Evolution of Air Quality Measuring Techniques

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Abstract - *The issue of air pollution and deteriorating air quality is surely and steadily increasing. This raises the concern about human health and safety. The first step of addressing this problem is by identifying it. Therefore, we will need to measure the exact concentrations of the various air pollutants. This paper details the different pollutants and addresses its source and significance. It also elaborates the evolution of techniques used to measure these pollutants from pre-agricultural times to the cutting-edge methods used today. This paper illustrates the modern methods and technologies that are far more efficient, compact, faster and cheaper.*

Key Words: Air Quality, Sensors, Gas Pollutants, Concentration Measurement.

1. INTRODUCTION

Air is one of the most essential elements of living. The rise in air pollution and toxic gases in the environment has been very significant over the past few decades. Some of these are measurable. But a lot of the harmful gases from other sources like volcanos, wildfires, etc are not well documented[1]. More than half of the modern, urban population around the world is exposed to air pollution that is at least 2.5 times higher than the recommended levels given by WHO[2]. Air quality is arguably the largest health risk in the world[3]. Approximately, 7 million deaths a year are attributed to poor air quality.

Monitoring air quality is important because polluted air can lead to the risk of stroke, heart disease, lung cancer and other respiratory diseases such as Asthma, Bronchitis, Emphysema. So clean air is the only solution that shows a positive impact on public health and welfare[4]. Studies show that clean air can boost one's cognitive power[5] as opposed to one exposed to moderate quality of air. Moreover, there are economic benefits for measuring the air quality on environmental improvements like population and ecosystem exposure. We can also understand their concentration fluctuations. This is why measuring air quality in a technologically advanced way will benefit humanity[6].

2. PARAMETERS TO BE MEASURED

There are several different gases and particulate matters in the atmosphere that are detrimental to various aspects of human life. The first step in measuring air quality is by identifying these gases and particulate matters. The main ones that cost the most to the decline in air quality are as follows;

Particulate Matter (PM) is a mixture of soot, smoke, metals, nitrates, sulphates, dust, water and tire rubber. The size of these particles determines their magnitude of health problems caused. Smaller particles such as PM2.5 pose the greatest problems because they easily go through our immunity and can affect our lungs and bloodstream. It is found that an increase of only 1 μg/m3 in PM2.5 is associated with an 8% increase in the COVID-19 death rate. Studies have shown that death rates due to the increase in the concentration of PM increase respiratory and cardiovascular diseases[7].

Carbon dioxide from respiration comes from the exhalation of humans and other animals. It is eventually absorbed by plants through photosynthesis or dissolved in the ocean. This creates carbonic acid. This carbonic acid eventually leads to the natural weathering of rocks which have been carried into the ocean[8].

Carbon dioxide (CO_2) and Carbon monoxide (CO) which comes from incomplete combustion of fossil fuels can cause much damage as well. Carbon monoxide competes with oxygen for the molecule that carries oxygen to the cells in our body. Therefore, at high concentrations, it is a deadly poison.

Ozone (O_3) is a "secondary pollutant" that is exclusively present in the troposphere[9] is a dangerous pollutant and can negatively affect human health and vegetation. This ground-level pollutant is produced by a chain reaction between sunlight and a "primary pollutant" from vehicle emissions, power plants, industrial boilers, etc.

Sulphur Dioxide (SO_2) is majorly obtained from burning oil and gas in energy-generating plants. They are also obtained from smelting and refining industries. Sulphur dioxide can easily dissolve with water droplets producing a highly corrosive acid rain. Inhalation of SO_2 leads to narrowing of the airways known as bronchoconstriction[10]. Moreover, it is more sensitive for people suffering from asthma.

Nitrogen Oxides (NO_x) generally stem from the result of various fossil fuel combustions. Around 50% of NO_x is produced by motor vehicles. NO_x can cause lasting damage to people with chronic lung diseases leading to breathing difficulty. It also results in higher mortality from cancer and heart diseases[11].

Lead compounds are usually released to the atmosphere from the exhaust of motor vehicles. Lead is overtly dangerous as it causes lead poisoning which results in mental retardation and sometimes, even death[12].

3. CASE STUDIES

Air quality is mostly related to the earth's climate change and human health conditions. Below are a few recent examples which show the importance of measuring air quality and making to follow the standards created by countries.

3.1 NEW DELHI

Delhi, the capital of India, records dangerous amounts of air pollution during winter due to weather, stubble burning, local sources of pollution and also of its geographic location. In just half of 2020, air pollution in Delhi has caused more than 24000 deaths [13].

3.1CALIFORNIA

California's wildfires in August 2020 have made a huge impact on both the ecosystem as well as human life. Studies show that heavy smoke causing sudden cardiac arrest was significantly higher within three days of exposure. This also leads to an increase in the vulnerability of airborne diseases[14].

3.1 CHINA

China is one of the most affected countries due to air pollution. It's reported that in China, chronic respiratory diseases remained within the top five leading causes of mortality in 2016, accounting for 9% (approximately 8,70,000 deaths) of the overall Non-communicable Diseases (NCD) deaths (9,259,000). Even Though from the continuous effort and significant improvements in air quality in China over the past decade, NCDs were responsible for roughly 89% of all total mortality in 2016, a little slightly higher than the global proportion of 60% for NCDs. Due to the unhealthy levels of PM2.5, it led to roughly 8,52,000 early deaths in China in 2017. Household air pollution from burning solid fuels resulted in additional 271,100 deaths that year. It is also with respiratory diseases continuing to be on the rise, the World Health Organization predicts by 2030 respiratory diseases will be the leading cause of morbidity and mortality. Due to the large impact of air pollution the country has reduced its manufacturing of iron and steel capacity and shut down coal mines. The government also introduced afforestation and reforestation programs like the Great Green Wall and planted more than 35 billion trees across 12 provinces [15].

4. HISTORICAL METHODS OF MEASURING AIR QUALITY

In order to properly signify the recent trends in modern methods of measuring air quality, we need to look into how it was done in the past. It will help in gauging the advancements better.

Humans have been measuring air quality since before the agricultural period to properly maintain their social lives and livelihood. They did this along with watching the migration of animals, changes in the length of the day, the appearance of certain plants during certain seasons. Optical visibility was a major factor in determining air quality. This was necessary because, during the post-agricultural period, peasants burnt trees in a controlled manner in order to increase yield[16]. But they also had to be immensely careful or the smoke would kill the crops. Therefore, knowing the approximate air quality was vital.

5. CONVENTIONAL METHODS OF MEASURING AIR QUALITY

There are mainly three broad ways of measuring air quality: Collection Analysis, Continuous Analysis and Concentration Meters. Collection Analysis is when the air sample or residue from ground solids like rocks is collected and transported to a laboratory. Here, the samples can be analyzed. This is typically done with spectrophotometers and gas chromatographs. Continuous Analysis is when the samples are analyzed on-site itself with respect to the time course and mean concentrations. This is generally more expensive but takes lesser time to come to a conclusion, as opposed to collection analysis. The final broad method, the concentration meter is highly portable, easy to operate and inexpensive. They are used for a very specific type of gas and measurements can be taken on-site.

Particulate Matter is generally measured using a gravimetric method [17]. Here a filter paper is first measured without any exposure to the air. Even the electric charges are removed. Its weight is measured and stored as a reference. Next, the same filter paper is exposed to sample air for a particular period of time. Finally, its weight is measured, and the difference is used to calculate the concentration of PM using the flow rate of the sample [18]. Another approach to measure PM is Optical Monitoring method. It uses the light scattering principle [19]. Here, a laser is directed at an air sample. A photodiode is situated at a particular angle and the laser beam reflected from a PM will be used to determine the concentration of it. The size of the particle is directly proportional to the time period of the light beam detected [20]. PM also can be measured with Beta Ray Absorption Method(**β**) with a measuring range of 0 - 1/5/10 mg/m3.

Tapered Element Oscillating Microbalance (TEOM) consists of an electric pump that draws sample air into the instrument through an inlet that allows particles of a certain size [21]. This airstream is passed to the tapered element which consists of a filter cartridge mounted on the tip of a hollow glass tube. The weight of the particles collected on the filter changes the frequency of the tube creating oscillations which are sensed and used to calculate the PM mass rate from the change in frequency [22]. Then the PM concentration is obtained by dividing the mass rate by the flow rate of sample air.

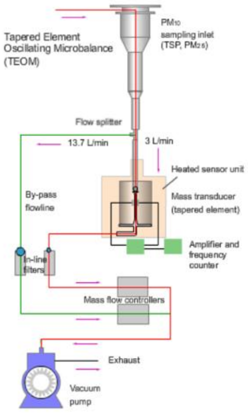

Fig -1: Tapered element oscillating microbalance

Carbon Monoxide can be measured using the Infrared Absorption method with a measuring range of 0 - 5/10/20/50/100 ppm. The sample air is transported in the measurement cell using an internal sampling pump. Since carbon monoxide absorbs electromagnetic radiation in a specific wavelength range, the concentration of carbon monoxide is obtained by measuring it at a wavelength of 4700 nm in the IR spectrum. This is the Non-Dispersive Infrared (NDIR) absorption method [23].

The concentration of Carbon Dioxide can be measured using an absorption technique where the CO_2 sensing element is made of a solid electrolyte situated between two electrodes along with a Ruthenium oxide (RuO_2) substrate [24]. The CO_2 concentration can be quantified by checking the difference in electromotive force (EMF) that is generated between the two electrodes. This EMF and the CO_2 concentration is linearly proportional to each other on a logarithmic scale [25].

Sulphur Dioxide can be measured using Ultraviolet Fluorescent method with a measuring range of 0 - 0.05/0.1/0.2/0.5/1.0 ppm [26]. The concentration of SO_2 can be determined by taking into account the amount of fluorescent radiation produced by the SO_2 molecules when they are bombarded by Ultraviolet radiation inside the chamber [27].

An ozone monitor works by collecting sample air using a pump. Inside the machine, a light beam from a stabilized low-pressure mercury discharge lamp of a specific wavelength (monochromatic light at 253.7 nm) is shone through the sample air and the amount of light absorbed is checked at the other end of the machine. The absorption of light is proportional to the concentration of ozone [28].

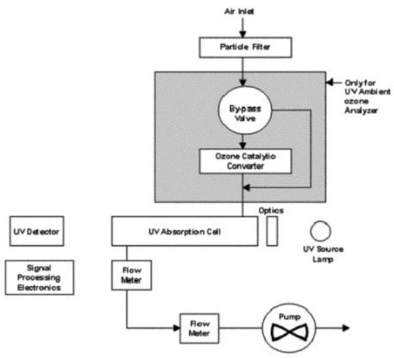

Fig -2: UV Absorption Method

Nitrogen Oxides are measured using Chemiluminescence method where light is emitted using a chemical method [29]. This light is directly proportional to the concentration of the nitrogen oxides present in the given sample air. Another method is by using Diffusion Tubes [30]. Here one end of the tube consists of a cap that is made of triethanolamine (TEA). TEA has a special property where it absorbs NO_2 and other forms of nitrite. Thereafter, this cap is thoroughly washed with water. Subsequently, UV light is shone on this water and the amount of UV light absorbed by the water is correspondingly equal to the concentration of the Nitrogen Oxides in the sample air stored in the diffusion tube

6. MODERN METHODS OF MEASURING AIR QUALITY

Over the past few years, science and technology have advanced a long way past the limelight of what was thought humanly possible. One of the biggest aspects of this advancement is in the field of environmental science and electronics. This paper shows a comprehensive view of several cutting edge technologies used to measure air quality and improve living standards. They are as follows.

Black Carbon is a major component of particulate matter. A revolutionary device that measures this is the Aerosol Black Carbon Detector (ABCD)[31], which incorporates a small waterproof body, solar-powered rechargeable battery, and GSM communication to enable long-term, remote operation. The ABCD can be classified as an aerosol absorption photometer. These meters measure the absorption of light from ambient particulate matter and is collected on a fibrous filter. It then converts the measured light absorption to Black Carbon mass concentration in the sample airflow. This outdoor deployment package includes rechargeable battery (12-volt, 10-amp-hour), rotary vane vacuum pump, airflow sensor and an integrated electronics board. The entire product costs $400.

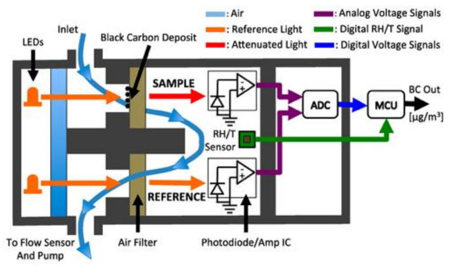

Fig -3: Functional diagram of the ABCD optical cell

The next generation of smart gas sensors must be highly advanced. One of them is the Modular Sensor System (MSS) with the Universal Sensor Interface (USI) [32]. The goal for this system is to streamline portability, energy efficiency, multiple wireless sensor networks compatibility, multiple sensing ability and configurable and adaptable sensing capability. Eight sensors are being integrated here. They are CO, SO2, O3, NO2, CO2, THP, NR1 and NR2 and they monitor the carbon monoxide, sulfur dioxide, ozone, nitrogen dioxide, carbon dioxide, temperature-humidity-pressure condition, β-γ radiation, and α-β-γ radiation, respectively. All the required sensors are connected to a microcontroller. The microcontroller is based on an ARMmbed LPC1768 platform. The USI is also integrated with Serial Peripheral Interface (SPI). A GPS module regularly updates location data via the Universal Asynchronous Receiver/Transmitter (UART) port. The time data is sent from a real-time clock module via the Inter-Integrated Circuit (I2C) port. When well-calibrated, this system provides a highly accurate, smart and transportable gas sensor array.

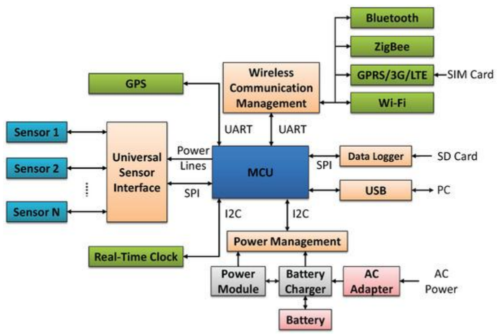

Fig -4: System architecture of a MSS sensor node

Researchers have created a low-temperature electrochemical hydrocarbon and NOx sensor using platinum and metal oxide electrodes. The electrolyte is a thin film of Yttria-Stabilized Zirconia (YSZ)/Strontium Titanate (SrTiO3) [33]. Most mixed potential sensors operate at over 400°C. This one operates at a much lower temperature of 200°C. This is mainly due to the oxygen ion conductivity. This sensor detects hydrocarbons in the open-circuit mode and NOx in the biased mode. It is also highly efficient as it only consumes 1W of power.

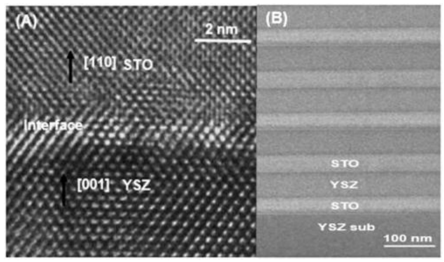

Fig -5: High-resolution TEM image YSZ/STO thin film

A new aspect into the measurement of air quality, especially indoors, is the use of Artificial Intelligence and more specifically Deep Learning. The parameters measured are carbon dioxide, fine dust, temperature, humidity, light quantity, and volatile organic compounds (VOC). Every one minute this data is regularly transmitted to a Linux server. It uses an Arduino microcontroller to process the information and store it in a MySQL database. This uses three Machine Learning models to achieve this far quicker and more efficient than conventional methods. The first one, Linear Regression, is used to take into account all the linear relationships of all the data sets and use that to predict the dependent variable value using independent variables. The second ML model is Long Short-Term Memory Network (LSTM). LSTM is used to overcome the problem with circular neural networks because they fail to store long term historical data. This data, however, is vital to the accurate prediction. Therefore, LSTM uses recurrent neural networks (RNN). The LSTM uses three gates, input, output, and forget the gate to properly regulate the storage. These three gates determine the amount of data to be stored from the past and to be transferred to the future. The final model is the Gated Recurrent Unit (GRU) network [34]. This is a variant of LSTM with only two gates, reset and update gate. The GRU is much less complex than LSTM because it combines the forget and input gate of the LSTM network into one update gate, moreover, it also combines the cell state and the hidden state into one reset gate.

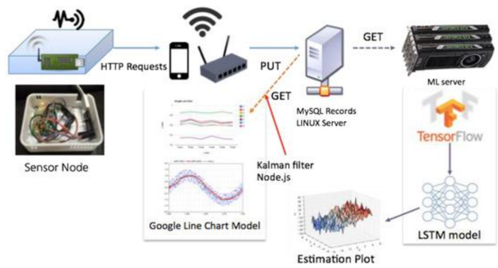

Fig -6: Module diagram for the periodic measurement and transfer of air quality data

A major pain point in portable PM meters is that they are usually very large and heavy. This is due to the method of light scattering they use to measure the concentration of PM. This comes with the addition of complex components as stated previously in this paper. But a revolutionary alternative to laser beam induced measuring methods is the use of optical fiber to measure the concentration on PM [35]. In this method, two optical fiber probes are placed along the same axis with a certain distance between them. The sample air is passed through this gap. When a particle passes through this gap, it changes the coupling between the two optical fiber probes by disrupting the electromagnetic mode. This disruption in turn causes a drop in transmission. This leads to lower coupling efficiency. This change in coupling efficiency can be used to determine the concentration of Particulate Matter.

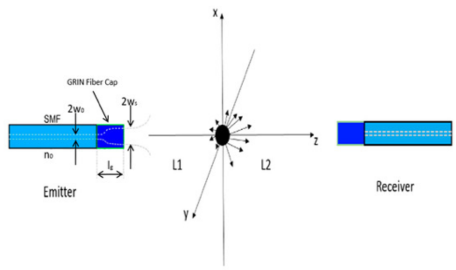

Fig -7: Particle in between two fibre optic probes

Gas sensors that are based on Laser Absorption Spectroscopy (LAS) are already highly selective and have low Minimum Detection Limits (MDL). But there is a way to improve this even better by using optical resonators/cavities since this increases the effective optical path length. The MDL can be improved by increasing the signal to noise ratio. This can be done by using wavelength modulation (WM) and frequency modulation (FM). In these cavities, we use ultra-sensitive microphones to detect the conversion of laser light matched to the targeted absorption line in the trace gas sample. But unfortunately, the input of these microphones is manipulated by various mechanical and acoustic vibrations. To rectify this problem, we can use Quartz-Enhanced photoacoustic spectroscopy (QEPAS) [36]. It follows the same principle as a Quartz Tuning Fork (QTF). QEPAS is immune to environmental mechanical and acoustic noise so it can be used in a wider range of gas sensing applications.

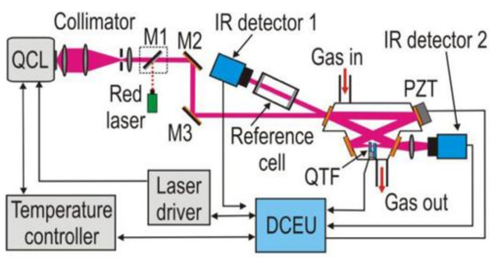

Fig -8: Schematic diagram of the QEPAS nitric oxide sensor

According to the EPA, indoor air quality is 100 times higher than outdoors. The obvious solution is to install a real-time monitoring and notification system. Focusing on measuring one pollutant, CO2, a complete IoT architecture with the use of ESP8266 as a microcontroller with wireless communication capability, MHZ-19 as CO2 sensor is developed by iAirCO2[37]. Since 32-bit MCU is utilized due to its lower power consumption, continuous monitoring is made more convenient. It was developed from open-source technologies which provide complete Wi-Fi systems along with web and mobile compatibility for real-time data analysis and notifications. By the use of NET web services and SQL server databases with SSL (Secure Sockets Layer) certificate for authentication, the data is collected and stored. Since measurement for every 15 seconds is stored in the database, it makes it easy to analyze and find out when things go wrong. All this increases its significance when compared with other systems due to its low cost of construction, easy installation with modularity and scalability.

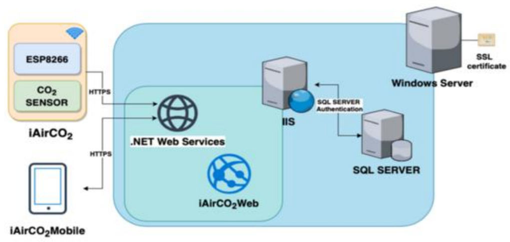

Fig -9: iAirCO2 block diagram

A graphene-based sensor for measuring NO2 has great potential these days because of its low power consumption and cost. NO2 is a strong oxidizer which withdraws electrons from the graphene surface leading to an increase in the resistivity. Under low NO2 exposure, the resistivity of the sensor increases linearly with time. Among all methods of graphene growth, epitaxial graphene on Silicon Carbide (SiC) has many advantages such as lower response time [38]. These sensors have poor cross selectivity with respect to different gases present in the ambient atmosphere. This chip was assembled with a Pt100 resistor for annealing/heating. The procedure for measuring is of 3 stages: regeneration, stabilization and exposure to sample air. Since the selectivity of NO2 with respect to O3 is less, Oxide-based catalysts are used to eliminate O3 from the air before measurements.

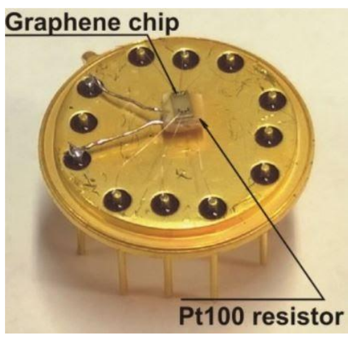

Fig -10: Graphene based NO2 sensor

7. CONCLUSIONS

The only way humanity moves forward in the coming generations is by incorporating technology in the most innovative and efficient way possible. The largest field that requires a dramatic improvement is the reality of air pollution and the deteriorating air quality. The first steps in combating climate change are by first identifying and calculating its concern accurately. The vast majority of the methods we use today to measure the concentration of air pollutants are outdated, clunky and unsophisticated. A new wave of engineering and environmental innovation has created the pathway to introduce bleeding-edge technologies to measure various harmful gases and do it quickly, accurately and efficiently. This paper has brought several of these technologies into the spotlight from researchers, scientists and engineers from all over the world. These alternate methods have several advantages over conventional methods. They are the most robust and resilient. They are much more compact and can be transported to anywhere in the world for some quick measurements. Unlike traditional methods, they can output the exact concentration levels on-site, soon after the measurement starts. They are modular, smart and capable of interfacing wirelessly from a wide variety of devices. Their processing speeds are faster due to the more energy-efficient and compact form factor. And finally, they are, for the most part, much more inexpensive than their conventional counterparts. This leads them to be more accessible and readily available to more people around the world. From NGOs to schools, more people will be able to access these new air quality measuring technologies and utilise them unhinged.

REFERENCES

1. https://www.washingtonpost.com/business/2019/10/23/air-pollution-is-getting-worse-data-show-more-people-are-dying/
2. https://www.airclim.org/acidnews/urban-air-quality-getting-worse
3. https://www.airclim.org/acidnews/air-pollution-world%E2%80%99s-largest-environmental-health-risk
4. https://www.nap.edu/read/10728/chapter/9
5. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6417586/
6. https://www.ppsthane.com/blog/benefits-of-air-quality-monitoring
7. https://www.eea.europa.eu/publications/2599XXX/page008.html
8. https://www.omicsonline.org/open-access/gaseous-pollutants-formation-and-their-harmful-effects-on-health-and-environment.php?aid=15178
9. https://hal.archives-ouvertes.fr/hal-00295690/
10. https://erj.ersjournals.com/content/17/4/604.short
11. https://www.sciencedirect.com/science/article/abs/pii/S1352231008005323
12. https://www.epa.gov/sites/production/files/2016-09/documents/lead-compounds.pdf
13. https://bit.ly/2SbUfRs
14. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4827747/
15. https://respiratory-research.biomedcentral.com/articles/10.1186/s12931-019-1117-8
16. https://link.springer.com/article/10.1007/s10661-005-0755-0
17. https://www.researchgate.net/publication/282511398_An_Overview_of_Particulate_Matter_Measurement_Instruments
18. https://www.mt.com/in/en/home/applications/Laboratory_weighing/emissions-testing-particulate-matter.html
19. https://www.sensirion.com/en/environmental-sensors/particulate-matter-sensors-pm25/
20. https://bit.ly/3ikRWG4
21. https://www.qld.gov.au/__data/assets/pdf_file/0024/68532/particle-posters-web.pdf
22. https://bit.ly/2HEbE30
23. https://onlinelibrary.wiley.com/doi/full/10.1002/3527600418.am63008e2019a
24. https://peer.asee.org/testing-of-carbon-monoxide-and-carbon-dioxide-sensors-with-simple-apparatus-in-an-engineering-education-laboratory.pdf

25. https://www.evelta.com/content/datasheets/tgs4161.pdf

26. https://www.env.go.jp/earth/coop/coop/document/apctm_e/01-apctme-09.pdf

27. https://www.care4air.org/air-pollutants/measuring-air-pollutants/

28. https://projects.nilu.no/ccc/manual/documents/03_9-Determination%20of%20ozone.htm

29. https://pubs.acs.org/doi/pdf/10.1021/ac50031a054

30. https://www.care4air.org/air-pollutants/using-diffusion-tubes/

31. https://www.mdpi.com/1424-8220/18/3/738/htm

32. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5795373/

33. https://www.researchgate.net/publication/321390615_A_New_Low-Temperature_Electrochemical_Hydrocarbon_and_NOx_Sensor

34. https://towardsdatascience.com/predictive-analysis-rnn-lstm-and-gru-to-predict-water-consumption-e6bb3c2b4b02

35. https://bit.ly/34hhw9Z

36. https://www.sciencedirect.com/science/article/pii/B9780081027097000152

37. https://link.springer.com/article/10.1007/s10916-019-1184-x

38. https://www.sciencedirect.com/science/article/pii/S0925400516307997?via%3Dihub

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