached 25%, the produced value of energy is ∼12,500 kJ/kg. In addition, moisture content >45% by weight would affect the efficiency of combustion system. The amount of bagasse varies between 24% and 30% by weight of sugarcane (Bio Energy Consult 2014). It is widely utilized as a cheap source of energy and for the manufacturing of fiber boards in Egypt (e.g., Dishna and Qena cities), as well as in pulp and paper manufactures (e.g., Qus and Idfu cities). Bagasse has low energy values compared to other fuels; one ton of bagasse (49% moisture) is equal to 0.28, 0.18, 0.55, and 0.15 tons (or 0.209 m^3) of bituminous coal, fuel oil, air-dried wood, and natural gas, respectively. This revealed how much bagasse should be used in sugar factories to get equal amounts of energy (Hindy 1991).

Air pollution in SCFs depends on the kind of fuel being used in boiling processes, as well as the performance of boilers and furnaces. Several studies have reported the harmful impacts of using bagasse fuel in SCFs (Hindy 1991; Janghathaikul and Gheewala 2005, 2006). Such investigations focused on the effects of settled dust resulting from firing bagasse in the boilers of SCFs (Hindy 1991) and the emission of gases such as NO_X and SO_X (Janghathaikul and Gheewala 2005, 2006). The common pollutants in SCFs are carbon monoxide (CO), nitrogen oxides (NO_X), sulphur oxides (SO_X), unburnt fuel and particulates of fly ash (Rainey *et al.* 2004), particularly when using bagasse as a fuel in ovens for boilers. Fly ash through stacks is very light and spreads over long distances in the atmosphere. It can be harmful and cause dizziness and irritation of the eyes, nose, and throat (Solomon 2005). Utilization of bagasse in the production process yields a considerable amount of CO and total suspended particulates (TSPs), which impacts the environment. CO causes difficulty in breathing, headache, nausea, chest pain, vomiting, seizures, blurred vision, confusion, heart failure, dizziness and coma, depending upon the specific levels and exposure time. Also, people who have heart or lung diseases are more sensitive to the toxic effects of CO. Pregnant women who breathe moderately high levels of CO can harm the development of their children (Kannan *et al.* 2006; Simkhovich *et al.* 2008; ATSDR 2012).

In Egypt, SCFs located in residential areas utilize bagasse as a fuel in the boilers to provide the steam needed for electric generation of the mill and heating during the sugar manufacturing processes (El Edessy *et al.* 2012; Shalaby *et al.* 2017). Most of these factories are aligned along the Nile, in areas of intense overpopulation (figure 1). Because of the dangerous impacts of gaseous emission for human beings and the environment, the main aim of the present study is to evaluate the environmental impacts of SCFs in Egypt by: (1) Assessing the gaseous emission levels discharged from the chimneys of SCFs compared to permissible levels and (2) developing a simulation model characterizing the gaseous dispersion downwind and delineating the dispersion zones of pollutant concentrations.

2. Study area

The study area is located in arid/hyper-arid conditions (Abdelkareem and El-Baz 2015, 2017). It covers three governorates: Qena (Nagaa Hamadi, Dishna and Qus factories); Luxor (Armant factory); and Aswan (Idfu and Kom Ombo factories) in southern Egypt, where there are ideal conditions (hot climates) for cultivating sugarcane (figure 1). The total amount of sugarcane cultivated in southern Egypt is about 16 million tons per year. Egypt, therefore, is representing the biggest producer of sugarcane in the Middle East (ESCWA, 2009). The process of extracting sugar from sugarcane extends from December to May every year, while the mills operate 24 hrs/7 days throughout the operation processes of the tested factories (El Haggar *et al.* 2014).

Throughout the mill operation, large quantities of residue are produced in the studied factories, such as bagasse, which is the main fibrous material residual produced after chopping and milling the sugarcane. The sugarcane juice and molasses are co-products from sugar manufacturing after filtering them from mud (table 1). According to personal communication with the operation managers of the studied sugarcane factories in southern

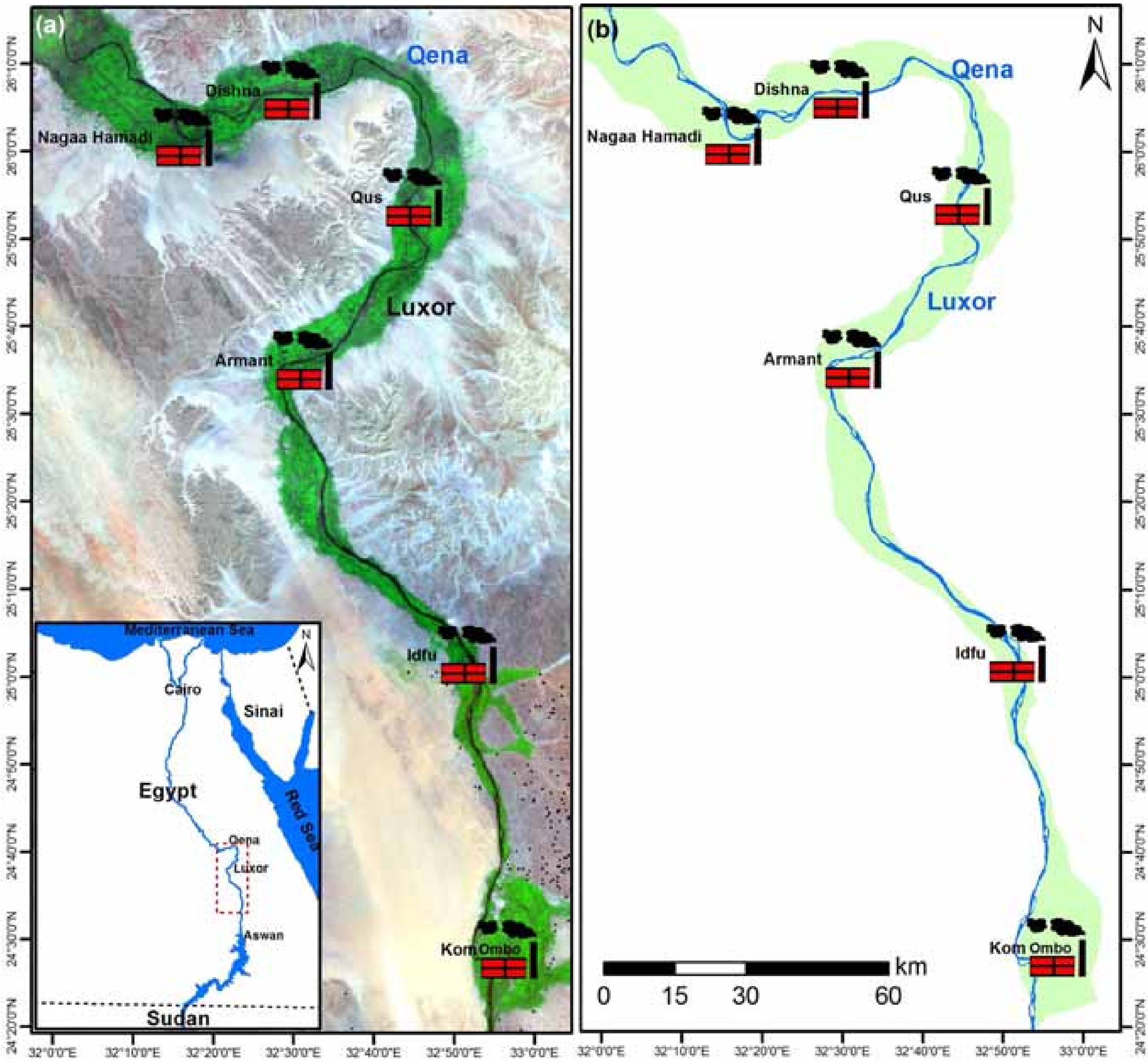

Figure 1. Location map of the studied sugarcane factories in southern Egypt within the residential zones along the Nile Valley.

Table 1. *The quantities of bagasse produced from sugarcane factories in South Egypt (El Haggar et al. 2014).*

Governorate	Factory	Cane processed in the factory (tons)	Amount of bagasse (tons)
Qena	Nagaa Hamadi	1,435,137	444,892
	Dishna	811,497	251,564
	Qus	1,496,836	464,019
Luxor	Armant	1,320,602	409,387
Aswan	Idfu	1,199,351	371,799
	Kom Ombo	1,821,253	564,588
Total		9,024,394	2,797,562

Egypt, the percentages of residue produced during the sugar manufacture process are 30%, 4%, and 3.5% of bagasse, molasses, and filter mud, respectively. Therefore, the annual production of sugar leaves behind about 3 million tons of bagasse, 370 thousand tons of molasses, and 316 thousand tons of filtered mud. In southern Egypt, most SCFs use bagasse as a fuel for sugar boiling, such as Nagaa Hamadi, Armant, and Kom Ombo, while Dishna and Qus utilize natural gas as a fuel for sugar boiling, other than Idfu, which uses a mix of bagasse and natural gas fuels for sugar boiling.

3. Materials and methods

The emission and concentration levels of CO, NO_X, and SO_2 emitted from stacks boilers of six SCFs (e.g., Nagaa Hamadi, Dishna, Qus, Armant, Idfu and Kom Ombo) were measured during operation seasons (December–May). Measurements were performed using portable stack gas analyzers (Shimadzu) division Kyoto, Japan: (1) Shimadzu NO_X analyzer, model NOA-7000; (2) Shimadzu SO_X analyzer, model SOA-7000; and (3) Shimadzu CO analyzer, model CGT-7000. Measurements were performed during January–April 2017. Several samples were measured from SCF stacks during the seasons, then the average concentrations for this period were computed (table 2).

The principle of Shimadzu SO_X and CO analyzer measurements is to irradiate with infrared light gas molecules SO_2, CO, CO_2, CH_4, and others. This process leads to shifts in vibrational and rotational kinetic energy levels for each gas (specific wavelength of IR), following the Beer–Lambert law:

$$I_2 = I_1 e^{-\varepsilon(\lambda)\, Cl}$$

where I_2 is the intensity of transmitted light, I_1 is the intensity of incident light, $\varepsilon(\lambda)$ is a coefficient determined by factors such as wavelength and type of gas, C is the gas concentration, and l is the length of the measurement cell.

In addition, the principle measurement of Shimadzu NO_X analyzer is a chemiluminescent technique involving NO and ozone (O_3). Exhaust gas from combustion equipment contains nitrogen oxide (NO) and nitrogen dioxide (NO_2), which together are referred to as NO_X. NO is the predominate component of NO_X, while the NO_2 content is only a few percent. In the NOA-7000, NO_2 is converted to NO, measured, then expressed as nitrogen oxides.

The instruments have been calibrated by using a multi-gas dilution system (serial no.: 3809) according to EPA methods and traceable to SI units (EPA-454/B-13-003). The calibration procedures were performed using the standard gases, zero gas (N_2 cylinder), and span gas (standard gas).

The concentration levels used for the calibration of analyzers of CO, NO and SO_2 cylinders are 3953, 2952, and 1800 ppm, respectively. While the linearity of SO_2 analyzer is ± 1.0%, it is ± 2% for CO and NO_X analyzers. Moreover, the measurement range of CO, NO_X and SO_2 analyzers are 0–5000, 0–4000, and 0–3000 ppm, respectively.

The data were processed and statistically visualized in diagrams. In addition, the dispersion simulation was carried out using the Ministry of Economic, Trade, and Industry Low-Rise Industrial Source dispersion model (METI-LIS), software version 2.03, to delineate potential areas of pollutants emitted from the SCF stacks. The simulation of CO dispersions was modeled using the METI-LIS program (Kouchi *et al.* 2004). The METI-LIS is a software program developed originally by the Japan Ministry of Economy, Trade, and Industry Low Rise Industrial Source dispersion model (METI 2006). The METI-LIS model software is an advanced Gaussian dispersion model that calculates concentrations in steps of one hour or less to simulate how air pollutants disperse in the ambient atmosphere from different sources (e.g., point and line), as well as the effects of terrain and building downwash. The model takes into account dry and wet depositions and includes mechanisms for determining the effects of terrain and buildings on plume dispersion. The estimation method selected in this study was for point source, the dispersion models require the following input data: objective substance (name and molecular weight of chemical substance); operation pattern data (short-term 24 hrs full operation or long-term); meteorological data (wind speed, wind direction, temperature, solar radiation and atmosphere stability class required); height and location of point source discharge (m); and volume flow rate. The process of the METI-LIS model can be conducted using a dispersion equation (equation 1) to calculate the transport and concentration of pollutants from a point source (plants) (Sutton 1932, 1947), as follows:

$$C(x, y, z) = \frac{QV}{2\pi u_s \sigma_y \sigma_z} \times \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (1)$$

where C is the concentration in x, y, and z directions (g/m^3: ppb, ppm, or other units); x is the downwind distance from the emission source (m); y is the crosswind distance from the emission plume centerline (m); z is the distance above the ground level (m); Q is the pollutant emission rate (g/s); V represents the atmospheric distribution of the Gaussian plume in the vertical direction

Table 2. *Gaseous emissions from combustion of bagasse and natural gas in boilers of sugarcane factories in southern Egypt.*

Sampling period	Kom Ombo	Nagaa Hamadi	Armant	Idfu	Dishna	Qus
Fuel type	Bagasse (mg /Nm^3)			Bagasse + gas (mg /Nm^3)	Natural gas (mg /Nm^3)	
CO						
January 2017	2518	2390	1383	1025	220	64
February 2017	2424	1207	1839	670	303	220
March 2017	2200	1973	2283	240	90	303
April 2017	4981	4156	1500	285	373	90
Average	3030	2431.5	1751.2	555	246.5	169.2
Permissible limits as per Egyptian environmental law	250 mg/Nm^3				100 mg/Nm^3	
SO_2						
January 2017	1	35	21	5	10	5
February 2017	7.2	56	33	6	5	1
March 2017	0	5	2.8	2	1	5
April 2017	2	15	1	4	5	1
Average	2.5	26.5	14.4	4.2	5.2	3
Permissible limits as per Egyptian environmental law	100 mg/Nm^3				150 mg/Nm^3	
NO_X						
January 2017	15	100	36	59	60	78
February 2017	21	18	65	270	78	60
March 2017	30	43	9	234	57	121
April 2017	36	15	44	36	121	57
Average	25.5	44	38.5	149.7	79.2	79
Permissible limits as per Egyptian environmental law	500 mg/Nm^3					

(equation 2); u_s is the wind speed at release height (m/s); and σ_y and σ_z are dispersion parameters in the lateral and vertical directions (m).

The dispersion parameters σ_y and σ_z are used in equation (1), which can be estimated from Pasquilll–Gifford curves (equations 2, 4, and 5). The values for dispersion coefficients (a, b, c, and d) are available in the technical manual of the METI-LIS model (Turner 1967, 1994).

$$\sigma_y = 465.11628(X)\tan(TH) \tag{2}$$

where X is the downwind distance (m)

$$TH = 0.017453293[c - d(\ln(x))] \tag{3}$$

$$\sigma_z = ax^b \tag{4}$$

where a, b, c, and d are the dispersion coefficients.

$$V = \exp\left[-0.5\left(\frac{Z_r - h_e}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{Z_r - h_e}{\sigma_z}\right)^2\right] \tag{5}$$

where z_r is the elevation of calculation point (m); and h_e is the effective plume-rise height (m). USEPA methods 1, 2, 3, and 4 were used to determine the dry volumetric emission rate from the stacks of sugarcane factories.

The meteorological data that input to the METI-LIS model were collected from the Aswan meteorological station located in Aswan Airport. The average temperatures of February and March were 16 and 18°C, respectively.

4. Results and discussion

The studied sugarcane factories are located in the inhabited regions along the narrow cultivated Nile Valley of Egypt (see figure 1). Average stack concentrations of CO, SO_2, and NO_X for different kinds of fuel utilized by SCFs during the study periodare listed in table 2. In addition to gas emission, the discharge of dust and fly ash was clearly observed in the studied SCFs, such as Kom Ombo, Armant, and Idfu (figure 3). Kom Ombo and Armant factories that use bagasse discharge a high amount of ash fly rather than Idfu, which uses bagasse and natural gas.

4.1 *CO emissions*

The measured CO emission values for the studied SCFs are higher than the permissible limits of Egyptian environmental law. Comparing the CO emissions and kind of used combustion fuels in SCFs revealed that the highest value (3030 mg/Nm^3) of CO recorded in the Kom Ombo sugar factory used bagasse (figure 2a, c). However, the lowest value (169.2 mg/Nm^3) detected in the Qus sugar factory used natural gas (figure 3). Noteworthy, the higher levels of emission were recorded in factories that burn bagasse as fuel for sugarcane boilers. However, adding natural gas fuel to bagasse reduces the CO emission gas during the burning process, such as the Idfu factory, which used natural gas mixed with bagasse as fuel. Factories such as Dishna and Qus recorded the lowest levels of exhaust from sugarcane factories, as they are using natural gas. Noteworthily, the fuel types and kinds of boiler firing practices used lead to imperfect burning and represent the most important causes of high CO levels (Purohit and Michaelowa 2007; Zimwara *et al.* 2013). High levels of CO emissions in sugarcane factories are mostly due to the imperfect burning of bagasse, which has a high humidity content between 45 and 55% by mass, and dense feeding of bagasse, which hinders the burning (Agarwal and Sharma 2006; Janghathaikul and Gheewala 2006). The reason behind the high levels of CO when using bagasse as a fuel is its higher water content. Another reason is that sugarcane factories use old boilers (horseshoe and fuel cell boilers). Moreover, these boilers are worked by a manual combustion system, which causes the uncontrolled quantity of bagasse fuel and air entering the boilers. This leads to the decreased effectiveness of combustion, and thus an increase of CO emission gas (Shalaby *et al.* 2017; US Environmental Protection Agency 1982).

During the combustion of bagasse, it is difficult to spread sufficient air through the fuel bed that causes incomplete combustion. This leads to a decrease in the burning efficiency and results in more than 30% of bagasse not burning, needing to be disposed (Jenkins

Figure 2. Field photographs displaying the plume that emitted from sugarcane factories stacks; In: Southern Egypt during operating months of 2017; **(a, c)** Kom Ombo factory, Armant factory; **(d)** Idfu factory.

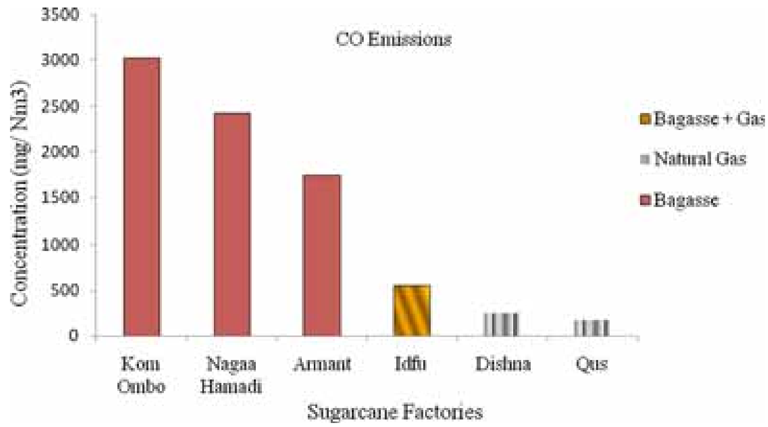

Figure 3. Stack concentration of CO for various SCFs using different kinds of fuel.

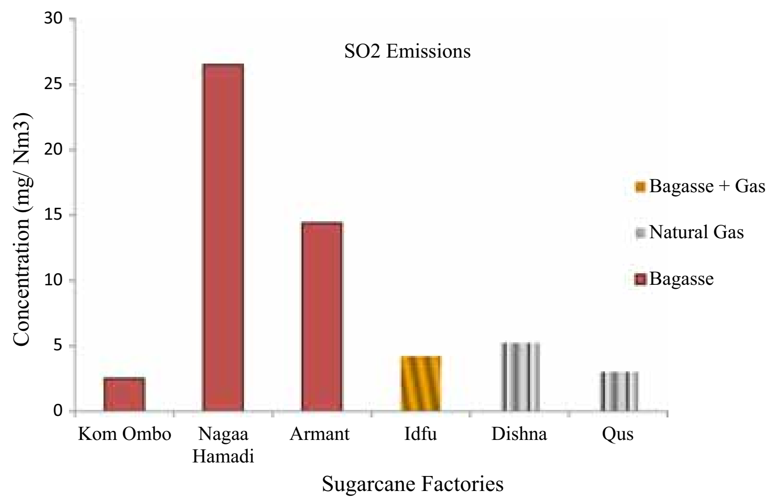

Figure 4. Stack concentration of SO_2 for various SCFs using different kinds of fuel.

1966; El Haggar *et al.* 2014). Sugarcane factories in southern Egypt, such as the Idfu factory, combine natural gas and bagasse, which results in lower emissions of CO. This is because fossil fuels (natural gas) normally have less humidity content and efficiency can be higher during the combustion process (Jang-hathaikul and Gheewala 2005, 2006) and minimizes CO emissions and discharged ash fly particulates.

Stringent regulations need to be implemented to control the emissions of CO as well as other pollutants. When it enters the environment, it stays in the atmosphere for about 2 months (Seinfeld and Pandis 2006). Air pollution by CO exacerbates the symptoms of asthma and allergic rhinitis in students 6–7 years in Spain (Arnedo-Pena *et al.* 2009). Increased levels of CO in the ambient air cause harmful impacts for pregnancy, because being subject to high levels of CO promotes hypo-oxygenation, which then may increase the risk of cord and fetal abnormalities (Ziaei *et al.* 2005).

4.2 *SO_2 emissions*

The higher value of 26.5 mg/Nm^3 of SO_2 was detected in Nagaa Hamadi, while the lower value of 2.5 mg/Nm^3 was recorded in Kom Ombo. The obtained SO_2 values are within permissible limits of Egyptian environmental law (table 2). The SO_2 emissions correlated with the kind of fuel combustion in sugarcane factories (figure 4). In this case, the bagasse is normally combined with heavy oil during the start-up firing to improve the burning effectiveness. Such a process releases high levels of SO_2 into the air.

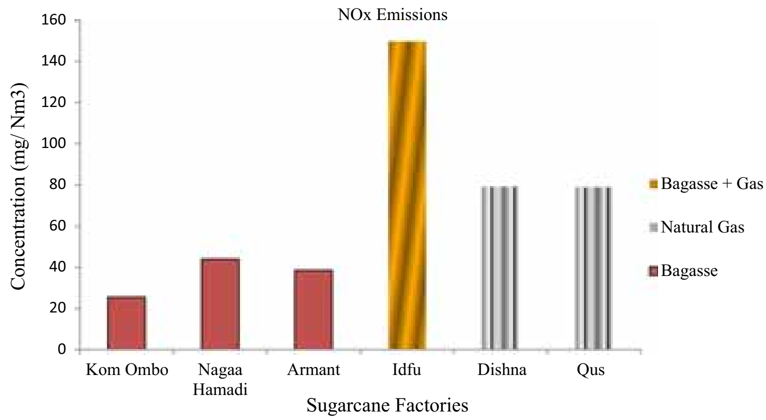

Figure 5. Stack concentration of NO_x for various SCFs using different kinds of fuel.

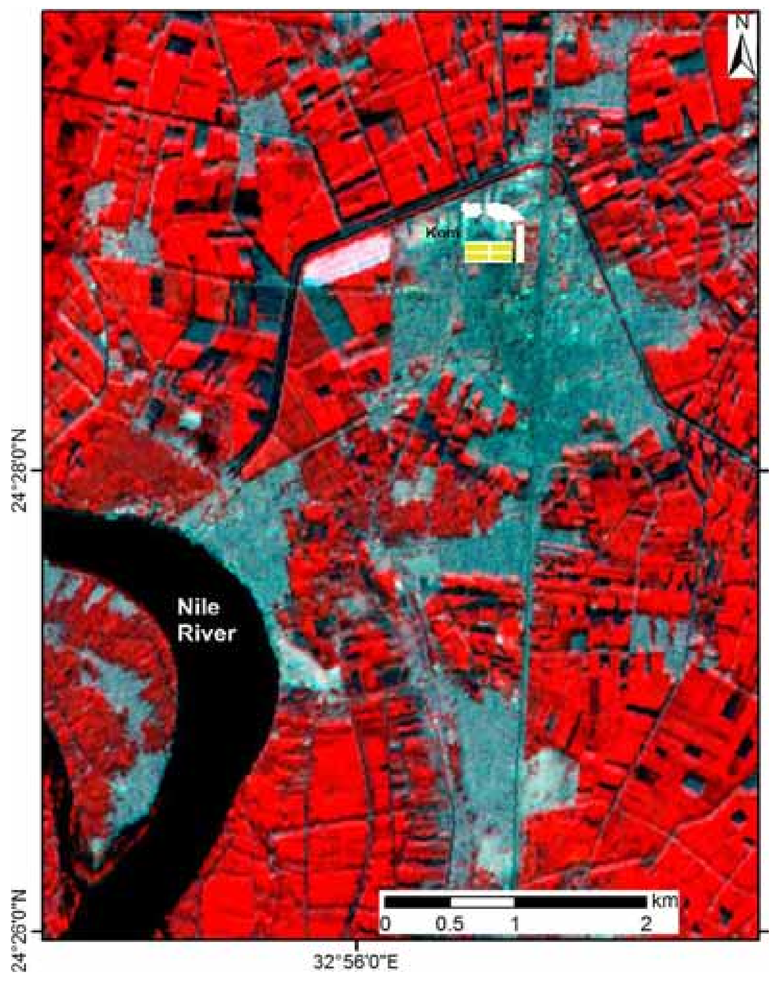

Figure 6. Aster bands 3, 2, 1 in R, G, and B showing that Kom Ombo Scf is located in a residential area marked by bluish grey colour the red colour belongs to vegetated areas, and the black colour is consistent with water bodies.

Auxiliary fuels (heavy oil or natural gas) can be used through turning on the boiler or when bagasse has a high content of humidity to improve burning efficiency. If oil fuel is used during these periods, the emissions of SO_2 will increase (El Haggar *et al.* 2014; US Environmental Protection Agency 1982). Since bagasse has lower sulfur content, lower SO_2 emission is seen in the case of Kom Ombo SCF (Janghathaikul and Gheewala 2005; Ren *et al.* 2017). In the case of using natural gas, the recorded SO_2 emissions came in low concentrations (figure 4).

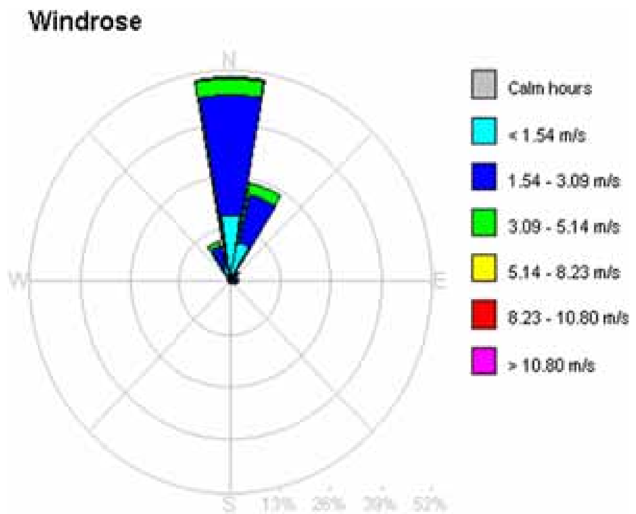

Figure 7. The wind direction and prevailing speed at Kom Ombo City, based on aswan Meteorological Station (2017).

4.3 *NO_X emissions*

The recorded NO_X emissions from the SCFs are within permissible limits of Egyptian environmental law. The high value of 149.7 mg/Nm^3 of NO_X was recorded in Idfu SCF, while the lower value of 25.5 mg/Nm^3 was detected in Kom Ombo SCF. NO_X emissions are clearly connected to the kinds of fuels indicated in figure 5. This figure indicates high levels of NO_X emissions detected as a result of the co-burning of bagasse and natural gas as fuels for sugarcane boilers. Furthermore, in the reactions of firing air and nitrogen content of natural gas, less NO_X is formed (US Environmental Protection Agency 1987). In factories that use bagasse only, the NO_X emissions are lower than that formed from conventional fossil fuels (Janghathaikul and Gheewala 2006; Kazanc *et al.* 2011), because of the low nitrogen content of bagasse and lower burning temperature.

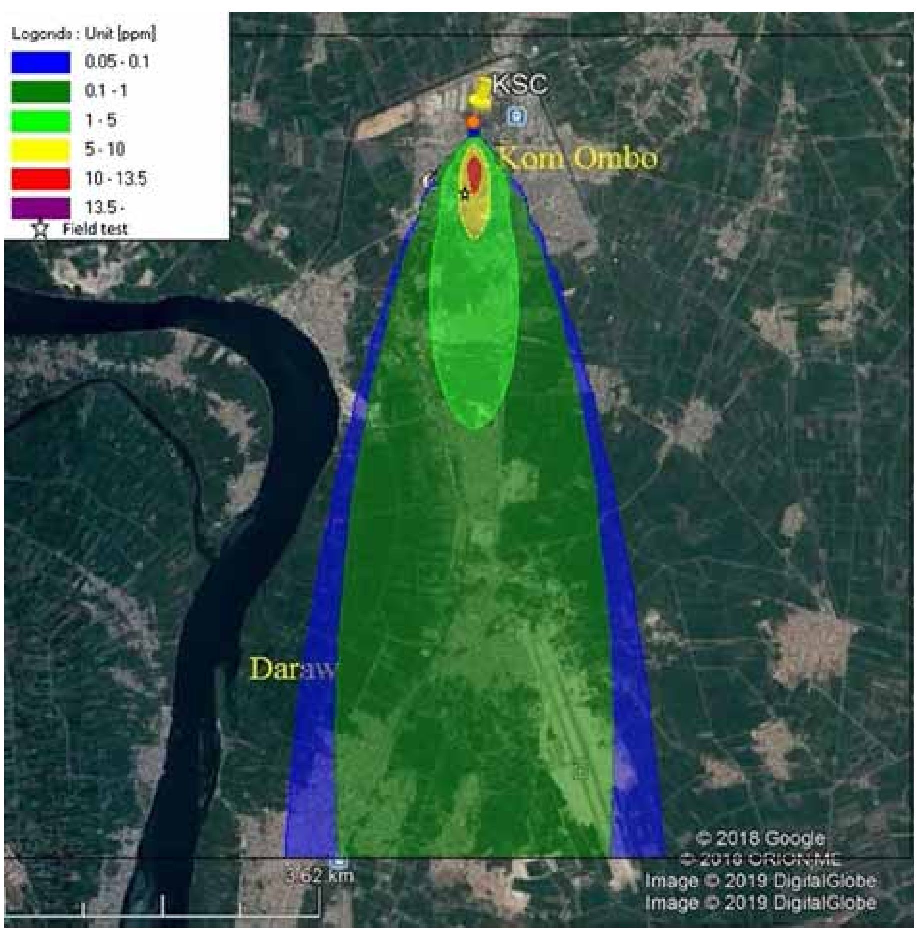

Figure 8. Distribution of the average concentration of Co in 24-hr for Kom Ombo sugarcane plant in February 2017, when the wind direction was northerly. The symbol of orange circle represents the point source, and the blue square is the building; the star symbol refers to the measurement location in the ambient air at about 9 ppmv.

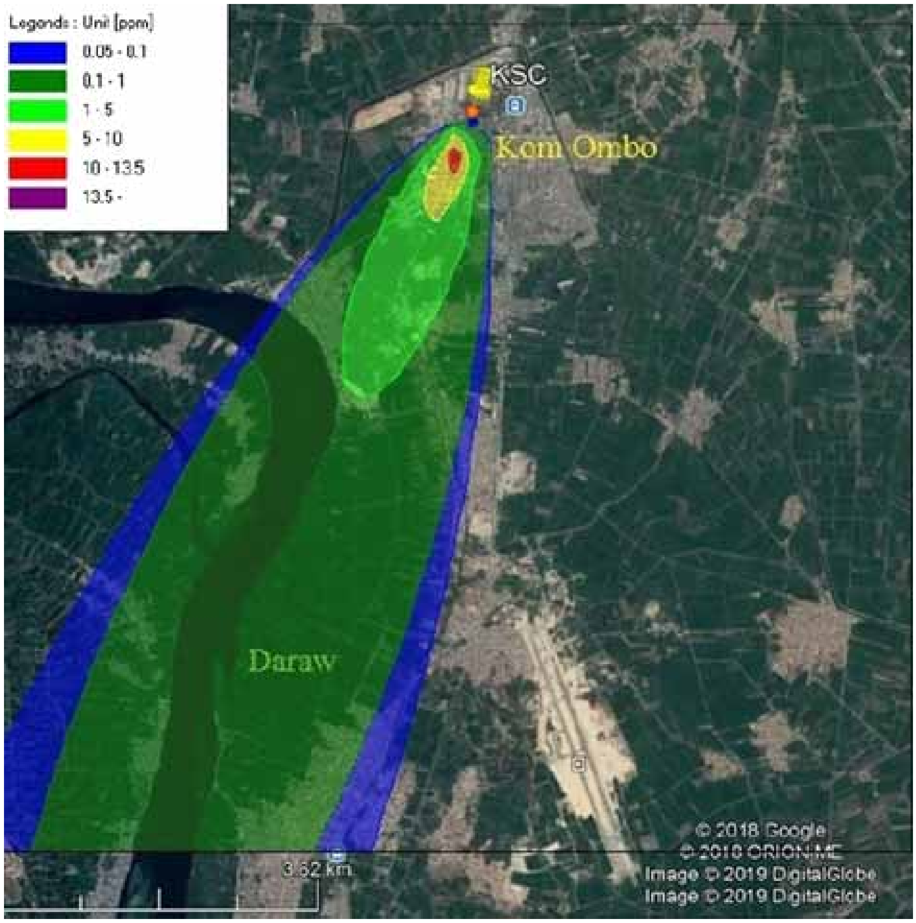

Figure 9. Model simulated distribution of the average concentration of CO in 24-hr for Kom Ombo sugarcane plant in March 2017, when the wind direction was north-easterly. The orange colour circle represents the point source, and the blue square is the building.

4.4 *Dispersion model for Kom Ombo SCF*

Kom Ombo SCF is situated in Kom Ombo city, Aswan governorate as seen in Advanced Spaceborne Thermal Emission and Reflection (ASTER) data. In this image, the residential area appears in bluish-gray colour, and water bodies in black. However, the agricultural areas appear in red (figure 6). The people in the residential area near Kom Ombo SCF can be affected by higher concentrations of CO. Thus, the METI-LIS model has been utilized to predict areas prone to high CO concentration and its impact on local air quality. This is to define the area where higher CO concentrations would occur under the influence of stack emissions. The selected area for the METI-LIS dispersion simulation of CO in Kom Ombo city is about 1 km × 1 km for a short-term (24-hr), which involves the point source of emission (chimney).

According to a daily report of early warning management in Egyptian Environmental Affairs Agency (EEAA), the weather factors during February and March (2017) in Kom Ombo city helped to concentrate pollutants, especially during the night, due to poor ventilation. Therefore, METI-LIS dispersion simulation of CO emissions is being done throughout this period. The essential data used by the METI-LIS model in the present study are wind-direction and speed, height of the chimney, and rate of emission. The detected wind direction in February and March 2017 is north and north–northeast, and the wind-speed for N and NE are 3.1 and 2.6 m/s, respectively (figure 7). The measured stack height of Kom Ombo sugarcane factory (point source) is about 45 m. Moreover, the present study revealed that the measured volumetric flow rate of stack in Kom Ombo factory is about 38106 m^3/min, but the emission rate for CO pollutants from bagasse fuel in Kom Ombo factory calculates as follows; emission rate = 38106 $m^3/min \times 2424\ mg/Nm^3 \times 60\ min/hr/10^6 =$ 5542 kg/hr.

Figures 8 and 9 explain the dispersion of average CO concentration within 24-hr (February–March) around Kom Ombo sugarcane factory, as calculated by METI-LIS model. The symbol of orange circle (24°28′56.38″N; 32°56′33″E) represents the source point of gaseous emission from Kom Ombo SCF.

Average CO concentration during the 24-hr around the area of SCF of Kom Ombo in February and March (2017) range from 0.05 to >10 ppmv. The expected average maximum concentration of CO in February is 13.5 ppmv, at a distance of 390 m downwind from the source point inside the zone of red colour. However, the average minimum concentration is 0.05 ppmv at a distance of 73 m from the source inside the zone of blue colour (figure 8). In March, the average maximum concentration of CO is 13.3 ppmv at a distance of 650 m downwind from the point source inside the red zone, as well as an average minimum concentration of 0.05 ppmv near the source point (figure 9). Noteworthily, the average maximum concentration of CO is high in February, due to weather factors and poor ventilation. Based on the results described above, the average maximum concentration of CO ~ 13 ppmv relatively exceeded permissible limits of Egyptian environmental law (10 mg/m^3 averaged over 8 hrs). The daily dispersion plume of CO emission calculated by METI-LIS model proved that people living in areas close to the Kom Ombo SCF, especially the areas located south and west (red colour zone) of the plant in downwind, are exposed to high concentrations of CO compared to the rest of the citizens.

According to personal communications of Chest Hospital in Kom Ombo city, many people living in the vicinity of the Kom Ombo SCF suffer from respiratory diseases, as people exposed to CO concentrations of 13.5 ppmv in ambient air lead to cognitive effects (altered time discrimination, learning, attention level, and driving performance), brain electrical activity, and neuro-behavioral/cognitive changes (WHO 1999) and EPA (2000, 2009). El Edessy *et al.* (2012) evaluated the effects of ambient air pollution by CO and PM_{10} in the Kom Ombo region of Aswan governorate. Six hundred pregnant women were categorized into two groups. The first group (patient group) consisted of 300 women residing in the zone of high risk area, and the second group (control group) contained 300 women settled in the non-polluted area. The results showed that people belonging to the first group were in danger of developing anemia, chest diseases, urinary tract infections, premature rupture of membranes, pregnancy-induced hypertension, and pre-term labor compared to the second group.

5. Conclusions

In this article, six sugarcane factories (SCFs) were studied in southern Egypt to assess air pollution caused by gaseous emissions (CO, SO_2 and NO_X), along with the release of soot and dust, and fly ash from the boiler stacks into the atmosphere during steam generation. Several samples of CO, SO_2, and NO_X were measured from SCF stacks during the operation season (January–April). The studied factories used various kinds of fuel, including bagasse, natural gas, and a mixture of them. The results showed the utilization of bagasse fuel in sugarcane factories emitted higher levels of CO emissions (e.g., Kom Ombo SCF; 3030 mg/Nm^3) than those using baggase + gas (Idfu; 555 mg/Nm^3) and natural gas only (Qus; 169.2 mg/Nm^3). The use of old technologic components of boilers in the studied sugarcane factories led to the imperfect burning of bagasse fuel. Although bagasse has low sulfur and nitrogen content, adding heavy oil or natural gas has improved the burning efficiency and minimized CO emissions, but relatively elevated NO_X (e.g., Idfu factory (149.7 mg/Nm^3)). In addition to estimating gaseous emissions, the distribution of the CO in the ambient air in residential areas was predicted using the METI-LIS model. The simulated mode showed the average maximum ambient concentrations of CO during the 24-hr at a distance of 390 m and 650 m from Kom Ombo SCF plant in residential areas during February and March (2017) are higher (>13 ppmv) than permissible limits of Egyptian environmental law. Based on the results of the model, we suggest many ways to reduce the emissions of CO such as (a) moving the residential areas about 1 km from Kom Ombo SCF, particularly to the south and west; (b) utilizing natural gas instead of bagasse; (c) operating automatic networks for continuous monitoring CO emission in the ambient air of the residential areas; (d) Egyptian Environmental Affairs should ensure that the SCFs meet the regulations of Egyptian Environmental law.

Acknowledgements

The authors would like to thank the editors and anonymous reviewers for their constructive comments, which helped us to improve the manuscript. The authors would also like to extend their sincere appreciation to Prof. Abbas Mansour, Professor of Environmental Geology and Former President of South Valley University for the support.

References

Abdelkareem M and El-Baz F 2017 Remote sensing of Paleodrainage systems west of the Nile River, Egypt; *Geocarto Int.* **32(5)** 541–555.

Abdelkareem M and El-Baz F 2015 Regional view of a trans-African drainage system; *J. Adv. Res.* **6** 433–439.

Agarwal A K and Sharma M 2006 Design improvements in the furnace of Khandsari industry for air pollution prevention and control; *Clean Air* **7** 1–17.

Agency for Toxic Substances and Disease Registry (ATSDR) 2012 Toxicological profile for carbon monoxide; Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service, 347p.

Aiman S and Stonington J F 1993 The pyrolysis kinetics of bagasse at low heating rates; *Biomass Bioenergy* **5(2)** 113–120.

Arnedo-Pena A, García-Marcos L, Carvajal Urueña I, Busquets Monge R, Morales Suárez-Varela M, Miner Canflanca I, Batlles Garrido J, Blanco Quirós A, López-Silvarrey Varela A, García Hernández G, Aguinaga Ontoso I and González Díaz C 2009 Air pollution and recent symptoms of asthma, allergic rhinitis, and atopic eczema in school children aged between 6 and 7 years; *Arch. Bronconeumol.* **45** 224–229.

Aswan Metrological Station 2015 The Metrological Data at Aswan Meteorological Station.

Bio Energy Consult (BEC) 2014 Powering clean energy future, energy potential of bagasse (http://bioenergyconsult.com/energy-potential-bagasse/).

Botha T and Blottnitz H 2006 A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life cycle basis; *Energy Policy* **34** 2654–2661.

Chauhan M K, Chaudhary V S and Samar S K 2011 Life cycle assessment of sugar industry: A review; *J. Renew. Sustain. Energy* **15(7)** 3445–3453.

Cheesman O 2004 *Environmental impacts of sugar production: The cultivation and processing of sugarcane and sugar beet*; United Kingdom, CABI International, 255p.

Economic and Social Commission for Western Asia (ESCWA) 2009 Increasing the competitiveness of small and medium-sized enterprises through the use of environmentally sound technologies; Assessing the potential for the development of second-generation bio fuels in the ESCWA region, United Nations, New York, 81p.

Egypt state of the environment report 2009, 382p. http://www.eeaa.gov.eg/english/reports/SoE2010En/Egypt%20State%20of%20Environment%20Report%202009.pdf.

El Edessy M S, Ali A M, Nasr A A and Najar M 2012 Effect of air pollution on maternal outcome in Upper Egypt; *AAMJ* **10(3)** 1.

El Haggar S M and El Gowini M M 2005 Comparative analysis of alternative fuels for sugarcane industry in Egypt; *1st Ain Shams International Conference on Environmental Engineering*, 9-11/4/2005, Cairo, Egypt.

El Haggar S, Ali B and Nakhla D A 2014 Achieving environmental sustainability of sugarcane industry in Egypt; An application of life cycle assessment, Ph.D. Thesis, School of Sciences and Engineering, American University in Cairo, 220p.

EPA 2000 Air quality criteria for carbon monoxide; Washington, DC: U.S. Environmental Protection Agency, EPA600P66001F, http://www.epa.gov/NCEA/pdfs/coaqcd.pdf.

EPA 2009 Integrated science assessment for carbon monoxide-first external review draft; Research Triangle Park, NC: U.S. Environmental Protection Agency, EPA600R09019.

Hindy K T 1991 Contribution of cane bagasse used as a fuel in the sugar industry to changes in outdoor and indoor air quality in middle Egypt; *Atmos. Environ.* **25(3)** 407–513.

Janghathaikul D and Gheewala S H 2005 Environmental assessment of power generation from bagasse at a sugar factory in Thailand; *Int. Energy J.* **6(1)**, Part 3.

Janghathaikul D and Gheewala S H 2006 Bagasse – A sustainable energy resource from sugar mills; *As. J. Energy Environ.* **7(03)** 356–366.

Jenkins G H 1966 *Introduction to Cane Sugar Technology*; Elsevier; Amsterdam, 496p.

Kannan S, Misra D P, Dvonch J T and Krishnakumar A 2006 Exposures to air borne particulate matter and adverse perinatal outcomes: A biologically plausible mechanistic framework for exploring potential effect modification by nutrition; *Environ. Health Percept.* **114** 1636–1642.

Kazanc F, Khatami R, Manoel Crnkovic P and Levendis Y A 2011 Emissions of NO_x and SO_2 from coals of various ranks, bagasse, and coal-bagasse blends burning in O_2/N_2 and O_2/CO_2 environments; *Energy Fuel.* **25(7)** 2850–2861.

Kouchi A, Okabayashi K, Okamoto S, Yoshikado H, Yamamoto S, Kobayashi K, Ono N and Koizumi M 2004 Development of a low-rise industrial source dispersion model (METI-LIS model); *Int. J. Environ. Pollut.* **21** 325–338.

METI 2006 Low rise industrial source dispersion model METI-LIS Model Ver. 2.03, Operation Manual, Ministry of Economy, Trade and Industry, 89p.

Nemerow N L 1995 Zero pollution for industry: Waste minimization through industrial complexes, United States; John Wiley and Sons, 240p.

Purohit P and Michaelowa A 2007 CDM potential of bagasse cogeneration in India; *Energ Policy* **35** 4779–4798.

Rainey T, Pennisi S and Joyce J 2004 Applying computational fluid dynamics modelling to optimize environmental performance at minimum cost; Proceedings from 58th Appita Annual Conference and Exhibition Incorporating the Pan Pacific Conference. Australia, pp. 239–243.

Ren X, Sun R, Meng X, Vorobiev N, Schiemann M and Levendis A 2017 Carbon, sulfur and nitrogen oxide emissions from combustion of pulverized raw and torrefied biomass; *Fuel* **188** 310–323.

Seinfeld J H and Pandis S N 2006 Atmospheric chemistry and physics: From air pollution to climate change; 2nd edn, Wiley-Interscience Publication, USA.

Shalaby E A, Ghatass Z F and Awad K S 2017 Study on air quality around cane sugar Factory, Kom Ombo City; M.Sc. Thesis, Department of Environmental Studies, Alexandria University, Egypt, 109p.

Simkhovich B Z, Kleinman M T and Kloner R A 2008 Air pollution and cardiovascular injury epidemiology, toxicology, and mechanisms; *J. Am. Coll. Cardiol.* **52** 719–726.

Solomon S K 2005 Environmental pollution and its management in sugar industry in India: An appraisal; *Sugar Tech.* **7(1)** 77–81.

Sutton O G 1932 A theory of eddy diffusion in the atmosphere; *Proc. Roy. Soc. London A* **135** 143–165.

Sutton O G 1947 The theoretical distribution of airborne pollution from factory chimneys; *Quart. J. Roy. Meteor. Soc.* **73** 426–436.

Turner D B 1994 *Workbook of atmospheric dispersion estimates: An introduction to dispersion modeling* (2^{nd} edn), CRC Press, 192p.

Turner D B 1967 Workbook of atmospheric dispersion estimates; U.S. Department of Health Education and Welfare, Public Health Service Division. Public Health Service, National Air Pollution Control Administration, Cincinnati, Ohio, 95p.

US Environmental Protection Agency (EPA) 1987 Background Information Document for Small Steam Generating Units; Research Triangle Park, NC 450/3-87-000.

US Environmental Protection Agency 1982 Non fossil fuel fired industrial boilers – background information; Research Triangle Park, NC, EPA-450/3-82-007.

UNDP 2000 Bioenergy Primer United Nations Development Program UNDP; http://www.undp.org/energy/publications/2000/2000b.htm.

United States Environmental Protection Agency, EPA.TTN-Web – Technology Transfer Network National Ambient Air Quality Standards, http://www3.epa.gov/ttn/naaqs/.

WHO 1999 Environmental health criteria 213. Carbon monoxide. World Health Organization; http://www.inchem.org/documents/ehc/ehc/ehc213.htm.

World Alliance for Decentralized Energy (WADE) 2004 Bagasse Cogeneration – Global Review and Potential; Scotland, United Kingdom.

Ziaei S, Nouri K and Kazemnejad A 2005 Effects of carbon monoxide air pollution in pregnancy on neonatal nucleated red blood cells; *Paediatr. Perinat. Epidemiol.* **19** 27–30.

Zimwara D, Mugwagwa L and Nherera K 2013 Soft computing methods for predicting environmental quality: A case study of the Zimbabwe sugar processing industry; *J. US–China Public Administration* **10(4)** 345–357.

Corresponding editor: Suresh Babu