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Air quality mapping using an e-nose system in Northwestern Turkey

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Abstract. A gas sensor based electronic nose system is developed for monitoring air quality dispersion in and around livestock barns. The mobile system can be used in various applications under laboratory and field conditions. The system consists of 10 metal oxide Figaro gas sensors and a temperature/humidity sensor integrated with custom made circuits and data acquisition software. The sensors are sensitive to major odorous compounds. The e-nose system provides an easy, cost effective and user friendly tool for air quality monitoring. There is a relationship with sensor responses and gas concentrations are linear. Therefore, instead of calculating concentrations using statistical methods such as PCA and ANNs raw sensor data is used to monitor air quality. In order to monitor spatial distributions of sensor responses Kriging method is applied. Interpolation maps for each sensor response are developed. In order to visualize the areas where air quality problems occur, response of an air quality module is used as reference. Results showed the effectiveness of the developed system and method.

Key words: Gas sensors, electronic nose, environmental quality, livestock housing, air quality.

INTRODUCTION

Odour generated from livestock buildings is considered to be one of the most important air quality problems in agricultural production systems. Air quality problems are not only an issue of nuisance it can also have effects on human/animal health by direct irritation or psychopathologic mechanisms (Schiffman & Williams, 2005). Therefore, measurement or evaluation of air quality problems associated with livestock odour is highly critical. However, there are still science-based approaches needed to evaluate air quality and related control technologies (Zhang et al., 2001). One of the most common techniques used to evaluate air quality related odour concentration is olfactometry. The olfactometers are used to gauge odour detection thresholds of substances. This technique employs human panellists in laboratory settings. The results are subjective to the panellists' senses (Powers & Bastyr, 2004).

Livestock odour is a mixture of various compounds and intensity of overall odour is not simply sum of all compounds since they interact with each other making the air quality assessment more complicated and complex (O'Neill & Philips, 1992; Schiffman et al., 2001; Zahn et al., 2001¸ Pan & Yang, 2007). Most of the odorous compounds are monitored with highly expensive systems. It is possible to conduct well comparable and controlled measurements with these technologies. However, it is not possible to monitor spatial distributions of air pollutants. Measurement of concentrations of only some components is not always enough to assess the air quality problem (Kaur et al., 2007).

There have been a great deal of effort to develop cost effective and mobile air quality monitoring devices that employ low-cost gas sensors integrated with navigation devices and mobile phones (Elen et al., 2012). There are applications of mobile devices used to acquire urban air quality data at a high temporal resolution. Also, use of mobile devices in such applications makes it possible to assess spatial variations of pollutants for short term studies which are not possible with stationary measurements (Westerdahl et al., 2005; Peters et al., 2012).

Electronic nose systems have been used as an alternative for non-invasive online monitoring of air quality issues especially related to biological processes (Bachinger & Haugen 2002). They can provide a signal that could be used to obtain information on various compounds (Romain et al., 2004). An e-nose also could be used to better understand odour release (Nicolas et al., 2001) because of their mobility and compactness. However, the cost of commercial and sophisticated e-nose systems is still high (Yin & Zhang 2016). Also, importing these systems to developing countries such as Turkey increases the cost considerably. Another shortcoming of using commercial systems is their easiness of use. They generally employ software or data management tools that are not user-friendly. Hence, there is a strong need to develop mobile and cost-effective (Jasinski et al., 2015), and user-friendly systems that is integrated with software written in native language, in our case Turkish.

In the development of e-nose systems gas sensors are used because of their high analytical performance and reasonable costs (Nenov & Yordanov, 1996). These sensors generate a current response signal that is proportional to ambient gas concentration. The relationship between sensor response and gas concentration is linear (Kızıl et al., 2000; Jasinski et al., 2015). In this study it was aimed to develop a mobile device and method that is applicable to on-site air quality monitoring based on the principle of this linear relationship. Development of e-nose system explained and a case study was conducted to evaluate the performance of the system.

MATERIALS AND METHODS

Study site

Aşağıokçular village (Fig. 1) is located in the North-western coastal province of Çanakkale, Turkey at 40° 3'N and 26° 27'E. The village is 14 km from the Çanakkale province, and 8 km from Kepez district. The economy is mainly based on agriculture. The province and districts' population have been increasing in recent years threatening the Aşağıokçular's agricultural land. There are poultry operations located nearby the village causing odour problems. Odour from a poultry operation housing total of 75,000 broilers in three deep-litter houses assessed. Rice hull, capable of absorbing moisture, is used as bedding and litter material. Charcoal is used within the heating system. Fan-pad evaporating cooling system is used in air conditioning.

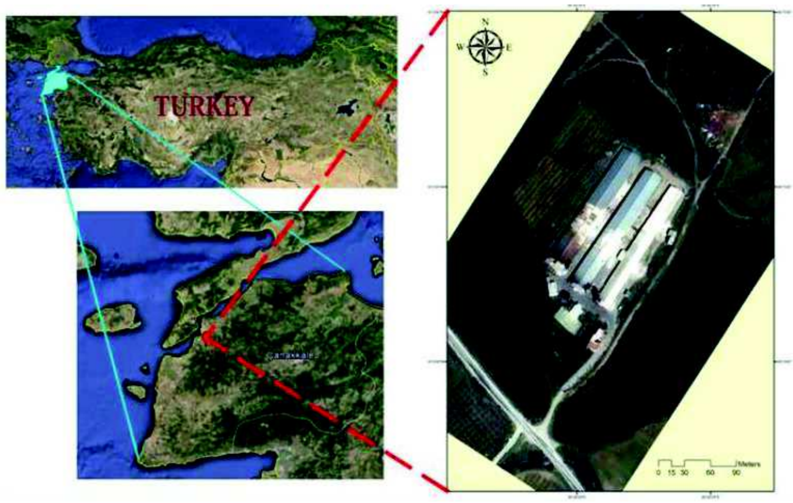

Figure 1. Study area and poultry operation.

The e-nose system

Kızıl et al. (2015a) developed an e-nose system consisting of main body (housing the sensor array, circuits and associated electronics), a desktop computer (software), a sample container, and purge gas unit. The system was designed to identify *Salmonella enterica* in poultry manure under laboratory conditions, and it was starting point for us to develop a new version to be used in monitoring of outdoor air quality. Both old and new versions are equipped with metal-oxide gas sensors (Figaro Engineering, Inc., Osaka, Japan). The metal-oxide gas sensors have low electrical conductivity in clean air. As they are exposed to odorous compounds their resistance changes resulting in more electrons to flow. By monitoring the change in the conductivity, concentrations of the odorous compounds can be evaluated. In its first version the e-nose system wasn't mobile and capable of being used in odour identification. Detailed technical information about sensors and other electronics is provided in Kızıl et al (2015a). The new version was developed to evaluate the potential use of this system in the assessment of air quality.

The system employs a sensor array requiring 5 V power for each sensor. Depending on the chemical characteristics of ambient air, output signals of each sensors range from 0.1 to 5 V. The sensor responses were acquired and released using a PIC16F877A microprocessor (Microchip Technology Inc., Chandler, Arizona, USA). Initially, we used two 18650 type batteries to power up the sensor array and data acquisition system, and three of same type batteries to power up micro air pump (Xavitech Intelligent Pumps, Härnösand, Sweden). This unregulated power unit was causing quick discharge of batteries. Then, two 18650 type power banks that provide regulated current were integrated to the system. These power banks are comprised of four 18,650 type special batteries with a circuit to control power flow. The output current-limiting protection avoids possible damages when overloaded. They operate with a charging input of 5V / 1A, and output of 5V / 3A. A DC to DC step-up converter was used with one of the power banks since the micro air pump requires 12 V power supply. The new version of the e-nose system is shown in Fig. 2.

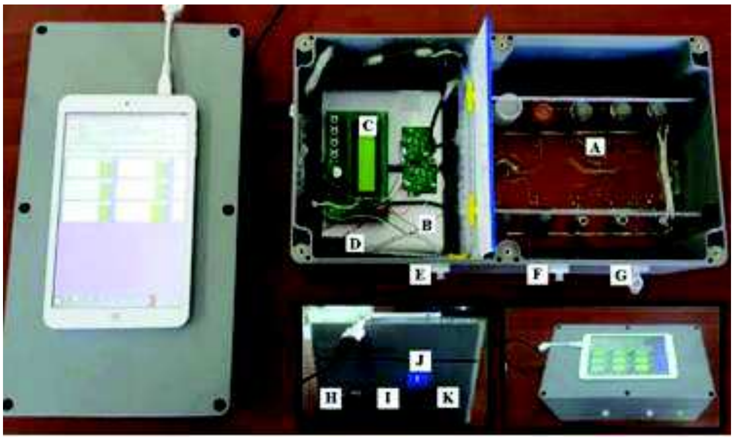

Figure 2. Modified e-nose system [A: sensor array, B: power bank, C: micro pump control unit, D: micro pump, E: sample air inlet, F: sample air outlet (reference gas inlet if needed), G: reference gas outlet (if needed), H: USB 4 port to tablet PC, I: sensor array power switch and USB charging port, J: power indicator LEDs, and K: micro pump power switch and USB charging port].

The e-nose has one main air inlet. The micro pump purges the odorous air sample from air inlet (E) to the sensor compartment. Air sample then leaves the system through outlet (F) due to the pressure difference caused by the micro pump. In some cases, especially in laboratory applications, a reference gas should be purged into the system. In such cases, outlet (F) serves as reference gas inlet. The reference gas will leave the system through outlet (G). Depending on the application, pump flow rate can be adjusted via control unit (C) by changing the pump frequency. The block diagram of the system is provided in Fig. 3.

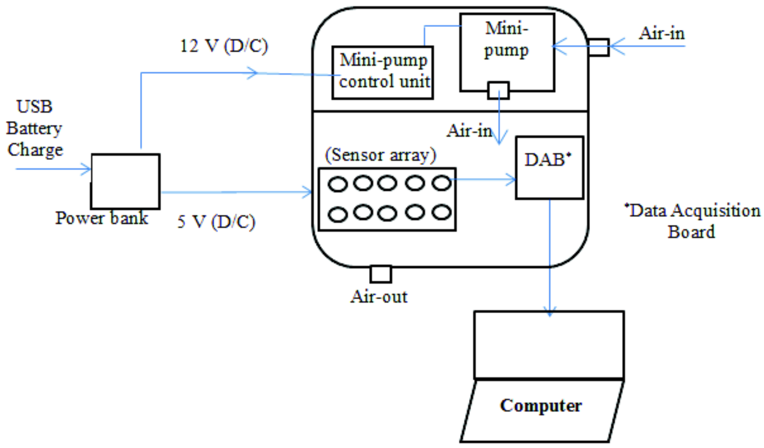

Figure 3. Block-diagram of the e-nose system.

In the graphical user interface (GUI) folder management and sampling options was handled. Once the sampling frequency, total number of sampling, and name and the location of reading file determined, software and micro air pump can be started simultaneously. The GUI allows monitoring real time sensor responses. The reading ends when the entered number of readings has been taken.

Experimental procedure

In order to verify the effectiveness of the e-nose system a field experiment was conducted. The e-nose was operated to determine the air quality conditions within a poultry operation where there are several odour sources such as three barns, two outdoor manure piles, an incineration pit, a chemical barrel and charcoal ash storage areas. An aerial image of the area was obtained from Google Maps application to determine the possible reading points. In the monitoring of wind velocity a handheld anemometer (Trotec GmbH&Co. KG, Heinsberg, Germany) that is capable of sensing ambient air temperature was used. Field measurements were conducted at 50 reading points. The readings were not collected simultaneously and the total duration of the experiment was about 3.5 h. Experiment was conducted in May. The coordinates of the reading points were recorded to be later used in GIS environment by a Garmin GPSMap 60CSx model GPS device (Garmin International Inc., Olathe, KS, USA). While at each point, e-nose readings, ambient air velocity and temperature, and coordinates were recorded. All the data collected by e-nose, GPS unit, and anemometer were used to develop GIS database in ArcGIS 10.3.1 software (ESRI, Redlands, CA, USA).

In air quality, especially odour, studies a reference method is used to evaluate the performance of the used or developed technique/method such as olfactometer or gas chromatography (GC). In this study, a Figaro AM-1-2600 (Figaro Engineering, Inc., Osaka, Japan) model air quality sensor module was used as the reference method. This module uses an air contaminant gas sensor and a microcomputer to measure the actual contamination levels. The air quality module was integrated with TD-200 (Paradox Security Systems, Istanbul, Turkey) dual tone, multi-frequency signalling system (DTMF) (Kızıl et al., 2015b).

Sensor responses under non-odorous, clean air conditions were determined using above mentioned air quality module. The microprocessor within the air quality module receives the output signal from the sensor and creates a benchmark level. In this study air quality conditions in a well ventilated non-odorous room was considered to be reference benchmark for each sensor. Both air quality module and e-nose system operated in a well ventilated room as the non-odorous conditions maintained. Response of each sensor within the e-nose was monitored and base-line non-odorous conditions were determined for all sensors.

Data processing

As the e-nose starts operating, it collects pre-determined number of readings at an entered frequency. At total of 50 points e-nose responses were recorded around the poultry operation. The data consisted of date and time of sensor readings, sensor responses in Volt, and temperature and relative humidity of the sensor compartment in MS Excel format. Initially, in e-nose systems a reference condition is obtained by exposing the sensor to a reference air (clean, non-odorous air). Non-odorous reference condition is a typical measurement in non-odorous ventilated room. Then, the sensors are exposed to odorous air or headspace gas of the sampled material. This creates a sensor response curve for each reading. In this study we used raw sensor response data. The major goal of this study was to spatially monitor the response of gas sensors that are reactive to certain air pollutants instead of measuring exact gas concentrations. The reason for this approach is that relationship between the sensor response and gas concentration is linear, as explained above. At each point the e-nose recorded 20 readings with a recording interval of 5 seconds. In order to monitor spatial distribution of air quality, a unique value representing each point for each sensor required. Plot of sensor readings showed that there are only minimal fluctuations observed during recording period at each point due to the change of wind conditions. Sample plots of all sensors will be given in the following section of the study. Average of 20 readings at each point was considered to be sensor response. Of those 10 gas sensors only 6 responded sampled air. Those sensors and corresponding target gases are; TGS 813 (CH_4, C_3H_8), TGS 822 (volatile organic compounds), TGS 825 (H_2S), TGS 826 (NH_3), TGS 2600 (H_2, CO), and TGS 2602 (NH_3, H_2S). Remainder yielded either extreme fluctuations or no response to odorous air samples. Polar compounds such as water vapour may cause these fluctuations (Balasubramanian et al., 2004). Once the averages of each sensor responses at each point were calculated, a point shape file overlaying on the aerial image of the experimental area was created in ArcGIS for further spatial analysis (Fig. 4). In the figure, green points represent the e-nose reading locations.

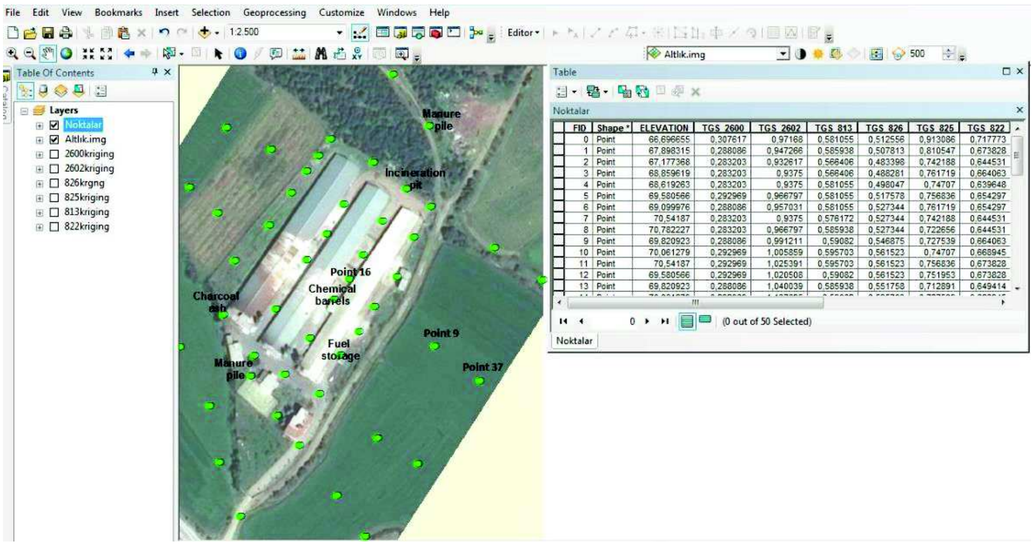

Figure 4. GIS database.

In the initial evaluation, 4 reading points which are within varying distances from the barns were selected (Fig. 4). Point 16 was selected in between 2 barns where there are ventilation fans operating, and protected from the prevailing wind. Point 9 is also close to barn where concentrations of odorous compounds are less than point 16 due to its location. Point 37 was located about 100 m east of the barn. In order to spatially visualize overall sensors' response, Kriging method was applied. This method is more applicable in terms of monitoring spatial distribution of air quality data (Ball et al., 2008). In this method, a value is predicted based on a trend that all values of known points follow and an additional element of variability (Kizil & Tisor 2011). Kriging uses a semi-variogram model to express the spatial dependence of each point. A semi-variogram model can be expressed as follows (Delhomme, 1983).

$$\lambda(d_{mn}) = \frac{1}{2N}\sum_{1}^{N}[(r_m - r_n)^2] \quad (1)$$

where; $\lambda(dmn)$ is the semi-variogram for the points P_m and P_n sensor readings r_m and r_n, d is the lag distance, and N is the number of pairs of reading points. Spherical, circular, exponential, and Gaussian, models are some of the mostly used semi-variogram models (Christakos, 1984). In this study, these models were applied to generate raster interpolation of each sensor response. Once the Kriging interpolations are developed, the best model that yields the smallest root-mean-square error (RMSE) was chosen as the semi-variogram model. Entire experimental study and data processing steps are illustrated in Fig. 5.

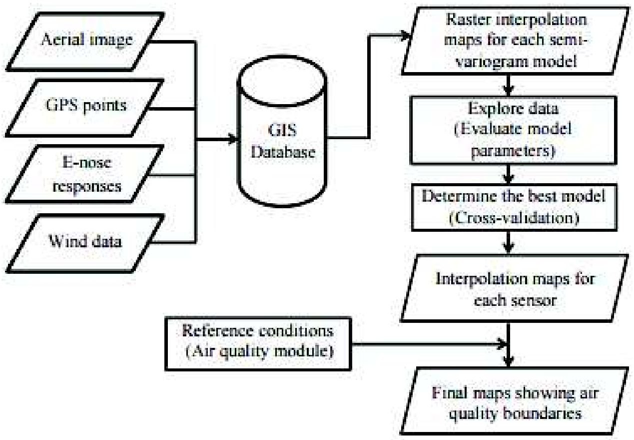

Figure 5. Schematic representation of experimental study and data processing.

RESULTS AND DISCUSSION

The sensors employed within the e-nose system are sensitive to chemical classes like alcohols or general combustible gases (Romain et al., 2004) that make each sensor sensitive to a variety of chemical compounds. Spatial distributions of each sensor response were monitored as a method to assess the surrounding air quality rather than monitoring overall odour which is a subjective method. Once the database was created responses of each sensor were compared. Readings form 3 different locations that are within various distances from the barns were collected (Fig. 4). Responses of each sensor at these locations were plotted in Fig. 6. As it was expected, sensor responses get larger values as the sampling location gets closer to barns. Considering the fact that there is a linear relationship between sensor responses and gas concentrations, e–nose readings can be used in air quality monitoring.

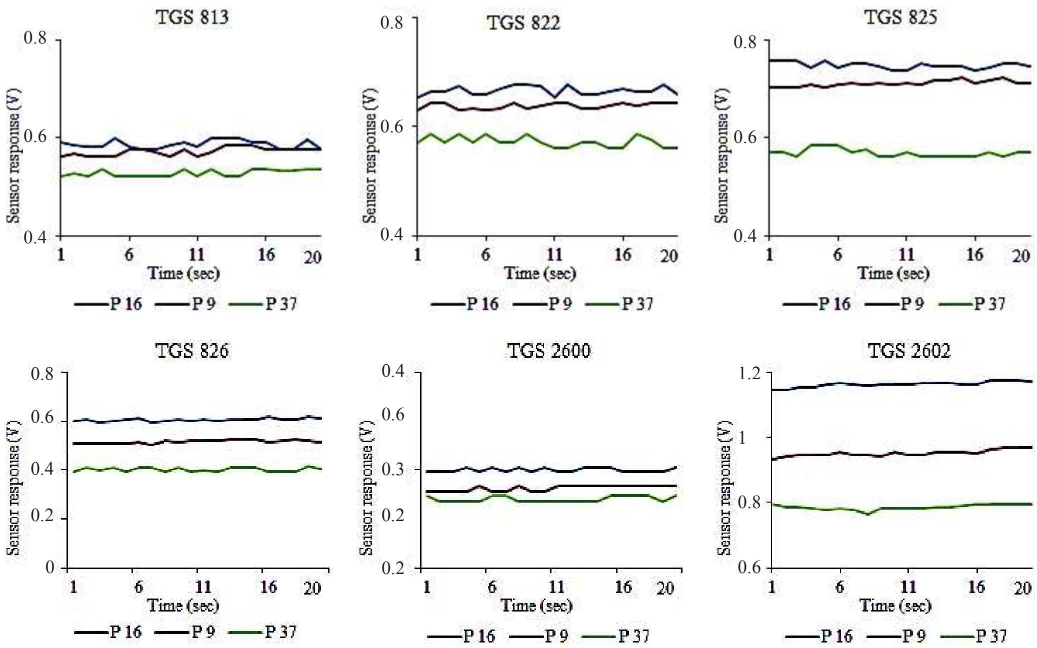

Figure 6. Sensor responses at 3 different locations.

Interpolation maps showing the spatial distributions of each sensor responses were created. In raster interpolation Geostatistical Analyst extension of ArcGIS software was used. The e-nose and GPS data containing sensor responses and coordinates of each reading point were used. Root–mean–square errors of spherical, circular, exponential, and Gaussian semi– variogram models were compared via cross-validation (Davis, 1987; Barton et al., 1999; Kizil & Tisor, 2011). This method is used to determine the best model that predicts the sensor response of unknown points in the creation of interpolation maps. The model predicts the sensor response value of a known point using the entire dataset and then compares the predicted value with actual value yielding a RMSE. The cross-validation results including RMSEs and other statistics are shown in Table 1. The cross-validation results show that of 4 models Gaussian is the best with lowest RMSE for all sensor responses.

Table 1. Cross – validation results for all sensors

	TGS 813			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00097	0.00104	0.00143	0.00091
RMS	**0.01406**	**0.01067**	**0.01075**	**0.00946**
AS	0.01538	0.01506	0.01773	0.01196
MS	0.03838	0.04027	0.04900	0.05885
RMSS	0.67420	0.70530	0.50160	0.88450

Table 1 (continued)

	TGS 822			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00271	0.00222	0.00274	0,00193
RMS	**0.02154**	**0.02173**	**0.02167**	**0.02167**
AS	0.02542	0.02490	0.02887	0.02333
MS	0.06385	0.05129	0.05657	0.05311
RMSS	0.86900	0.90400	0.75510	1.00500
	TGS 825			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00352	0.00402	0.00488	0.00325
RMS	**0.04200**	**0.04307**	**0.04256**	**0.04130**
AS	0.04996	0.04904	0.05659	0.03900
MS	0.04063	0.04744	0.05079	0.06532
RMSS	0.85200	0.89310	0.74490	1.18400
	TGS 826			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00365	0.00315	0.00415	0.00323
RMS	**0.03219**	**0.03300**	**0.03397**	**0.03071**
AS	0.04690	0.04602	0.05395	0.04381
MS	0.04857	0.04310	0.04821	0.05055
RMSS	0.72010	0.74920	0.63660	0.77290
	TGS 2600			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00057	0.00052	0.00055	0.00055
RMS	**0.00652**	**0.00662**	**0.00639**	**0.00648**
AS	0.00757	0.00759	0.00774	0.00751
MS	0.05307	0.04885	0.04551	0.05299
RMSS	0.89150	0.90220	0.85040	0.90170
	TGS 2602			
Error	Spherical	Circular	Exponential	Gaussian
M	0.00581	0.00642	0.00685	0.00534
RMS	**0.05466**	**0.05578**	**0.05587**	**0.05309**
AS	0.08701	0.08658	0.09739	0.08423
MS	0.04144	0.03155	0.04419	0.04372
RMSS	0.66760	0.68120	0.61580	0.69570

M: mean; RMS: root-mean-square; AS: average standard; MS: mean standardized; RMSS: root-mean–square standardized.

The next step in the study was to visualize the areas where the sensor responses are below the reference threshold values. As explained above, response of AM–1–2600 air quality module under non-odorous, clean air conditions were used as the threshold values. It was observed that under non-odorous conditions sensor responses remain similar within a minimal deviation range depending on the temperature and humidity conditions. Average responses of each sensor under these conditions were determined as given in Table 2. All sensor responses above these values considered to be odorous conditions.

Table 2. Threshold sensor values for non-odorous conditions

Sensor	Reference sensor responses (V)
TGS 813	0.56
TGS 822	0.63
TGS 825	0.67
TGS 826	0.49
TGS 2600	0.27
TGS 2602	0.88

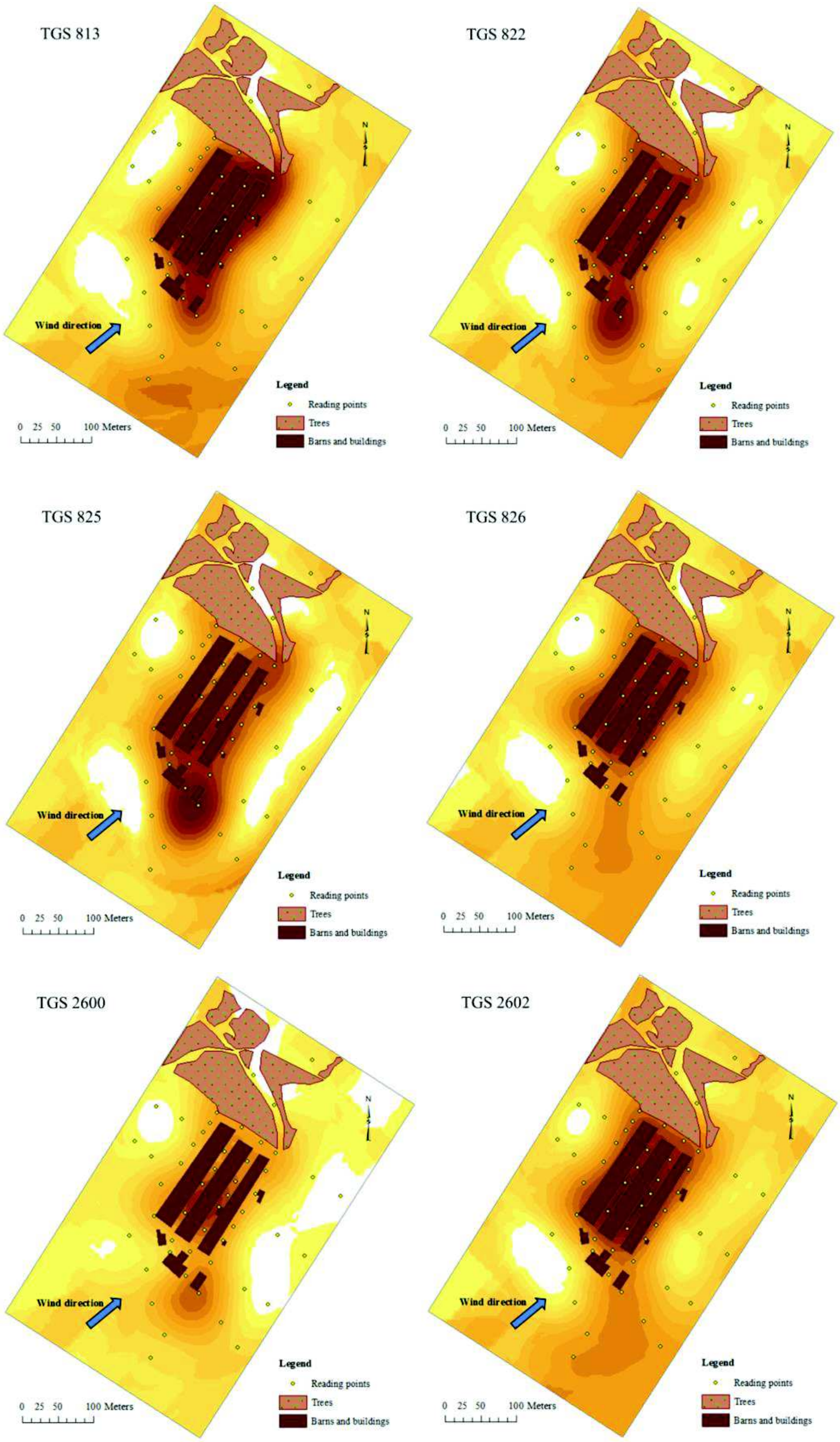

Figure 7. Air quality dispersion over the study area.

Finally, on the Kriging interpolations, areas where the sensor responses are below the threshold values were determined to be non-odorous areas. In Fig. 7, e-nose reading points, buildings, trees, and the interpolated responses of each sensor are represented. As expected, the sensor responses get larger values as they get closer to odour sources. The larger values were indicated with darker colours. On the interpolation maps areas where the sensor responses are below threshold values white-coloured. As it is clearly seen there are two white spots denoting non-odorous conditions on west-side of the barns and odour sources. Even though they are on downwind direction there are white areas on NE direction of the operation. This is because the trees that function as windbreak reducing the odour dispersion. White areas on the west of operation can be explained by the topography of the study area. Elevations of those areas are above the operation. The wind blows the odorous air in between the hill and barns creating a passage that moves odour beyond the operation. It was reported in ÇCAAP (2014) that the most frequent wind direction in study area is north-northeast (NNE) with a frequency of 35 to 50% during warm seasons. They also noted that, in the cold seasons of the location prevailing wind direction are southwest (SW) and south-southwest (SSW) which was observed during the study. Therefore, it could be concluded that depending on the season dispersion of odour will change shifting the direction of problem. The meteorological data of the study area is provided in Table 3 and Fig. 8 (MGM, 2016).

Table 3. Meteorological data of the study area

	Max.	Min.	Average
Temperature (°C)	39.0	-11.8	15.0
Wind speed (m s^{-1})	139.3		3.9

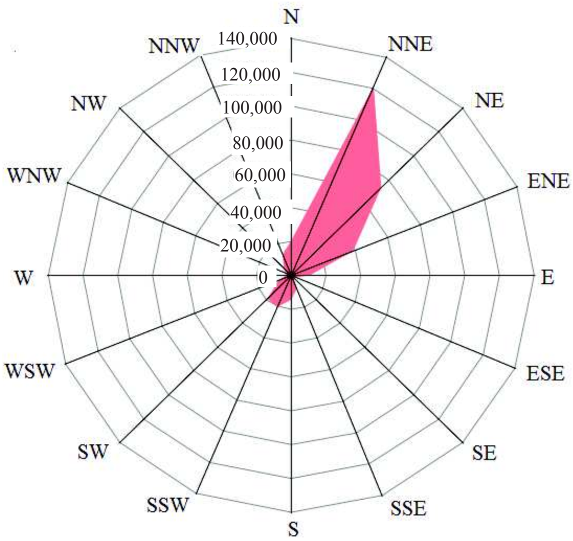

Figure 8. Wind rose of the study area.

CONCLUSIONS

Air sample readings were collected at poultry operation in Aşağıokçular village of Çanakkale, Turkey that included 3 deep-litter houses. In order to evaluate the potential use of an e-nose in air quality monitoring an e–nose containing metal-oxide gas sensors was developed. The major advantage of the e-nose system was its cost. The system employed a custom-made software and data acquisition board to acquire process and store the air quality data that made it cost-effective. The mobile e-nose system provides a user-friendly technique that could be used in various areas including air quality monitoring. With the e-nose system it was possible to visually monitor air quality dispersion within an area. It should be noted that e-nose readings were not collected simultaneously. Thus actual sensor responses at a given time may vary. Considering the fact that during the study meteorological conditions didn't vary a lot results were still a good representation of aerial conditions. In the current version of e-nose system reading locations are acquired via a separate GPS unit. In the next version a GPS sensor will be integrated with the hardware and software components of the system. The results demonstrated that gas sensors associated with relevant software can be used to monitor air quality within an area. However, sometimes concentrations of aerial pollutants must be identified. For such cases, it is possible to calibrate employed gas sensors to monitor odorous gas concentrations. In the next version it also planned to calibrate gas sensors for this purpose. Finally, it can be concluded that with current technology it is possible to monitor and evaluate air quality problems caused by livestock operations. Then, further action can be taken to eliminate and/or limit the air quality problems.

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