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# Intelligent Real-Time Air Quality Monitoring with ESP Technology: A State-of-the-Art Approach for a Sustainable Future

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**Abstract**
Pollution is the major issue worldwide in which Air pollution, considered the major concern which is the most dangerous and severe pollution among all the others i.e., water pollution, noise pollution, thermal pollution etc. Air pollutants are responsible for various health problems such as asthma, heart attacks, lung cancer etc. Monitoring these pollutants is very important because it then add to the air in the shape of air pollution which directly effects the human health. This will able the environmental planners to design and develop some new policies and develop public awareness. The project aims to deploy the efficient power usage, low cost, small size compact system, high accuracy. (RAQMS) Real-time Air Quality Monitoring System is a combination of hardware which includes Gas sensors (CO, $NO_2$, $SO_2$, Smoke) Temperature and Humidity sensors and a microcontroller ESP-32, Server, and android application. It is used for the interfacing with the equipment's where Real-time Index (RQI) are measured and transferred it to the centralized system through IOT (Internet of Things) where it is monitored on Lab View (software) Real-time platform. The measured data will be in real time and according to the standard values, based upon the parameters considered as standard which will give the indication about the environment condition either polluted or safe. The goal is to make pollution level estimation, share data and interfaces to design the air quality models, support research and also make this project as less costly as we can so that the people belong to any background and society, can use it. If researchers want to improve its efficiency by investing some amount for the further research. It will turn out to be a less costly and most compact solution as a weather station for the air quality monitoring.
**Keywords:** Pollution, Air Pollution, Gases, Sensors, Real-time monitoring, Air Quality Index, Pollution Parameter, Lab View software, Mobile Application (Blynk).

## Introduction
Air quality has become one of the most critical concerns worldwide, particularly

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in urban areas where rapid industrialization, transportation, and population growth have led to significant environmental challenges. Air pollution is when the quantity of harmful gases or particles in air increases. Whether it's a developed or a developing country, air pollutions is the significant issue of each country. Health issues have been developing at quicker rate explicitly in the urban areas where there is release of a lot of gaseous pollutants because of industrialization and increase in the count of vehicles. Pollutants include nitrogen dioxide, carbon monoxide, sulfur dioxide, ozone, $PM_{2.5}$ and $PM_{10}$ particles, humidity. Air pollutants mainly come from the wood burning, industries wastes and smoke coming out from the vehicles. Detrimental effects of pollution include the allergic reactions like inconvenience of the throat, irritation in the eyes and nose, and some other significant issues such as asthma, bronchitis, pneumonia, heart issues including heart attacks, asthma, and lungs issues [1]. Air is the valuable and essential thing for every single living thing. Researching on this major issue is the framework's primary reason and it was to gauge the nature of air for every individual and other living thing which exists on earth. It's something imperative that our living things should know is that how much at the protected end we are currently, and how the climate and environment has changed because of air contamination. Through this system we can easily know about the air quality. Four significant gas sensors which are answerable for the air contamination mostly, is being utilized in the framework to know the best consequence of the condition of the air [2]. CO, $NO_2$, $SO_2$. Air pollutions is also caused by humidity. All these are utilized in our designed system. This system also includes Smoke and Temperature sensor in order to monitor the temperature of surrounding. A server, and an android application have been utilized to know the insights at any place because now days now days nearly everybody has an android working gadget and feel at ease to access through web which will sum up its worth. Carbon monoxide (CO) is a dry, unscented, dull gas created by consuming gas, wood, propane, charcoal, or other fuel. ventilated apparatuses and motors, especially in a firmly fixed or encased space, may permit carbon monoxide to aggregate to perilous levels. Smoke and exhaust vapor likewise contain carbon monoxide. It is a typical air pollutant whose levels are commonly not experienced high outside, always present in low concentration which is not harmful to the human health. High levels can occur in encased spaces inside. For example, because of a broken gas heater in inside room, experience a genuine side effects from breathing and trouble in breathing because of significant degrees of carbon monoxide. Individuals having heart issues are at danger and at risk of brain damage and can even die on before anybody came to know there is an issue. Its standard values averaged over one hour in ppm according to the *NAAQS standard* are considered good when its concentration is less than 30 ppm, poor when its concentration is between 30- 70 ppm, and it will be extremely poor when it is more than 70 ppm which will cause death. Nitrogen Dioxide (NO2) is one of the exceptionally responsive gases known as oxides of nitrogen or nitrogen oxides (NOx) [3]. NO2 is utilized. NO2 principally gets noticeable all around, from the consuming of fuel. NO2 structures from depletes of vehicles, trucks, coal fire power stations, ventures, power plants. At the point when a high convergence of NO2 contained noticeable all around is inhaled, can aggravate aviation routes in the human respiratory system. When exposed for the short time can cause respiratory illnesses, asthma,

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prompts respiratory manifestations (which includes Dry Cough, wheezing or trouble in inhalation and exhalation). When exposed for long time to $NO_2$, it might grant the occurrence of asthma and then leads towards the extreme respiratory illnesses. Folks with asthma including elders and children are at higher risk of being affected due to $NO_2$. While it's environmental effects, particulate matter, ozone, and acid rain is formed when nitrogen di oxides and its other oxides reacts with oxygen and water. Acid rain anguish sensitive ecosystems such as lakes and forest. Its standard values averaged over one hour in ppb according to the *NAQ standard* are considered good when its concentration is less than 60 ppb, fair when it's between 60-120 ppb, poor when its concentration is between 120- 180 ppb, it will be very poor when its concentration for average one hour is in between 180- 360 ppb, and it will be extremely poor when it is more than 360 ppb which will cause death. Sulfur dioxide is uncolored gas with a suffocating smell [4]. As being liquid when some pressure is applied it can easily dissolve into water. Sulfur dioxide is produced mainly due to copper smelting, coal burning, and burning of oil at power plant. It is released in the air whenever there are volcanic eruptions. When we breath in the sulfur containing atmosphere, it directly affects our health depending upon its level and the duration of time. At the point when levels, are high, experience indications shortly after inhaling it in. Symptoms includes, the breath shortness, coughing and wheezing. wheezing, hacking and windedness. Individuals with lung conditions, like asthma are generally influenced by high degrees of sulfur dioxide. Its standard values averaged over one hour in ppb according to the *NAAQS standard* are considered good when its concentration is less than 100 ppb, fair when it's between 100-200 ppb, poor when its concentration is between 200-300 ppb, it will be very poor when its concentration for average one hour is in between 300- 600 ppb, and it will be extremely poor when it is more than 600 ppb which will results into death. Smoke is a mixture of airborne particles, water vapor and other complex gases [5]. Breathing in smoke can also be harmful to our health. It is made up of mixture of gases and particles. Due to the burning of organic materials and wood, smoke is produces which contain a mixture of particles and different gases. Fine particles are considered as the biggest threat for health. When these minute particles enter into your lungs, it causes different health issues of various range such of eyes burning, lung diseases, heart attacks and runny nose. Smoke from bushfires and landfill, peat, tire, and coal fires can impact the quality of our air and cause particle pollution. Exposure to these particle pollutions results in premature death. Humidity is the proportion of the measure of water vapor noticeable all around in air, when there is high humidity, it means the air will contain high amount hazardous and toxic chemicals [6]. It likewise causes dust particles in our homes dampening the nature of air. Because of the different levels of humidity either high or low, leads towards the different respiratory diseases. Low moistness additionally causes airborne germs. If, the humidity level of indoor is not maintained at optimal level then I will have an adverse effect upon the health. In order to maintain the humidity level of air indoor, needs careful attention. As per standards, the human body the human body is substantially more agreeable when the stickiness of the specific region ranges between 20 – 60 %. The suggested moistness relative normal for the indoor is between 30 to 50 % when the temperature outside is 20 °F or more. On the off chance that the indoor relative stickiness is above 60%, shape and buildup

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start to frame, and these can present a significant issue to the wellbeing of the tenants. In the end, smelly scent will begin, and the inside will have a damp vibe. At the point when the general stickiness of the inside is under 30%, there is again the danger of medical issues. Under 30% of relative moistness can cause friction-based electricity issues, aggravation of the skin and dry eyes. The mucous layers can begin drying, which might diminish the individual's obstruction towards upper respiratory sickness. It is significant, that the detainees see surrounding temperature dependent on the general mugginess of the spot. In winter, the surrounding temperature would be a between 69 to 78°F at a general stickiness of 30%. In any case, in summer, when the general stickiness is 60%, the indoor regulator will fall between 68 to 75°F. Particulate matter is fluid or strong matter which is infinitesimal and suspended in Earth's environment [7]. Our heart and lungs are continuously affected due to this particulate matter. Till now, a lot of investigations have been done in climate monitoring utilizing IOT (Internet of Things) gateway. Wi-Fi has been used for data communication between sensor node database, internet. Analysts and researchers have checked natural boundaries like Temperature, sulfur dioxide, Humidity, carbon monoxide, Barometric pneumatic pressure of air [8]. The fundamental motivation behind the pollution observing isn't just to give the gathered information to the end client it might likewise help the organizers, strategy designers and researcher to take it seriously and take precautionary steps for the improvement of environment [9].

Traditional air quality monitoring systems, while accurate, are often costly and limited in scope, typically deployed in fixed locations, and lack the flexibility needed to provide a comprehensive picture of air quality across diverse urban and rural environments. Additionally, these systems often fail to offer real-time data or easy accessibility for the general public, reducing their effectiveness in fostering timely responses to pollution. Recent advancements in microcontroller technology, particularly the ESP32 and ESP8266 family of microcontrollers, have opened new possibilities for cost-effective, scalable, and real-time air quality monitoring solutions. These devices, with their built-in Wi-Fi and Bluetooth capabilities, offer seamless wireless communication and integration with cloud-based platforms, making them ideal for building intelligent, connected systems. This paper presents an ESP-powered, intelligent real-time air quality monitoring system designed to provide accurate, continuous, and accessible air quality data. By leveraging low-cost sensors and the versatility of the **ESP32** microcontroller, the system can measure key air pollutants, including particulate matter (PM2.5, PM10), CO2, and NO2, in real-time [10]. The data is transmitted wirelessly to a cloud platform or accessible via a web/mobile interface, enabling users to monitor air quality on-demand. The primary goal of this project is to enhance environmental monitoring capabilities, raise public awareness about air quality, and contribute to sustainable development by empowering individuals, communities, and policymakers with real-time, reliable information. The proposed system aims to foster a proactive approach to managing air pollution, promote healthier living environments, and support smarter urban planning in alignment with sustainable development goals (SDGs).

**Research Objective**

The primary objective of this research is to design, develop, and implement an

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intelligent real-time air quality monitoring system powered by **ESP32** microcontrollers. This system aims to provide accurate, continuous, and accessible air quality data for both urban and rural environments. The specific objectives of the research are as follows:

- To design a low-cost, scalable real-time air quality monitoring system using ESP-32 microcontrollers capable of measuring key air pollutants, such as PM2.5, PM10, CO2, and NO2, with high accuracy and reliability.
- To integrate wireless communication capabilities of the ESP microcontrollers (Wi-Fi/Bluetooth) to transmit air quality data in real-time to a cloud-based platform or mobile/web application, ensuring easy access and timely insights for users.
- To evaluate the performance and accuracy of the air quality sensors and the ESP-based system in various environmental conditions, ensuring that the system provides reliable and consistent data across different monitoring locations [11].
- To develop a user-friendly interface for displaying real-time air quality data, allowing users (both individuals and communities) to track pollution levels, make informed decisions, and take proactive actions to improve air quality.

## Methodology

The methodology of this research focuses on the design, development, and implementation of an ESP32-powered intelligent real-time air quality monitoring system. The system aims to measure key air pollutants, such as PM2.5, PM10, CO2, and NO2, and provide continuous data in real-time for accessible monitoring and informed decision-making. The following sections describe the process involved in building the monitoring system, data collection, and system testing.

## System Design

The design of the real-time air quality monitoring system consists of both hardware and software components:

### Hardware Components

- **ESP32 Microcontroller**: The core of the system, which handles sensor integration, data processing, and wireless communication [12]. The ESP32 is chosen due to its versatility, built-in Wi-Fi and Bluetooth capabilities, and low power consumption.
- **Air Quality Sensors**: Various low-cost sensors are selected to measure common air pollutants:
    - **PM2.5 and PM10 Sensors**: Laser-based particulate matter sensors (such as the Nova PM SDS011 or Plantower PMS5003) to measure fine particulate pollution in the air.
    - **CO2 Sensor**: An infrared sensor like the MH-Z19 for measuring carbon dioxide (CO2) concentration.
    - **NO2 Sensor**: A gas sensor such as the MiCS-5524 or similar for detecting nitrogen dioxide (NO2) levels.

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- **Power Supply**: A stable power source, such as a USB power adapter or battery, is used to provide constant power to the ESP32 and the sensors, ensuring the system can run continuously. The flow chart diagram are shown in Figure 1.

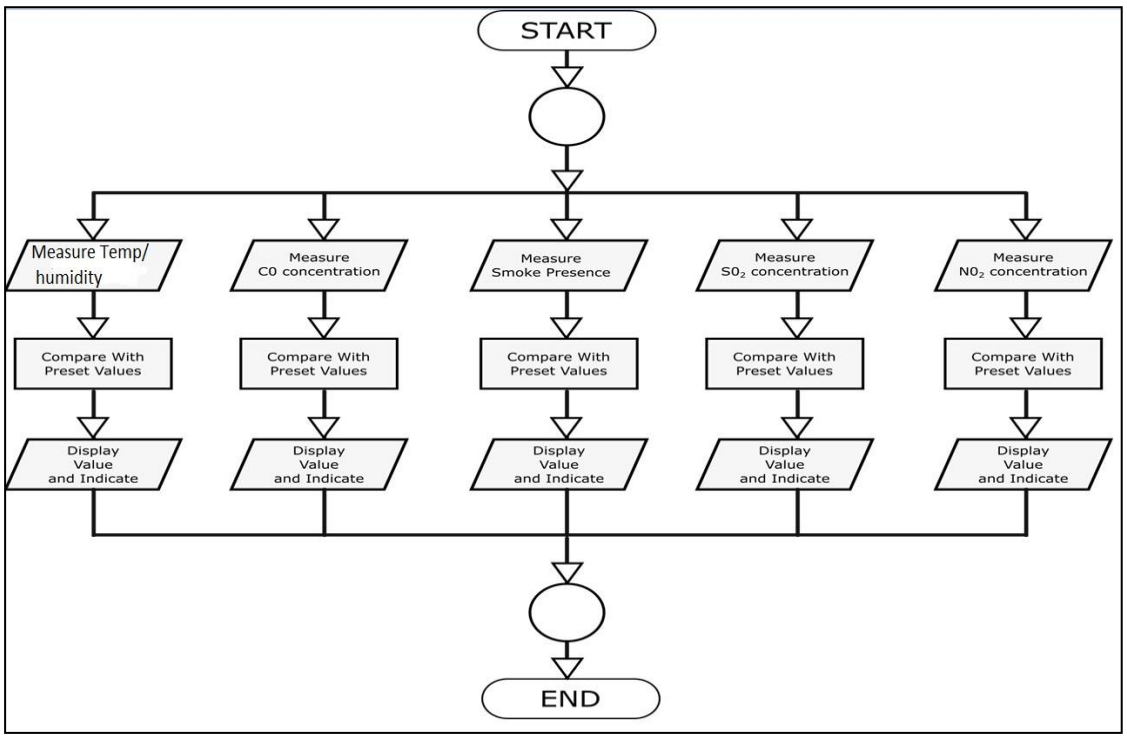


**Figure 1:** Flow Chart Diagram

### 3.1.1- Software Components:

- **Firmware Development**: The system is programmed using the Arduino IDE, utilizing libraries to interface with the ESP32 microcontroller and the connected sensors. The firmware is responsible for:
  - Collecting data from the sensors at regular intervals.
  - Processing the raw sensor data to provide meaningful air quality readings.
  - Formatting the data and transmitting it to a cloud platform via Wi-Fi.
- **Cloud Platform and Data Visualization**:
  - **Data Storage and Analysis:** The air quality data is transmitted to cloud storage, such as Thing Speak or Google Firebase, where it is stored and analyzed.

### Data Collection

To evaluate the accuracy and reliability of the system, real-time air quality data is collected from various monitoring sites, including urban, suburban, and rural areas. The following steps are involved in data collection:

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- **Initial Calibration**: Sensors are calibrated in controlled environments to ensure their accuracy. Calibration involves comparing sensor readings with reference devices or known air quality standards. Adjustments to the sensor readings are made as necessary to minimize discrepancies [13].
- **Deployment of the System**: The monitoring system is deployed in different locations to gather air quality data over an extended period. The sensors collect readings of PM2.5, PM10, CO2, and NO2 in real-time at predefined intervals, such as every 5 minutes.
- **Environmental Variables**: Additional environmental variables, such as temperature and humidity, are also monitored, as they can influence sensor performance. These variables are collected using dedicated temperature and humidity sensors like the DHT11 or DHT22. The Circuit diagram of the system are shown in Figure 2.

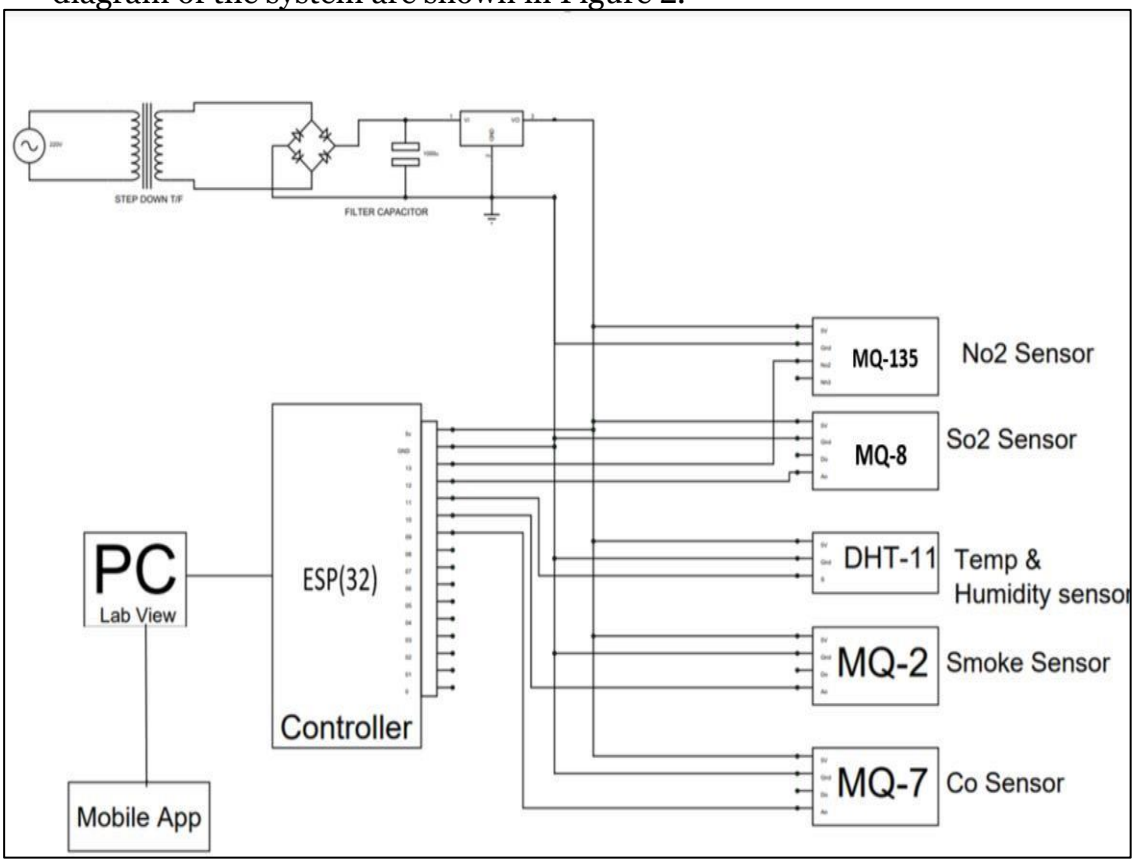


**Figure 2:** Circuit diagram of the system

**Deployment**

The final system is deployed in multiple locations, and real-time air quality monitoring is carried out continuously. The collected data is made available to both the public and policymakers, helping raise awareness about air quality issues and enabling informed decisions regarding air pollution management. The final hardware of the system are shown in Figure 3.

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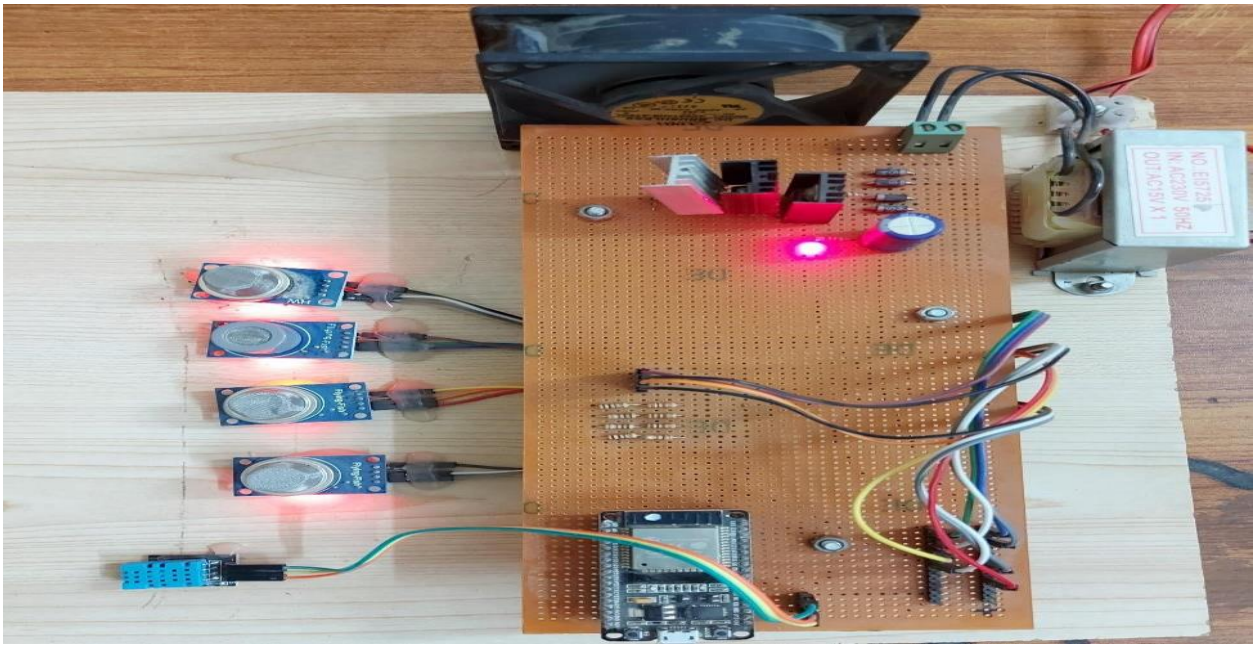

(NO2), and temperature and humidity [14]. The collected data was transmitted in real-time via Wi-Fi to a cloud platform for analysis and visualization [15]. The Figure 4,5,6,7 and 8 shows the block diagram of Temperature Sensor, Smoke Sensor, Humidity Sensor, CO Sensor, NO2 Sensor and Air Quality Index

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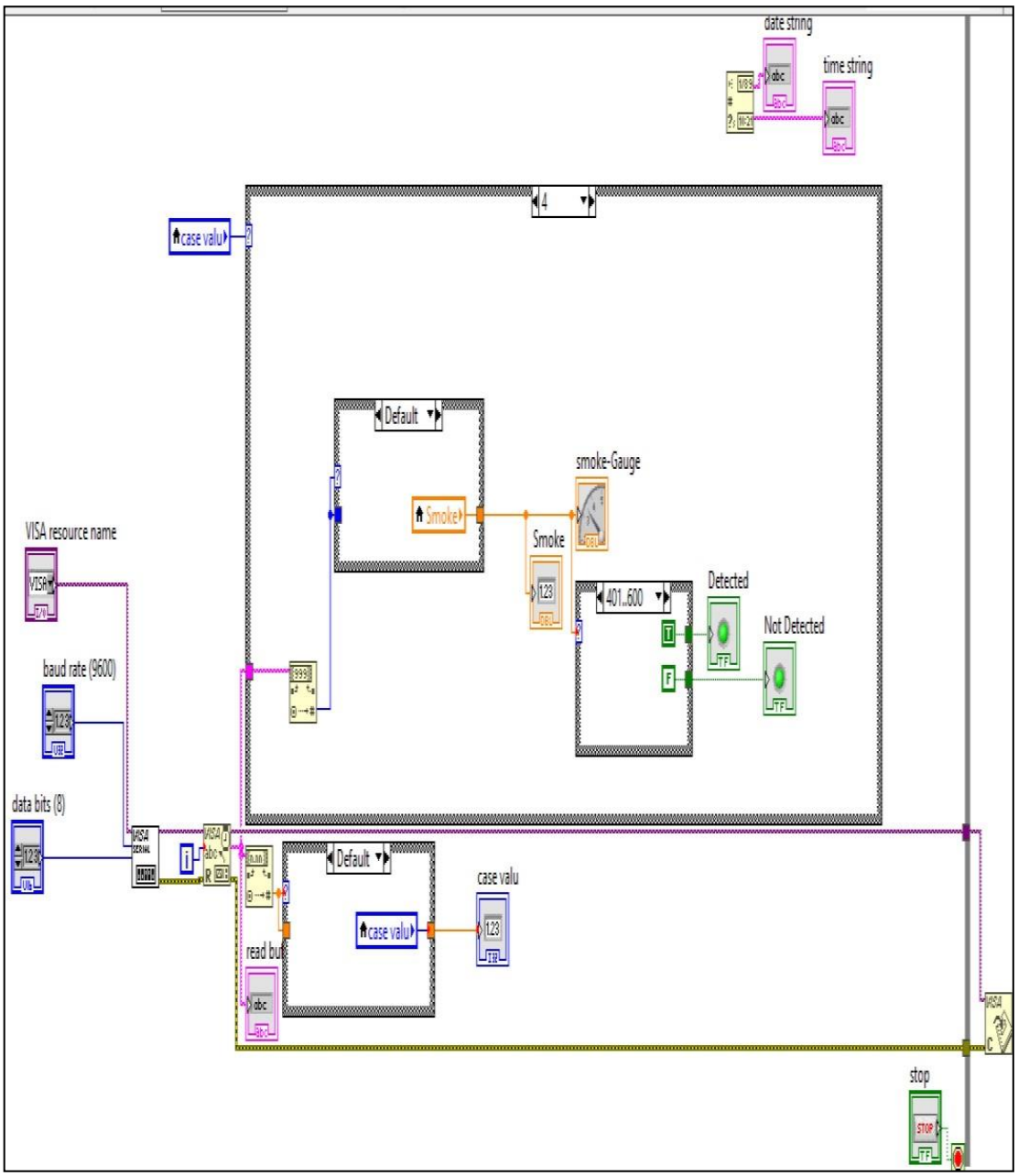


**Figure 5:** Block diagram of Smoke Sensor

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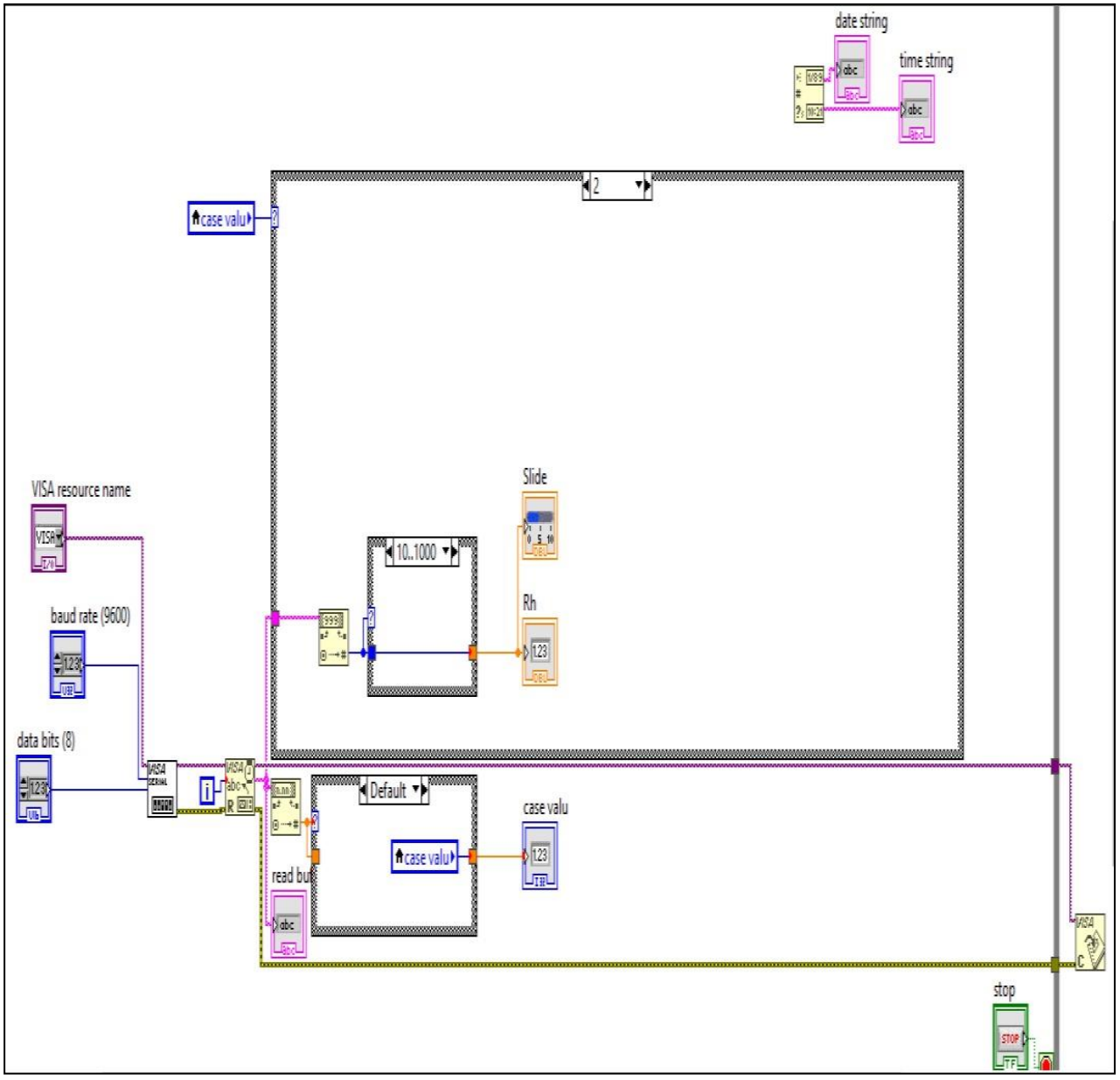


**Figure 6:** Block Diagram of Humidity Sensor

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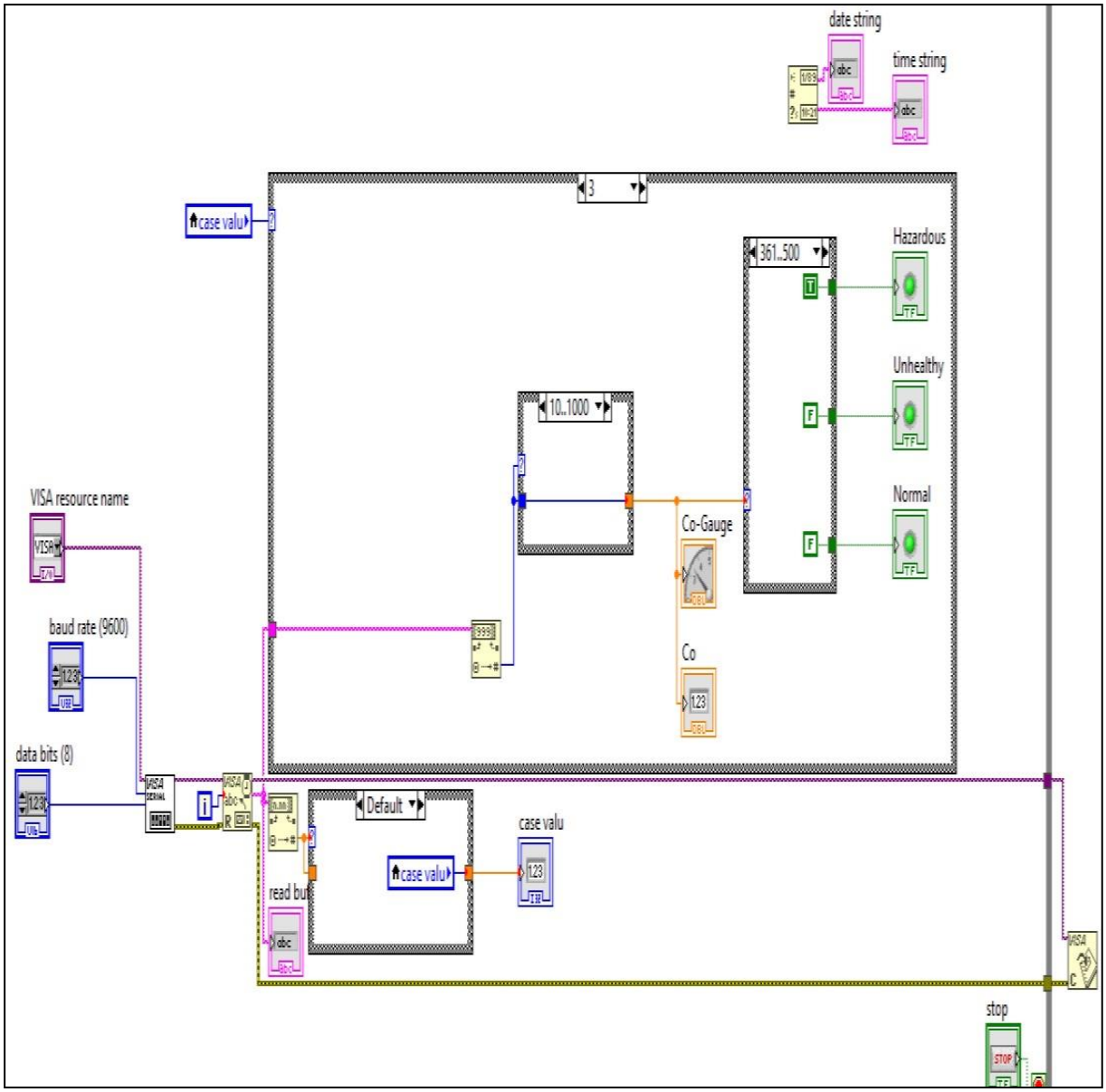


**Figure 7:** Block Diagram of CO Sensor

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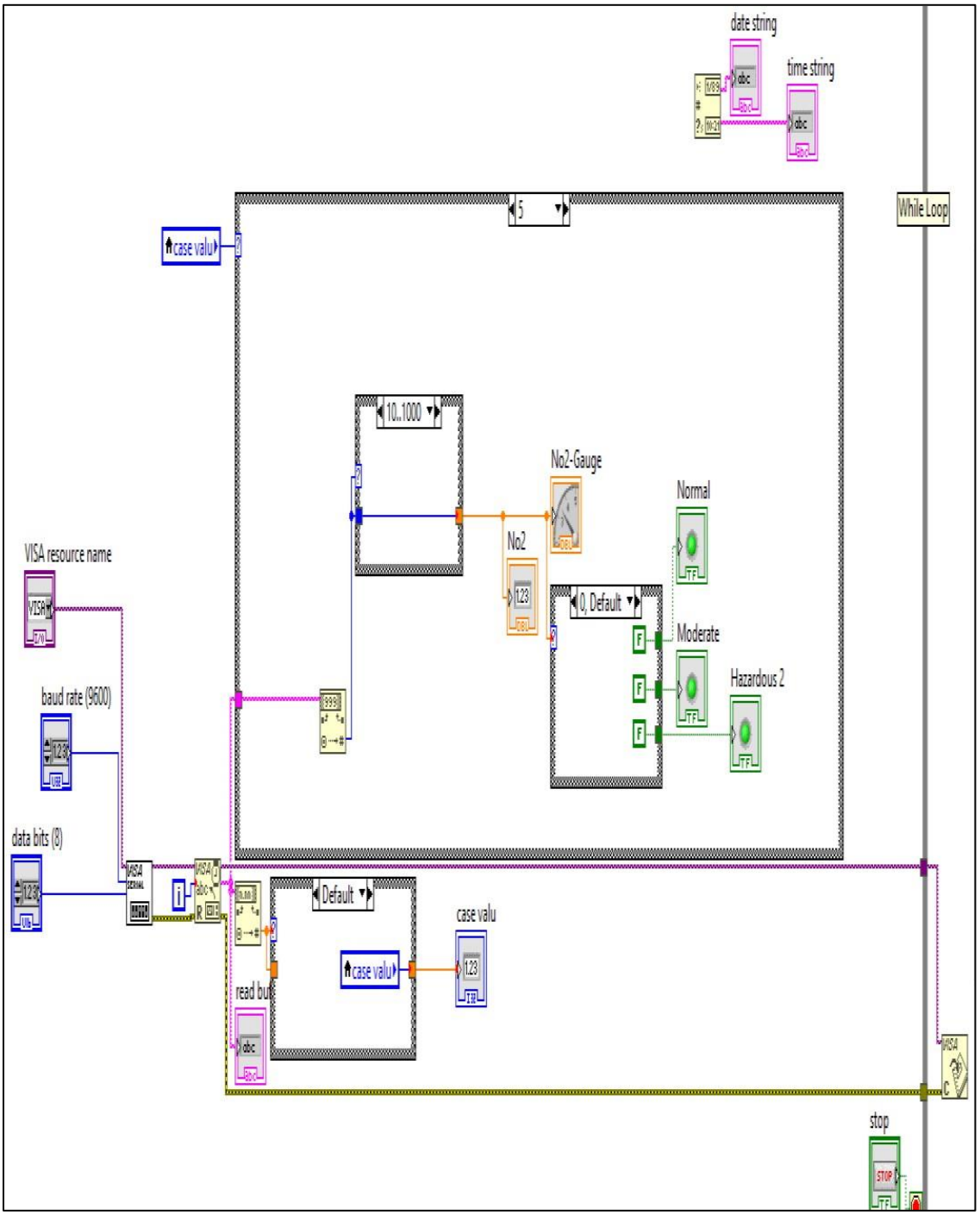


**Figure 8:** Block Diagram of NO2 Sensor

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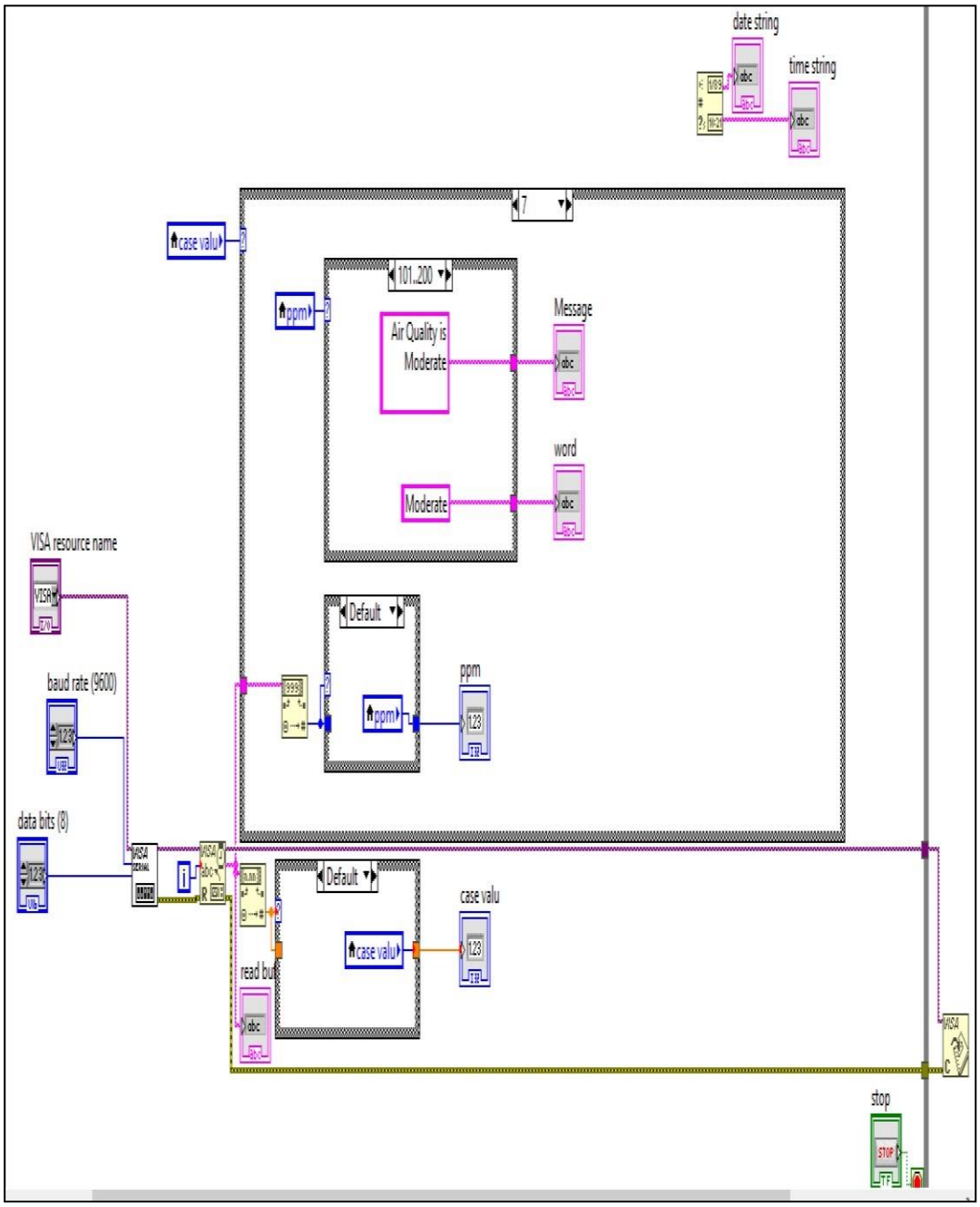


**Figure 8:** Air Quality Index

**Simulation of DC Power Supply**

This is basically a linear power supply which is designed on Proteus software and stimulated [16]. The results gained from the supply is also observed on oscilloscope, which is Proteus built-in feature. Figure 9 Shows the DC power supply schematic diagram.

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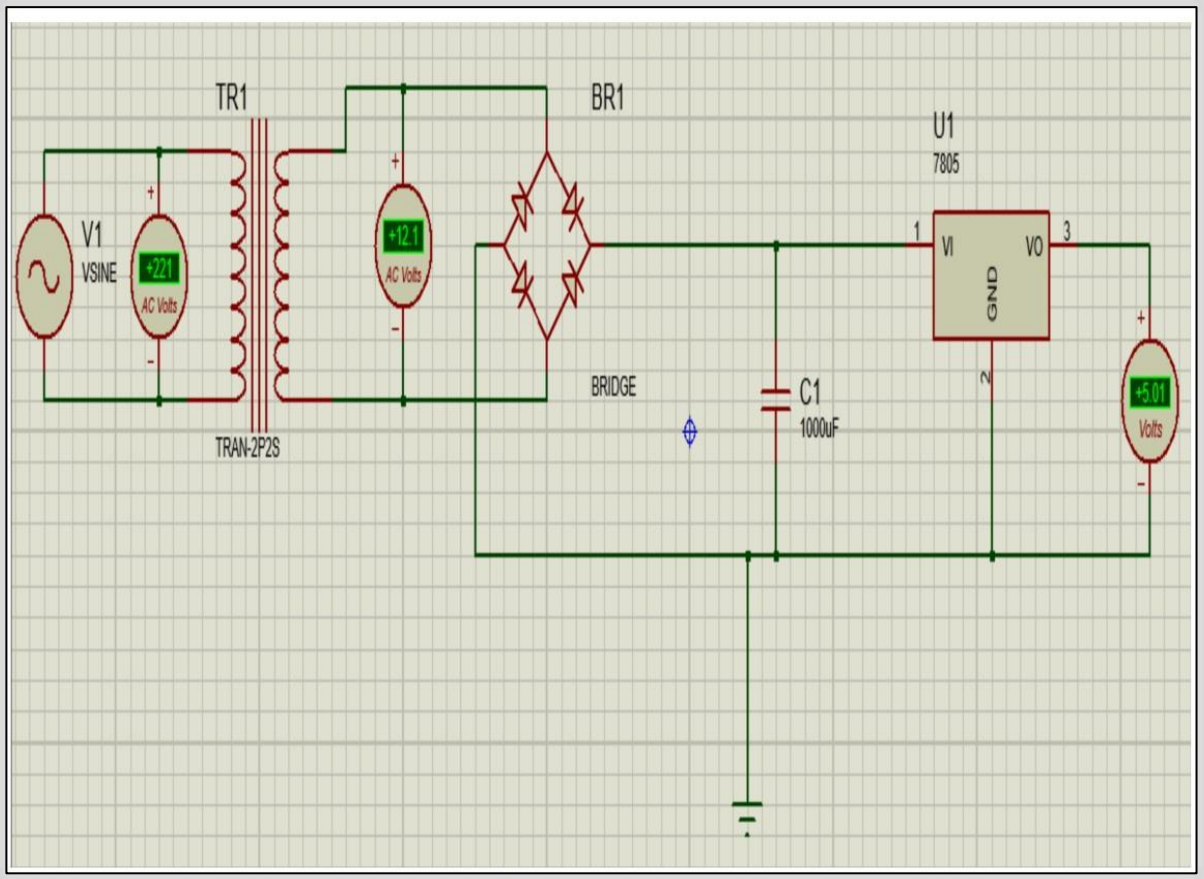


**Figure 9:** Simulation of Power Supply on Proteus Software

**Discussion**

AC source is supplied at first which is approximately 230 voltage AC and having a frequency of 50 hertz as per country standard then voltmeter is connected to it in parallel which shows the current value of voltage at the source and then a step-down transformer is attached which is basically used to convert the 230 voltages in low volts such as 30 voltages. Further, a circuit used is a bridge rectifier. It converts Alternating current into the direct current (DC) and step-down voltage with an AC voltmeter across the secondary terminal of transformer after the bridge circuit. In order to filter the ripples, there is a filtration capacitor attached, in our case the value of filtration capacitor is 1000 microfarad after that a regulator is used which will regulate the voltage at its output terminal [17]. No matter how much the voltage changes at its input terminal the voltage change at the output terminal should be with in its given limits. The output voltage depends upon the number of regulators attached. The voltage regulator is 7824 which will basically convert the input voltage into output voltage which are 24 volts [18].

**Ripple Waveform Discussion**

At the output terminal of 7824, when the constant voltage is observed so the voltage waveform will be observed at this stage, which was the output from the bridge rectifier circuit. It is observed that how much ripple is showing on

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oscilloscope so when the oscilloscope probe is attached to the output of bridge, which is in parallel to the filter capacitor [19]. It is observed that after varying the load, the ripples in the waveform were also changing. A simple voltage waveform is observed which can be seen in figure which is showing basically that there are some ripples due to load. The ripples value in voltage varies with respect to the load. So, when all the load is turn off and it is observed that there is a very smooth DC wave and the reason is that there is no load attached and the capacitor charged at peak and remains charged and not going to discharge so we will obtain very smooth wave form, but when load is connected, showing some ripple voltage from which ripple factor will be calculated.

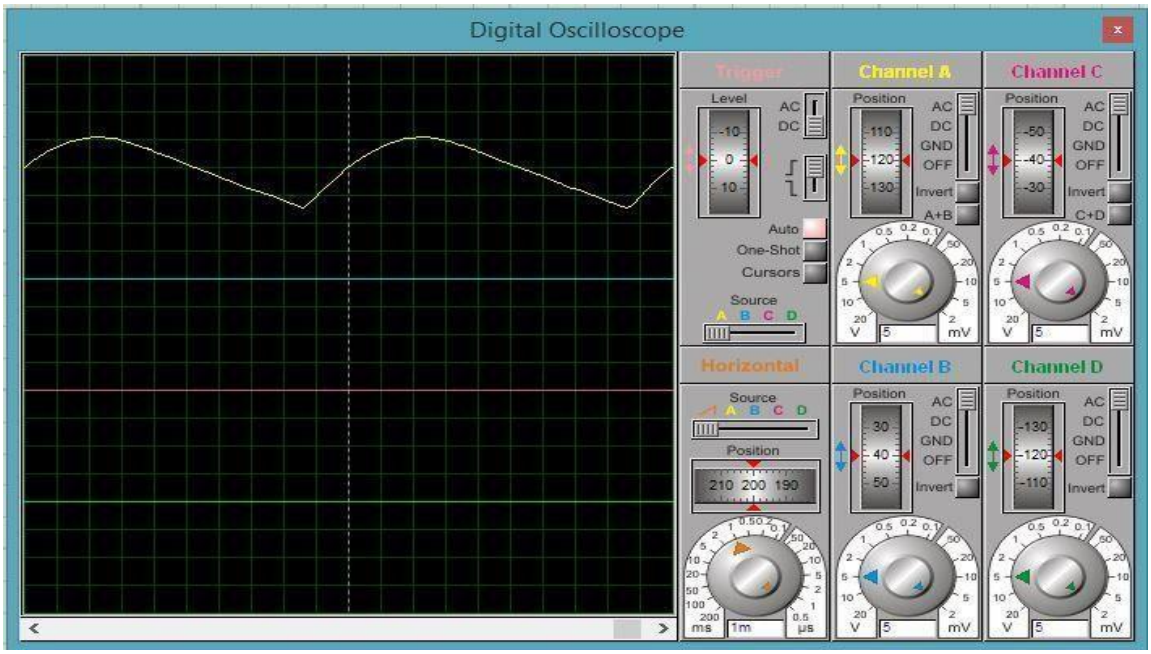


**Figure 10:** Results of waveform on Oscilloscope

**Mobile Application:**

The main idea behind Android application is to provide developers with the freedom and power to formulate at any time, any place. Thus, the development of mobile applications was made free to all users, and anyone can get benefitted from these capabilities since it is open source. The ESP-32 has the feature that it can also be connected to mobile application through server. The visible data on computer system can also be accessed through mobile app [20]. The specific app MAC address can be added through coding to the controller and can assessed the data anytime. The application we used in this project named as Blynk. It supports both the IOS and android apps to tackle and control the controller.

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**Figure 11:** Blynk Application Interface

## Future Work

Our work exhibits extensive opportunities to work on the device, application and furthermore on the field by utilizing gadget that we have been used. The gadget can be utilized effectively, any time in various areas of a city and afterward research with the accomplished information for that specific region around there. By replacing with high quality sensors in place of these sensors so more accurate results will be obtained from slightly improved ranges. Similarly, some other sensors can also be added to the device to monitor the gases such as $O_2$ and $H_2$ and many others as well. These gases will give the state of the environment continuously and authority can take into additional decisions in like manner. The android app which we have developed to access the data on mobile instead of computer, can be up to date with the market, by carrying out fundamental codes [21]. In future time, our system can be continued trying for checking whether the sensors run appropriately and give ongoing information correctly. This work can be additionally reached out with usage of up-to date by using servers in accordance with wireless sensors network by increase in the nodes where sensors are installed. As it's a small system so can be installed easily everywhere in static as well as ambient nodes are also introduced from where the data can be continuously monitored, fetched, and then sent to the main station. In this way accurate data can be obtained rather than estimated based through satellite.

## Conclusion

The article contains the modish, cheapest, and compact way to monitor the quality of air specifically the pollutant in the air is highlighted in this paper. It is

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efficient method which can be implemented anywhere being cheapest. Engineering elements of various sensors and their functioning technique have been discussed. It also includes working, applications, their uses optimally, tackling information and correlation with standard base information are additionally highlighted here. The real-time air pollution monitoring system tried for observing the gas levels on various places of the country. It additionally sent the sensor parameters to the main server which is called the main station. The project device we are making showed that it is effective and low-cost device and able us to monitor the air quality in real- time anytime, at any place. In place of cheap sensors if it is replacing with quality sensors, then its working will be more efficient than previous and can be reliably installed anywhere which can help in the sorting out the pollutant area where easily precautionary steps been taken to get safe from the damage that will be caused in future.

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