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Web-Based Environmental Monitoring System Design and Dust Concentration Modeling for Dairy Barns

Umut Efe YONAR[1] Buğra UYSAL[1] Ünal KIZIL[1*]

[1]Çanakkale Onsekiz Mart University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Çanakkale
***Corresponding author's email:** unal@comu.edu.tr

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Abstract: This study focuses on designing and evaluating a web-based environmental conditions monitoring system for dairy barns, targeting dust concentration and temperature/humidity levels. A prototype device integrating Arduino technology with GSM module was developed to enable real-time data transmission to a web-based platform. The system was tested in a small-scale dairy barn, where it effectively monitored dust, temperature, and humidity while calculating the Temperature Humidity Index (THI). Statistical analysis using multiple regression (MR) and artificial neural networks (ANN) revealed that temperature and humidity significantly influence dust concentrations, with both models achieving strong predictive performance (MR: R^2 = 0.7, ANN: R^2 = 0.71). These results indicate that both methods can accurately predict dust levels based on environmental conditions. This low-cost solution not only improves air quality monitoring but also offers a viable tool for controlling heat stress in dairy barns, enhancing animal welfare and productivity. The system's affordability makes it accessible for small family farms and adaptable for broader agricultural applications.

Keywords: Air quality, Arduino, dairy cattle, dust concentration, temperature humidity index.

Süt Sığırı Ahırları İçin Web Tabanlı Çevre İzleme Sistemi Tasarımı ve Toz Konsantrasyon Modellemesi

Öz: Bu çalışmada, süt ahırları için toz konsantrasyonu ve sıcaklık/nem seviyelerini ölçmeyi hedefleyen web tabanlı bir çevre koşulları izleme sistemi tasarımı ve değerlendirilmesi amaçlanmıştır. GSM modülüyle Arduino teknolojisini entegre eden bir prototip cihaz, web tabanlı bir platforma gerçek zamanlı veri iletimi sağlamak için geliştirilmiştir. Sistem, Sıcaklık Nem İndeksi'ni (SNI) hesaplayarak tozu, sıcaklığı ve nemi etkili bir şekilde izlediği küçük ölçekli bir süt sığırı ahırında test edilmiştir. Çoklu regresyon (ÇR) ve yapay sinir ağları (YSA) kullanılarak yapılan istatistiksel analiz, sıcaklık ve nemin toz konsantrasyonlarını önemli ölçüde etkilediğini ve her iki modelin de güçlü tahmin performansına ulaştığını ortaya koymuştur (YSA: R^2 = 0,7, YSA: R^2 = 0,71). Bu sonuçlar, her iki yöntemin de çevre koşullarına bağlı olarak toz seviyelerini doğru bir şekilde tahmin edebileceğini göstermektedir. Bu düşük maliyetli çözüm yalnızca hava kalitesi izlemeyi iyileştirmekle kalmayıp aynı zamanda süt ahırlarında ısı stresini kontrol etmek, hayvan refahını ve üretkenliğini artırmak için uygulanabilir bir araç sunmaktadır. Sistemin uygun fiyatlı olması, onu küçük aile çiftlikleri için erişilebilir ve daha geniş tarımsal uygulamalar için uyarlanabilir hale getirmektedir.

Anahtar kelimeler: Hava kalitesi, Arduino, süt sığırı, toz konsantrasyonu, sıcaklık nem indeksi.

1. Introduction

Sustainable production in livestock operations can be achieved where human-animal-environmental factors are considered. Environmental conditions affecting animals are of great importance in the quantity and quality of the product. Hence, parameters such as temperature, humidity, lighting and pollutant gas emissions are the most important environmental conditions. In a sustainable livestock enterprise, as well as fulfilling the environmental demands of the animals housed in barns, the negative effects of the animals on the environment during the production process must be taken into account.

Dairy cattle farming is the branch of livestock operations where the highest productivity loss due to inadequate indoor environmental conditions occur. The majority of dairy cattle operations Türkiye are small family enterprises with less than 50 dairy animals (Uzundumlu, 2012). Almost all of these operations have ventilation-related problems. Natural and/or mechanical ventilation systems are either not used or inadequate.

The environmental problems encountered in barns, especially in dairy cattle operations, are not limited to temperature and humidity, but indoor air quality also has significant effects on both the health and welfare of the animals kept and the health of the workers working in the operations. It is known that there are approximately 250,000 livestock operations and approximately 1 million workers employed in these enterprises in the United States alone. Since livestock barns are structures where concentrated pollutants are present and many animals are housed, the health risks they may pose are much higher than other structures (Tan & Zhang, 2004).

One of the most important pollutants in the indoor air of animal barns is particulate matter (PM). PM found in shelter air is almost entirely of biological and organic origin and consists of a mixture of feed, animal dander, feathers, urine, manure and many microorganisms (Harry, 1978; Carpenter, 1986). PM concentrations vary depending on animal species, barn type, feeding methods, animal density, how effectively cleaning is done, seasonal conditions and even time of day (Carpenter, 1986; Takai et al., 1997). It is known that bronchial diseases and inflammatory complaints occur as a result of breathing PM contaminated by endotoxins (Bakutis et al., 2004). Epidemiological studies conducted on farm animals have shown that long-term exposure to endotoxins causes chronic bronchitis and lung failure (Hartung, 1999).

Although the relationship between indoor dust concentration and ammonia/odor concentration has not been mathematically demonstrated (Hartung 1986, Williams 1989, Maghirang et al. 1991, Gay et al. 2003), there are studies showing that when any of these are controlled, the concentrations of the others are significantly reduced (Ullman et al. 2004). For example, it has been observed that odor-related problems are largely eliminated as a result of effective ventilation and removal of dust inside the shelter (Hartung, 1986, Burnet, 1969, Donham et al., 1986, Bottcher et al., 2000).

There are no specific standards regarding the upper permissible limits of dust emissions in shelters. However, OSHA (American Occupational Safety and Health Administration) recommends 15 mg m^{-3} as the total allowable dust concentration (Kirkhorn & Garry, 2000). Takai et al. (1997) stated the upper limit value of respirable dust concentration in barns as 0.38 mg m^{-3}.

There is no economical environmental monitoring and control system that can be used in small family operations Türkiye. A system that can be used especially for monitoring dust concentrations along with temperature and humidity is needed. The aim of this study is to design an on-site dust concentration and temperature/humidity monitoring device with the latest low-cost, easy-to-use and web-based data management system that can be easily accessed over the internet. The developed device can also be used in other agricultural structures.

2. Materials and Methods

2.1. Prototype and software development

Arduino microprocessor card was employed in the prototype. This board has a cost effective and high-capacity microprocessor that can easily integrate different sensors. It was chosen due to its ease of programming, ability to use MS Office applications and other technical features. This card, which can accommodate multiple sensors, be integrated with a touch screen, and provides its own software platform free of charge, provides a dynamic technology development opportunity.

The microprocessor card, the temperature/humidity and dust sensor integrated on it are low-cost technologies, and the data received from the sensors are stored and processed in the same environment and the results are made meaningful with the software developed. The GSM circuit has also been integrated into the system, allowing the data obtained to be transmitted to cloud data storage.

After procuring the necessary electronic material, the prototype system was designed by taking into account the dimensions and technical specifications of the material. The goal here was to bring together the microprocessor, sensors, GSM module and touch control screen on a main body of the smallest possible size. It was thought that if dusty air was pushed into the sensor with a mini air pump, dust would accumulate inside the pump and cause the pump to malfunction in a short time. Therefore, the active surface of the sensor was mounted on the top of the device in a way that it would be in constant contact with the air outside. A rechargeable battery unit was created by connecting two Li-ion 18650 batteries in series. It was used with a TP4056 battery charging module and a 5 V 1 amp DC power supply. The dimensions of the device are given in Figure 1.

The optical sensor integrated into the system is used to measure dust concentration (Sharp Corporation, Japan). There is an infrared transmitter and phototransistor on the sensor. It works by measuring the reflection of the emitted infrared ray from dust particles. The dust sensor, which has a very low current consumption (20mA max.) and can operate with a supply voltage of up to 7 V, has a sensitivity of 0.5 V $1mg^{-1}$ m^{-3} and provides analog voltage output proportional to the dust density. The Sharp GP2Y1010AU0F dust sensor generates an analog

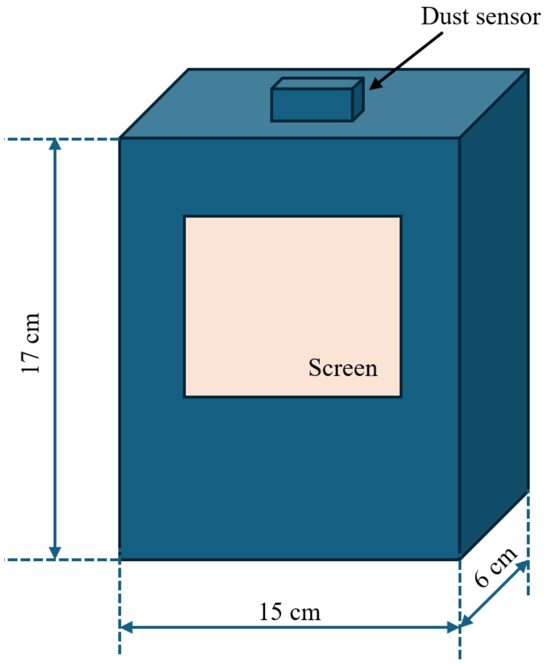

Figure 1. Dimensions of the prototype
Şekil 1. *Prototipin boyutları*

voltage output that corresponds to dust density. It is designed to deliver reliable measurements as shipped therefore calibration is not necessary (Sharp, 2024).

SHT11 temperature and humidity sensor was used to read and record the temperature and relative humidity values inside the barn (Sensirion AG, Staefa ZH, Switzerland). This sensor measures air temperature and relative humidity with high accuracy and sends it to the microprocessor unit. It is capable of preventing interference and data loss problems due to its single path connection and use of standard bandwidth signals. The SHT11 sensor is placed inside the box of the prototype device and its sensing component is suspended out of a small hole opened in the box. To ensure the reliability of the sensor data, it was fixed by soldering directly to the relevant terminals on the Arduino with 10-cm cables, as stated in the technical manual. Dust and temperature/humidity sensors are shown in Figure 3.

The operation of the developed system and the materials used are schematized below (Figure 2).

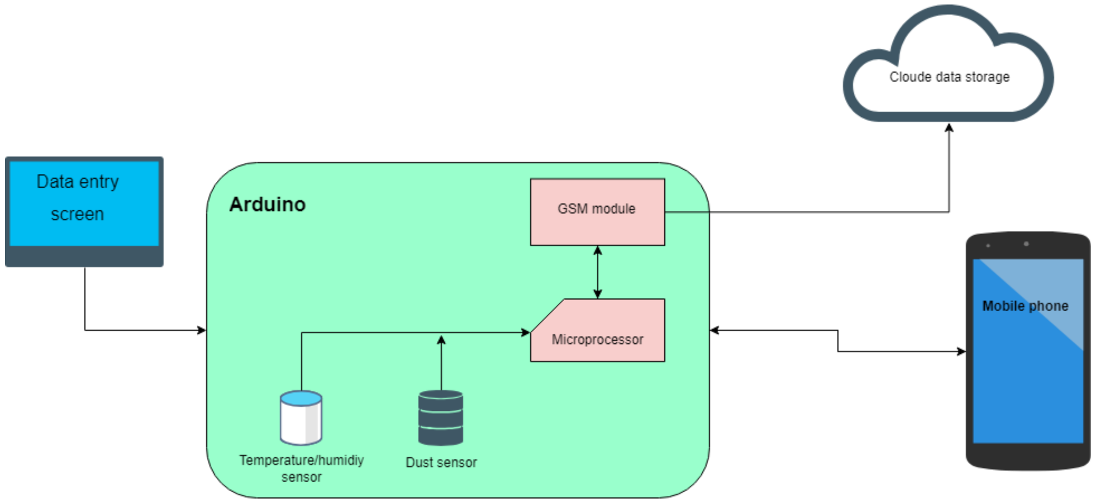

Figure 2. Schematic representation of the prototype
Şekil 2. *Prototipin şematik gösterimi*

The optical sensor integrated into the system is used to measure dust concentration (Sharp Corporation, Japan). There is an infrared transmitter and phototransistor on the sensor. It works by measuring the reflection of the emitted infrared ray from dust particles. The dust sensor, which has a very low current consumption (20mA max.) and can operate with a supply voltage of up to 7 V, has a sensitivity of 0.5 V 1mg^{-1} m^{-3} and provides analog voltage output proportional to the dust density. The Sharp GP2Y1010AU0F dust sensor generates an analog voltage output that corresponds to dust density. It is designed to deliver reliable measurements as shipped therefore calibration is not necessary (Sharp, 2024).

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a) Dust sensor b) Temperature/humidity sensor

Figure 3. Sensors used in the prototype
Şekil 3. *Prototipte kullanılan sensörler*

Arduino GSM Shield-Simcom/Sim800C unit was used to ensure that the data from the both sensors were sent to the internet server via the mobile network. Because of its ability to operate in four different bands and its internal antenna, data interruption is prevented in areas where the network signal is weak. By adding the DS1307 RTC Module to the entire system, it was possible to send the actual date and time information to the microprocessor and ensure the accuracy of the time stamp of the data received from the sensors.

The platform provided by the microprocessor card was used for the software. The software recorded the dust concentrations of the data received from the dust sensor on the SD card depending on the entered time intervals. The data created in the microprocessor was also transmitted to the Web-based data storage system via the GSM module. The threshold value to be used for dust concentration was taken into account as 0.38 mg m^{-3} (Takai et al., 1998).

The Temperature Humidity Index (THI) equation was used as the temperature-related threshold value. Various indices have been available over the years to measure heat stress, which occurs as a result of the combination of many environmental factors. Since temperature and humidity are both controllable and easily measurable environmental factors, the most common of these indices is THI (Herbut & Angrecka, 2012). The equation for dairy cattle heat stress is given below (NRC, 1971).

$$THI=(1.8\times Ti+32)-(0.55-0.0055\times RHi)\times(1.8\times Ti-26) \quad (1)$$

In the equation, THI is the temperature humidity index; Ti is indoor air temperature (^{o}C) and RHi is indoor relative humidity (%).

In this context, the values obtained from the temperature/humidity sensor were used in the embedded software in the device to calculate THI. When the specified threshold values for dust and THI are exceeded, an SMS was sent to the mobile phone to provide a warning. Considering that the THI value will always remain between 72-90 in shelters that do not have air conditioning systems, especially in hot seasons, 90 will be taken into account as the threshold value within the scope of this project.

The developed prototype can measure temperature/relative humidity, THI and dust concentration values within a one minute time interval. All these values can be constantly checked from the internet database via any computer, phone or smart device with an internet connection.

The platform provided by the microprocessor card (Arduino) was used for the software that collects and processes sensor data. MySQL, a relational database, was used to store data online. The database system, installed on a server computer open to the Internet, is constantly running to respond to incoming requests. A web-based application has been developed to access data in the database. Since its a web-based database, it can be run on any device with internet access without requiring installation. JavaScript and derivative programming environments were used for this application.

2.2. System testing and data collection

Before the developed system was installed in the trial barn, it was tested in the Digital Agriculture Laboratory at Çanakkale Onsekiz Mart University, Faculty of Agriculture. Error handling was done by testing the performance of the sensor data, GSM module and software at the lab.

A stalled-dairy cattle barn with a capacity of 60 cows located in Durali Village, Çan District, Çanakkale Province was chosen as the operation where the system was tested. The barn had a floor area of 25 × 30 = 750 m^2 and a ridge height of 6 m. The average milk yield in the farm was 20 lt day^{-1}. Since the aim of the project was to design a device that can be used by small family businesses, a barn suitable for the capacity and barn type commonly used in the region was selected. An interior picture of the barn showing the prototype device is given in Figure 4.

When choosing where to mount the device, a location was chosen where it would not be affected by air currents and would be as close to the center of the barn as possible. The height above the ground was mounted approximately 2.5 m above the ground so that animals could not reach it.

Figure 4. The prototype device in operation in the barn
Şekil 4. *Prototip cihazın barınakta çalışması*

2.3. Data analysis

The data was primarily used for modeling purposes. It was then checked whether the relationship between recorded temperature, relative humidity and dust sensor data is statistically significant. The dust concentration was estimated using temperature and relative humidity values for this barn. Multiple regression (MR) and artificial neural networks (ANN) algorithms were used for this purpose. Before data analysis, the raw dust sensor data were processed and concentration values were calculated (Equations 2 and 3).

$$D_C = 0.1642V_S - 0.09 \quad (2)$$

$$V_S = \frac{5}{1024} \times R_S \quad (3)$$

In equations; D_C, dust concentration (mg m^{-3}); V_S, sensor voltage; R_S, raw sensor value; 5/1024 coefficient required to calculate sensor data in the 0-5 volt range.

When the database was examined, it was seen that the dust concentration remained within the detection range of the sensor for only 50 minutes between the dates during the study. It was observed that these values were generally exceeded in the 5th and 6th months, when temperature and humidity were relatively higher. This shows that the dust problem is more intense in hot and humid weather. In this context, the relationship between temperature and humidity was intended to be determined by MR and ANN analysis using the available data. Considering technical specifications of the air quality sensor, it can be seen that the dust concentration cannot be calculated when the voltage value is less than 0.6. Therefore, dust concentration was considered zero at values less than 0.6 volts.

The device was designed to record data once per minute. A total of 75,594 minutes of data were collected during the trial period. Using this data, the relationship between dust concentration in response to temperature and relative humidity inputs was examined. However, during the project, unexpected fluctuations in sensor data occurred in cases such as problems arising from the power supply or the intervention of the producer or his children into the device. In this case, the web database, which is constantly under control, enabled these unwanted measurements to be detected in a timely manner. However, there are still values recorded that can be considered as outliers. For this purpose, outlier analysis of the data was performed before multiple regression analysis. The cloud-based Google Colab data analysis platform was used in both outlier and MR/ANN analysis. In the coding Python programming language was employed.

Outliers were determined by the Boxplot method. A boxplot is a statistical plot used to visualize the distribution of a data set. It is frequently used in outlier analysis. The basic components of a boxplot are as follows:

Box: The box represents the quartiles of the data set. The lower boundary of the box is called the first quartile (Q1), and the upper boundary is called the third quartile (Q3). The horizontal line inside the box represents the second quartile or median of the data set (Q2 or median).

Outliers (Whiskers): The lines at the top and bottom of the box show the overall distribution of the data set. These lines usually start at a certain distance from the boundaries of the box and represent minimum and maximum values. However, this distance can be determined by a certain number of standard deviations or a certain percentage.

Outliers: Outliers are values that differ significantly from other data points, usually beyond the whiskers. Boxplot uses a certain threshold value to identify outliers. This threshold is usually determined based on the overall spread of the data set.

After performing outliers analysis the new dataset was used in MR/ANN analysis.

3. Results and Discussion

The prototype device was installed in the barn on 10.01.2023, and 75,594-minute readings were made in a period of approximately 6 months until 09.06.2023. The data downloaded from the web-based database was converted into an Excel file and the necessary statistical analyzes were performed. The database included dust concentration (mg m^{-3}), temperature (C), relative humidity (%) and temperature humidity index readings as explained above.

In order to evaluate the effects of temperature and humidity on dust concentration a multiple regression analysis was conducted. A screenshot of the multiple regression analysis results performed in Google Colab is given in Figure 5.

```
                            OLS Regression Results
==============================================================================
Dep. Variable:                   Dust   R-squared:                       0.699
Model:                            OLS   Adj. R-squared:                  0.699
Method:                 Least Squares   F-statistic:                 8.233e+04
Date:                Wed, 29 Nov 2023   Prob (F-statistic):               0.00
Time:                        09:40:53   Log-Likelihood:                -73304.
No. Observations:               70793   AIC:                         1.466e+05
Df Residuals:                   70790   BIC:                         1.466e+05
Df Model:                           2
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const         32.8524      0.019   1730.193      0.000      32.815      32.890
Temp           0.2427      0.001    379.877      0.000       0.241       0.244
Hum            0.0087      0.000     42.573      0.000       0.008       0.009
==============================================================================
Omnibus:                    19604.374   Durbin-Watson:                   0.664
Prob(Omnibus):                  0.000   Jarque-Bera (JB):           112039.988
Skew:                           1.213   Prob(JB):                         0.00
Kurtosis:                       8.665   Cond. No.                         408.
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
```

Figure 5. Multiple regression analysis results
Şekil 5. *Çoklu regresyon analizi sonuçları*

According to the results of multiple regression analysis, the change in dust concentration depending on temperature and relative humidity can be calculated with the following equation (4).

$$D_C = 0.2427T + 0.0087RH + 32.8524 \tag{4}$$

In equation; D_C, dust concentration (mg m^{-3}); T, inside air temperature (C); RH, inside relative humidity (%).

It can be seen that the coefficient of determination (R^2), which explains the effects of the independent variables on the dependent variable, is about 0.7, which shows that temperature and relative humidity have a significant effect on the dust concentration. Again, if we look at the standard errors of the coefficients in Figure 4 (std err), it shows that these values are quite small, meaning that the accuracy of the predictions is high. Summarizing the analysis results, it shows that the multiple regression equation can be used to determine the dust concentration.

An ANN algorithm was also used to evaluate the performance of temperature and relative humidity in determining dust concentration in Google Colab. Numpy, pandas, sklearn, tensorflow and matplotlib libraries were used in modeling. 70% of the data was used in model development and the remainder was used in testing the model. By trial and error, the parameters that yielded the highest R^2 value in the test data were determined. The parameters of the ANN model developed are given in Table 1.

Table 1. ANN model parameters
Çizelge 1. *YSA model parametreleri*

Parameter	Value
Number of neurons in input layer	2
Number of hidden layers	3
Number of neurons in each input layer	8
Number of neurons in output layer	1
Activation functions in hidden layer	Relu
Activation function in output layer	Linear
Number of epochs	100
Model optimizer	Adam
Mean Squared Error on Test Set	0.45
R-squared on Test Set	0.71

When the results obtained from both methods are compared, it is seen that there is no significant difference between them. Therefore, both approaches can be used to determine dust concentration depending on temperature and relative humidity.

Although the primary purpose of this study was to observe and model dust concentration, THI values, which reveal the combined effect of temperature and relative humidity, were also calculated. The results were evaluated using the limits given in Table 2.

Table 2. Stress categories and precautions that can be taken (Xin & Hamson, 1997)
Çizelge 2. *Stres kategorileri ve alınabilecek önlemler (Xin & Hamson, 1997)*

THI value	Meaning	Precautions that can be taken
THI < 72	No stress	-
72< THI< 80	Alarm	Animal behavior is carefully observed. Their breathing is checked. Cooling fans are turned on and animals are given plenty of water
80 < THI < 90	Beginning of danger	If possible, evaporative cooling systems such as sprinklers and fan-pads are activated or the interior is tried to be cooled with water. Meanwhile the animals are carefully observed
THI > 90	Emergency	Animals are moved as little as possible, for example they are not taken to market. In addition to the measures in the danger category, animals are not fed during the hottest hours of the day and the light level inside the shelter is reduced to reduce animal activity and therefore heat production.

Considering Table 2, it may be a correct approach to take the threshold value required for the developed system to send SMS as THI = 72. However, due to the lack of adequate air conditioning systems in barns in Türkiye, especially in small family businesses, this value is easily exceeded for most of the year. Although the study period in which data were collected in the barn (January - June) generally coincided with the winter months, it was observed that the threshold value of 72 was exceeded 64 hours in total (Figure 6). It is obvious that the threshold value will be exceeded almost throughout the day during most of the spring, summer and fall months. Therefore, the threshold value for SMS was taken as 90, which is the beginning of the emergency. Since the developed prototype can be adapted to an air conditioning system, it has a high potential to be used as an automation device.

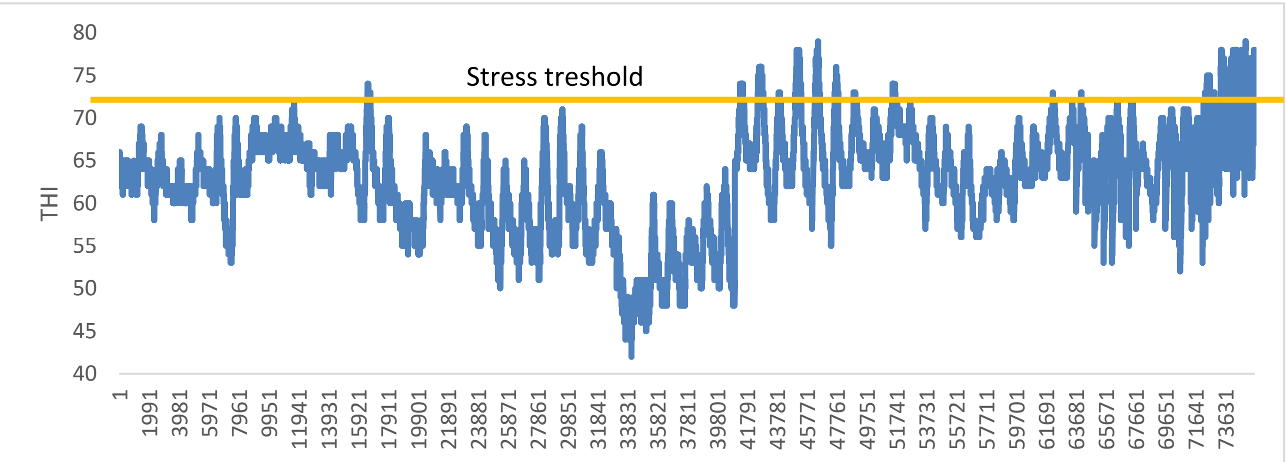

Figure 6. THI values and critical threshold value
Şekil 6. *THI değerleri ve kritik eşik değeri*

4. Conclusion

In this study, a prototype device developed to monitor dust-related air quality in small family operations and the applied methods are reported. In addition, the system has been adapted to control heat stress, which causes low productivity in dairy cattle. Using the collected data, the predictability of dust concentration with temperature and relative humidity values was also tested. For this purpose, performance of MR and ANN algorithms have been evaluated. The analysis of the data showed that both approaches can estimate dust concentration as a parameter of temperature and relative humidity. The cost of the developed prototype device is approximately $250 according to the 2023 exchange rate. This is a very reasonable cost for an automation system that will control dust, temperature and humidity. It offers an economical solution for small family businesses with a small number of animals, especially in Turkey. As a result of this study, it has been seen that being able to access today's technology at very low costs will make significant contributions to finding solutions to agricultural problems.

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