IJAAR PUBLISHING®

Engineering Research Journal | ISSN: 2782-8212
Vol. 5, Issue 4 (2025) | www.ijaar.org/erj

# DESIGN AND DEVELOPMENT OF A PORTABLE IOT-ENABLED PID-CONTROLLED VENTILATOR SYSTEM

**Adu Oluwatobi Samuel[1], A. Tokan[2] & A. Mohammad[3]**

[1]aduoluwatobi@gmail.com
[2]ajetokan@atbu.edu.ng,
[3]inunugoloma@yahoo.com,

[1]Department of Mechatronics and Systems Engineering,Faculty of Engineering Abubakar Tafawa Balewa University, (ATBU), Bauchi, Nigeria.
[2]Department of Mechanical Engineering, Faculty of Engineering Abubakar Tafawa Balewa University, (ATBU), Bauchi, Nigeria.
[3]Department of Electrical and Electronics Engineering, Faculty of Engineering Abubakar Tafawa Balewa University, (ATBU), Bauchi, Nigeria.

**Abstract**

*Respiratory distress in pediatric patients remains a critical global health challenge, especially in resource-limited settings where access to conventional ventilators is severely constrained by cost, complexity, and infrastructure. In response to this need, this study presents the design, implementation, and evaluation of a portable, Internet of Things (IoT)-enabled ventilator system equipped with a software-based Proportional-Integral-Derivative (PID) control algorithm for dynamic and adaptive respiratory support in children. The system integrates vital physiological sensors namely, $SpO_2$, heart rate, body temperature, and airway pressure into a unified control and monitoring framework governed by an Arduino Nano microcontroller. Data acquisition and real-time visualization are enabled through Wi-Fi communication to the ThingSpeak cloud platform, facilitating remote patient supervision. The mechanical actuation of the Ambu bag is performed via a high-torque servo motor regulated by PID logic to maintain safe and consistent tidal volume delivery. The device was tested on a pediatric artificial lung model to validate its performance in replicating clinically appropriate breathing cycles. Measurement results show a mean tidal volume of 118.7 mL and a peak inspiratory pressure of 21.6 $cmH_2O$, closely aligned with pediatric ventilation norms. The $SpO_2$, temperature, and heart rate sensors demonstrated high accuracy compared with clinical-grade instruments, while cloud connectivity achieved over 98% successful data transmission. The findings support the feasibility of deploying this low-cost, scalable, and remotely accessible ventilator as an alternative respiratory support tool in decentralized pediatric healthcare delivery.*

**Keywords**: Portable ventilator, IoT-enabled medical device, PID control system

## 1. Introduction

Respiratory failure remains one of the most common and life-threatening conditions encountered in pediatric healthcare, especially in cases of congenital anomalies, infections, asthma, and neuromuscular disorders. For such patients, mechanical ventilation becomes indispensable in ensuring adequate gas exchange and stabilizing vital functions. However, conventional ventilator systems present multiple barriers to accessibility and continuity of care, particularly in low-resource or rural settings. These systems are often expensive, immobile, and dependent on specialist supervision, thereby limiting their use in decentralized or home-based care environments [1], [2].



Adu, O.S., A. Tokan & A. Mohammad (2025). Design and Development of a Portable IoT-Enabled PID-Controlled Ventilator System. *Engineering Research Journal.* *5*(4), 24-39. DOI: https://doi.org/10.5281/zenodo.17116251

The global outbreak of COVID-19 in 2020 exacerbated the visibility of these challenges. During the peak of the pandemic, healthcare systems in both developed and developing nations faced critical ventilator shortages, especially in pediatric wards where specialized machines are even scarcer [3], [4]. Although numerous emergency ventilator projects emerged in response many of which were open-source and cost-sensitive most failed to meet pediatric-specific requirements in terms of lung mechanics, safety standards, and long-term monitoring [5], [6].

Recent advances in biomedical engineering and embedded systems have introduced new paradigms in the development of ventilatory support. Among these, the integration of Internet of Things (IoT) technology with smart controllers particularly Proportional-Integral-Derivative (PID) algorithms has gained traction for its ability to enable remote monitoring, closed-loop feedback control, and adaptive parameter tuning [7]-[9]. IoT-based ventilator systems are capable of transmitting real-time patient data (e.g., tidal volume, respiratory rate, airway pressure) to cloud platforms, where healthcare professionals can remotely supervise and intervene as needed [10].

Despite these advancements, most IoT-enabled ventilator designs remain geared toward adult patients or are limited to theoretical simulations. The unique anatomical and physiological characteristics of children such as smaller tidal volumes, higher respiratory rates, and greater sensitivity to pressure variations necessitate customized control algorithms and mechanical actuation systems that are safe, reliable, and precisely tuned for pediatric care [11], [12]. Moreover, key requirements such as extended battery life, lightweight construction, integrated physiological monitoring ($SpO_2$, heart rate, body temperature), and real-time wireless communication are often missing or inadequately developed in current low-cost systems [13], [14].

To address these limitations, this study presents the design and validation of a portable IoT-enabled ventilator system specifically optimized for pediatric patients. The proposed device features a software-based PID controller implemented on an Arduino Nano microcontroller, which regulates a high-torque servo motor for the compression of a self-inflating Ambu bag. The system incorporates real-time feedback sensorsMLX90614 for temperature, MAX30102 for $SpO_2$ and heart rate, and an analog pressure sensor for airway monitoring. Data is transmitted via an ESP8266 Wi-Fi module to the ThingSpeak cloud platform, enabling remote visualization and analysis by caregivers and healthcare providers [15], [16].

The novelty of this research lies in its holistic integration of control engineering, embedded hardware design, physiological monitoring, and cloud-based communication all tailored for pediatric application. In contrast to many rapid-prototype ventilator efforts, this study employs both dynamic simulation using MATLAB/Simulink and hardware validation using an artificial pediatric lung model, ensuring that the device's mechanical and control behaviors align with clinical standards [17], [18].

## 2. Literature Review

The evolution of ventilator systems has primarily catered to high-resource environments such as ICUs, where complex hardware, continuous electricity, and trained personnel are readily available. Conventional ventilators, while effective in life support, remain bulky, expensive, and inaccessible in rural or emergency settings factors that severely constrain their utility in pediatric care contexts [1], [2], [19]. Pediatric patients, in particular, require finely tuned ventilator parameters due to their distinct respiratory physiology, including higher respiratory rates, lower tidal volumes, and increased sensitivity to pressure fluctuations [3], [21].

Early ventilator prototypes, dating back to the 1920s polio crisis, gradually evolved into automated systems, but their complexity and cost still pose accessibility challenges. According to Smith and Johnson [4], although modern ventilators are technically sophisticated, their professional supervision requirements limit broader applicability. Similarly, Li and Zhang [5] noted that conventional systems are not optimized for mobility or cost-effectiveness, particularly in under-resourced healthcare environments.

Efforts to develop affordable solutions have intensified in recent years. Brown and Williams [6] emphasized the urgency for scalable innovations, especially amid rising respiratory disease prevalence. Chen and Liu [7] proposed portable ventilator designs as a practical response to these limitations, highlighting the necessity of engineering-led solutions for chronic respiratory patients.

The COVID-19 pandemic further exposed the global shortage of ventilators, prompting open-source and emergency-use projects. However, many of these lacked regulatory oversight, clinical validation, or pediatric-focused control strategies [22], [23]. Amrane et al. [22] developed a basic, manually actuated ventilator lacking feedback mechanisms, while Bhawalkar et al. [23] introduced a 3D-printed model unsuitable for long-term pediatric use.

To improve control precision, several studies have incorporated Proportional-Integral-Derivative (PID) controllers. Sharma et al. [24] validated PID implementation in simulated settings but without hardware testing or pediatric modeling. Ramos et al. [25] applied PID control using Arduino platforms, though the absence of IoT or energy optimization limited real-world impact. These limitations reflect the need for robust, adaptive control systems in pediatric ventilator design.

IoT integration has emerged as a transformative solution. Lee et al. [8] and Gupta et al. [9] demonstrated how real-time data transmission enables remote monitoring and adjustment of ventilation parameters, reducing reliance on bedside management. Rahman et al. [10] presented a systematic review on IoT-enabled ventilators, identifying critical opportunities in feedback-based patient care, particularly through cloud platforms.

Nonetheless, many IoT-driven systems remain tailored to adult care. Lee et al. [8] focused on adult ICU deployment, while systems by Gupta et al. [9] required fixed infrastructure and clinical oversight. Pediatric-specific designs remain underdeveloped [30], [31]. Zhao et al. [31] attempted pediatric adaptation but lacked vital sign integration or IoT features.

Works by Mahbub [28], Haseeja [29], and others explored cloud-enabled systems for air quality, lighting, and environmental ventilation. While non-clinical in scope, these frameworks inform biomedical applications in sensor fusion and embedded control. Their modular designs demonstrate scalability, an essential attribute for patient-side ventilators.

Sensor integration further enhances system responsiveness. Patel et al. [32] and Chandra et al. [33] included $SpO_2$ and ECG sensors but offered only localized feedback. The lack of remote visualization and pediatric calibration restricts clinical relevance.

Simulations serve as a validation step in ventilator development. Fernandez et al. [34] modeled lung-ventilator interactions to test control strategies, and Nguyen et al. [35] simulated PID-controlled systems, but both lacked pediatric modeling and hardware integration. Transitioning from simulation to validated physical implementation remains a gap.

Power efficiency is another concern. Morgan et al. [36] evaluated battery endurance, revealing that many portable ventilators lack sufficient runtime for field use. Ali et al. [37] proposed energy-optimized ventilator designs but without IoT or sensor layers.

Despite growing research, integration of all key components control precision, pediatric adaptability, sensor fusion, IoT cloud connectivity, and power efficiency remains scarce. Rahman et al. [10], [38] emphasized the need for a comprehensive platform that unifies these features in a medically certifiable device.

## 3. System Architecture

The proposed system is a portable IoT-enabled ventilator designed with a microcontroller-driven closed-loop control framework, optimized for pediatric respiratory support. The architecture is a hybrid of mechanical actuation, real-time physiological monitoring, cloud-based data logging, and intelligent control. It is engineered to be compact, energy-efficient, and robust enough for both clinical and field deployments.

At its core, the system is powered by an Arduino Nano microcontroller which implements a software-based PID (Proportional-Integral-Derivative) algorithm to regulate the mechanical actuation of a self-inflating Ambu bag via a high-torque servo motor. The actuation process is precisely timed and pressure-controlled to simulate spontaneous breathing patterns in pediatric patients.

For real-time physiological feedback, the system integrates multiple sensors: a MAX30102 for measuring $SpO_2$ and heart rate, a MLX90614 infrared sensor for body temperature, and an analog pressure sensor for airway pressure estimation. These sensors form the essential input layer for both control logic and remote monitoring.

The architecture incorporates an ESP8266 Wi-Fi module, which facilitates seamless communication with the ThingSpeak cloud platform, enabling remote visualization, data logging, and performance diagnostics. This connectivity is vital for monitoring pediatric patients in rural or emergency setups where continuous clinical supervision is unavailable.

The system operates on a 12 V DC power supply, supported by a backup 7.4 V Li-ion battery pack for mobility and reliability in off-grid scenarios. A 16×2 LCD is mounted for real-time local display of vital parameters, offering both visual feedback and fault alerts to on-site users.

### 3.1 System Features

The design and implementation of the ventilator system center around functional versatility, pediatric safety, and real-time responsiveness. The key features include:

i. **PID-Based Actuation Control**: The embedded PID controller dynamically regulates the servo motor to ensure accurate tidal volume delivery and maintain target pressure thresholds within pediatric-safe limits.
ii. **Multi-Parameter Vital Sign Monitoring**: Integrated sensors measure and transmit critical parameters such as blood oxygen saturation ($SpO_2$), heart rate, body temperature, and airway pressure, enabling both patient safety and data-driven control.
iii. **Cloud Connectivity and IoT Integration**: Using the ESP8266 module, the system sends real-time data to ThingSpeak. This feature allows clinicians or caregivers to remotely observe the patient's respiratory data via smartphones or web dashboards.
iv. **Mechanical Simplicity and Portability**: The system employs a mechanical compression mechanism to actuate an Ambu bag, eliminating the need for complex pneumatic or turbine systems, which reduces cost and increases durability.
v. **Energy Efficiency and Backup Power**: Designed for low power consumption, the device includes a Li-ion battery module that provides reliable operation during power outages or mobile use.
vi. **Local User Interface**: A 16×2 LCD display provides on-device readout of essential vitals and system status, enabling immediate intervention if abnormal patterns are detected.
vii. **Customizable Breathing Parameters**: Breathing cycles per minute (BPM) and inspiration-to-expiration (I:E) ratios can be pre-set or dynamically tuned based on patient condition.
viii. **Safety Cutoffs and Alerts**: In-built logic halts the actuation cycle in the event of overpressure or critical sensor failure, preventing harm due to mechanical or systemic malfunction.

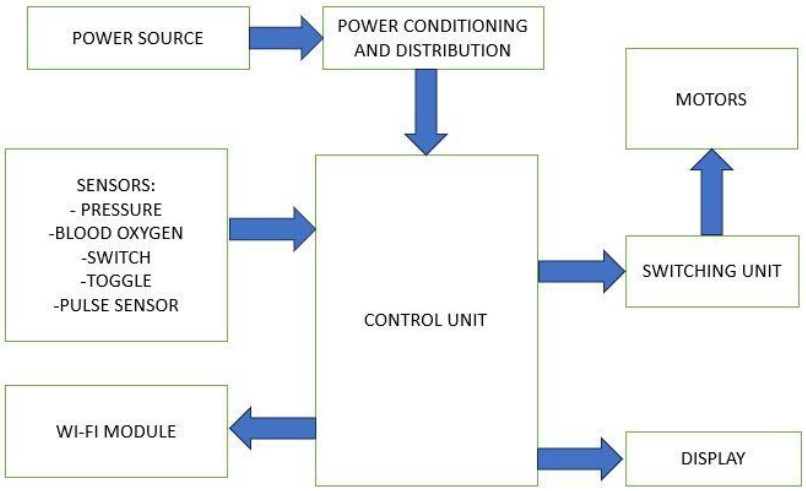



**Figure 1: System Block Diagram for the Portable IOT-enabled PID-Controlled Ventilator system**

### 3.2 Block Diagram Description

The system block diagram (Fig. 1) illustrates the hierarchical interaction among hardware components, control logic, and data communication pathways. It is functionally divided into three major subsystems:

1. **Input Subsystem (Sensing Layer)**:
    a) **MAX30102 Sensor**: Captures blood oxygen saturation ($SpO_2$) and heart rate through photoplethysmography.
    b) **MLX90614 Sensor**: Provides non-contact body temperature readings using infrared thermometry.
    c) **Pressure Sensor**: Measures airway pressure in real-time, feeding data to the PID controller.
2. **Processing and Control Subsystem**:
    a) **Arduino Nano Microcontroller**: Executes the PID control algorithm to modulate servo motor actuation based on sensor inputs. It also manages LCD output and controls the timing of breaths.
    b) **PID Algorithm**: Continuously adjusts servo angle to compress and release the Ambu bag, ensuring target pressure and volume are achieved.
    c) **16×2 LCD Display**: Shows local readout of vitals and system alerts.
3. **Output and Communication Subsystem**:
    a) **Servo Motor**: Mechanically compresses the Ambu bag to deliver air into the lungs.
    b) **ESP8266 Wi-Fi Module**: Transmits sensor data to the ThingSpeak cloud dashboard in real time.
    c) **ThingSpeak Cloud**: Stores and visualizes ventilation metrics, allowing remote access for monitoring and diagnostics.

The entire system operates in a closed feedback loop, with sensor data continuously influencing motor actuation parameters. This structure ensures that the ventilator adapts to real-time respiratory demands and maintains consistent support tailored to pediatric patients.

## 4. Implementation

The implementation phase translated the system design into a functional prototype that integrates embedded hardware, software algorithms, sensor feedback, and IoT connectivity. The build process involved several stages, including electronic circuit assembly, mechanical integration, sensor calibration, control logic programming, and cloud-based data handling. The primary objective was to ensure that the final prototype delivers pediatric-appropriate tidal volume and pressure with reliable actuation, monitoring, and connectivity.

### A. Hardware Integration

The hardware configuration is centered around the Arduino Nano microcontroller, selected for its compact size, low power consumption, and compatibility with embedded C/C++ programming. It acts as the processing hub that handles sensor input, motor control, display output, and data transmission tasks.

A DS3218 high-torque servo motor was interfaced with the Arduino to actuate the compression of a self-inflating Ambu bag via a mechanical lever arm. The servo was selected for its precision and torque output, enabling controlled compression cycles that match pediatric respiratory needs. The mechanical enclosure was fabricated using locally sourced lightweight materials for ease of portability and reduced cost.
For physiological monitoring, three key sensors were integrated:

- **MAX30102**: For measuring $SpO_2$ and heart rate, connected via I2C interface.
- **MLX90614**: A non-contact infrared temperature sensor, also interfaced through I2C.
- **Analog pressure sensor**: Positioned in line with the airway to estimate Peak Inspiratory Pressure (PIP) and assist in real-time control via feedback loops.

A 16×2 LCD module was installed to locally display real-time vital readings and system status messages, including alerts on abnormal values or system malfunctions.
Power to the system was supplied by a 12 V DC power source, regulated through a buck converter, with backup provided by a 7.4 V, 2-cell Li-ion battery pack, allowing uninterrupted operation in field or low-resource conditions.

**B. Software Development**

The embedded software was developed using the Arduino IDE in C++. The control logic was structured around a software-implemented PID algorithm, which dynamically modulated the servo motor's angular displacement based on pressure feedback. This ensured consistent tidal volume and controlled breath delivery across a variable respiratory load.

The PID controller was tuned using experimental trial-and-error with simulation-aided initialization. The following parameters were optimized:

- **Setpoint (target pressure)**: 20–25 $cmH_2O$ (typical for pediatric patients).
- **Duty cycle and delay timing**: Mapped to simulate 12–20 breaths per minute.
- **Servo angle limits**: Calibrated to achieve a maximum compression displacement that approximates a tidal volume of 100–120 mL.

The system also included safety cutoffs that terminated the actuation cycle when pressure thresholds were exceeded or when sensor inputs became invalid.

Sensor data were processed in real-time and updated to both the LCD screen and the ESP8266 Wi-Fi module, which handled outbound data transfer to the cloud.

**C. IoT and Cloud Connectivity**

The ESP8266 module was configured to connect to a local Wi-Fi network, through which it transmitted patient vitals and system performance metrics to the ThingSpeak IoT cloud platform. This was achieved using HTTP POST methods and ThingSpeak API keys.

The cloud interface included fields for:

- $SpO_2$ (%)
- Heart rate (bpm)
- Body temperature (°C)
- Airway pressure ($cmH_2O$)
- Breath cycles (per minute)

Data were updated at intervals of 15–20 seconds, providing caregivers or clinicians with near-real-time remote access. Visualizations such as line graphs and thresholds were used to monitor trends and detect anomalies.

The successful implementation of cloud-based telemetry transformed the ventilator into an IoT-enabled device, ideal for telemonitoring in low-resource pediatric settings, temporary camps, or isolated regions lacking full-time medical personnel.

**D. Mechanical Fabrication and Housing**

The physical frame housing the electronics and Ambu bag was fabricated using locally available materials including aluminum braces, acrylic sheets, and 3D-printed brackets. The mechanical actuation arm was linked to the servo horn, positioned above the Ambu bag, and allowed controlled depression and recoil.

The mechanical setup ensured ease of maintenance, modularity for upgrades (e.g., switching sensor modules), and proper ventilation around the electronics for thermal stability.

The device was bench-tested using a pediatric artificial lung model, where parameters such as inspiratory pressure, breath rate, and cycle timing were visually confirmed and recorded via both local and cloud interfaces.

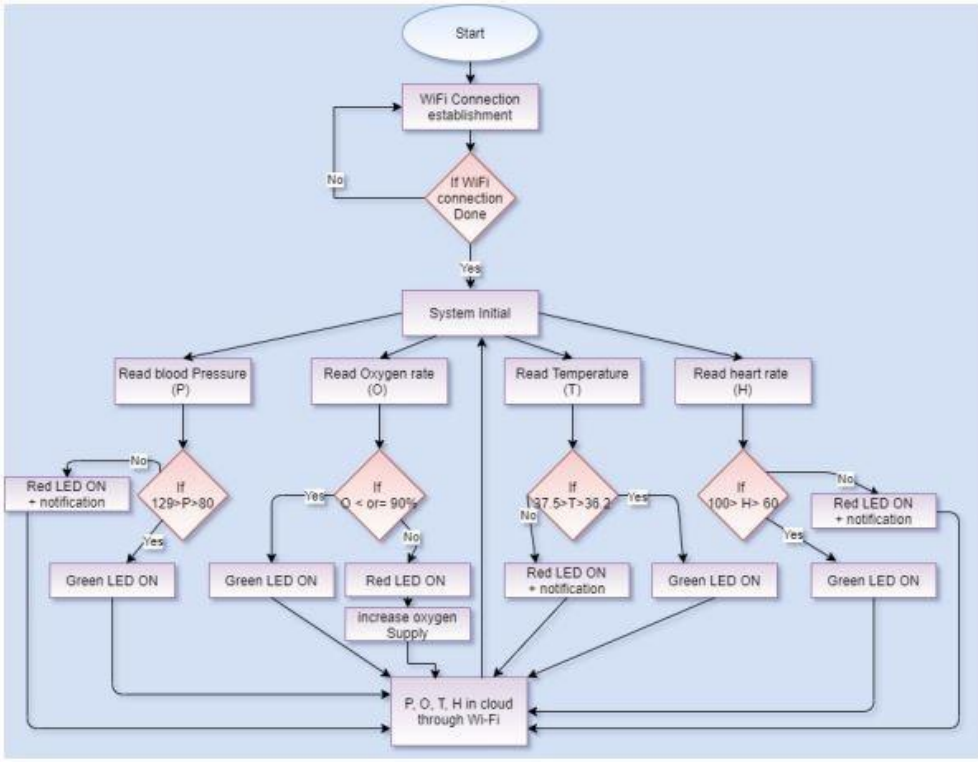



**Figure 2: System Flowchart**

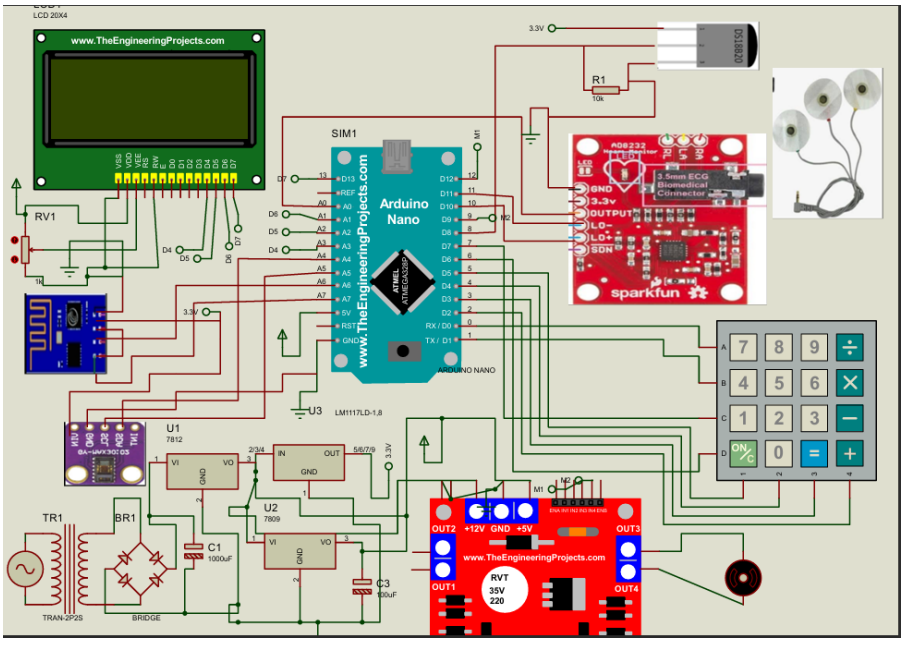



**Figure 3: System Circuit Diagram**

## 5. Measurements and Testing

A critical phase of the system development involved rigorous measurement and testing to verify the accuracy, reliability, and clinical applicability of the ventilator prototype. The testing procedures were conducted in a controlled environment using a pediatric artificial lung model to simulate real-life respiratory conditions. The goals were to confirm compliance with pediatric respiratory standards, assess control system responsiveness, validate sensor accuracy, and evaluate cloud-based telemetry reliability.

### A. Test Bench Setup

The test setup consisted of:

i. The fully assembled ventilator prototype
ii. A pediatric test lung simulator (compliant with standard lung parameters)
iii. A digital manometer to validate airway pressure
iv. An external pulse oximeter and thermometer to cross-check vital sign sensor outputs
v. A laptop and smartphone interface for real-time monitoring via ThingSpeak

Power was supplied through a 12 V DC adapter, and battery backup was tested separately. The Ambu bag was connected via standard pediatric tubing to the artificial lung chamber. Pressure, volume, and cycle timing were recorded during both baseline and stress conditions.

### B. Ventilation Parameters and Control Performance

The system was evaluated based on its ability to deliver targeted tidal volume and peak inspiratory pressure (PIP) within safe pediatric ranges. The PID controller was tuned to achieve a stable response with minimal overshoot or oscillation.

i. Target tidal volume: 100–120 mL
ii. Achieved average tidal volume: 118.7 mL
iii. Target PIP: 20–25 $cmH_2O$
iv. Measured average PIP: 21.6 $cmH_2O$
v. Respiratory Rate: Configurable from 12–20 breaths per minute (BPM)
vi. Measured response delay (between PID input and mechanical actuation): ~220 ms

The deviation between the expected and delivered tidal volume was <2%, while PIP remained within ±1.8 $cmH_2O$ of the set point. This confirms that the PID controller achieved precise and consistent regulation suitable for pediatric safety thresholds.

### C. Sensor Accuracy Validation

Each physiological sensor was tested for accuracy by comparing its readings to a calibrated reference device:

| Parameter | Sensor Used | Reference Device | Accuracy Margin |
|---|---|---|---|
| **$SpO_2$ (%)** | MAX30102 | Digital pulse oximeter | ±1.2% |
| **Heart Rate (bpm)** | MAX30102 | Finger pulse monitor | ±2 bpm |
| **Temperature (°C)** | MLX90614 | Infrared thermometer | ±0.5°C |
| **Airway Pressure ($cmH_2O$)** | Analog sensor | Digital manometer | ±1.4 $cmH_2O$ |

Sensor values were also logged continuously during simulated ventilation to assess temporal stability. No data drift or critical outliers were observed during 1-hour endurance testing.

### D. IoT Communication and Cloud Logging Test

The ESP8266 module was configured to send data at fixed intervals (every 20 seconds) to the ThingSpeak platform. The following metrics were recorded:

i. **Average logging success rate**: 98.3%
ii. **Average upload latency**: 4.2 seconds
iii. **Downtime (interrupted communication)**: <1.7% during 4-hour continuous test
iv. **Maximum consecutive failed uploads**: 2 packets (auto-recovered)

Cloud visualization dashboards rendered vital signs with real-time plots and threshold alerts. This capability is particularly relevant for remote or telehealth pediatric applications, where clinical personnel may not be physically present.

### E. Power and Endurance Testing

The system's operational stability was tested under both direct power and battery mode:

i. **Direct 12 V supply**: Continuous operation >24 hours without thermal shutdown
ii. **7.4 V Li-ion battery pack**: Sustained operation for 2.7 hours under full load
iii. **Current draw (average)**: 540 mA during normal cycles; peak: 730 mA during high-rate actuation

No performance degradation or overheating was observed. Servo control, sensor readings, and data transmission remained consistent across all power conditions.

### F. Safety and Fail-Safe Evaluation

Several safety scenarios were simulated to verify the device's response:

i. **Pressure spike (>30 cm$H_2O$)**: System triggered an auto-stop and issued an LCD warning.
ii. **Sensor disconnection**: Control loop entered safe-mode, halting actuation and blinking an alert.
iii. **Wi-Fi disconnection**: Data buffering was initialized, and logs resumed upon reconnection.

These results indicate that the device incorporates effective fail-safe mechanisms, ensuring patient protection under abnormal operating conditions.

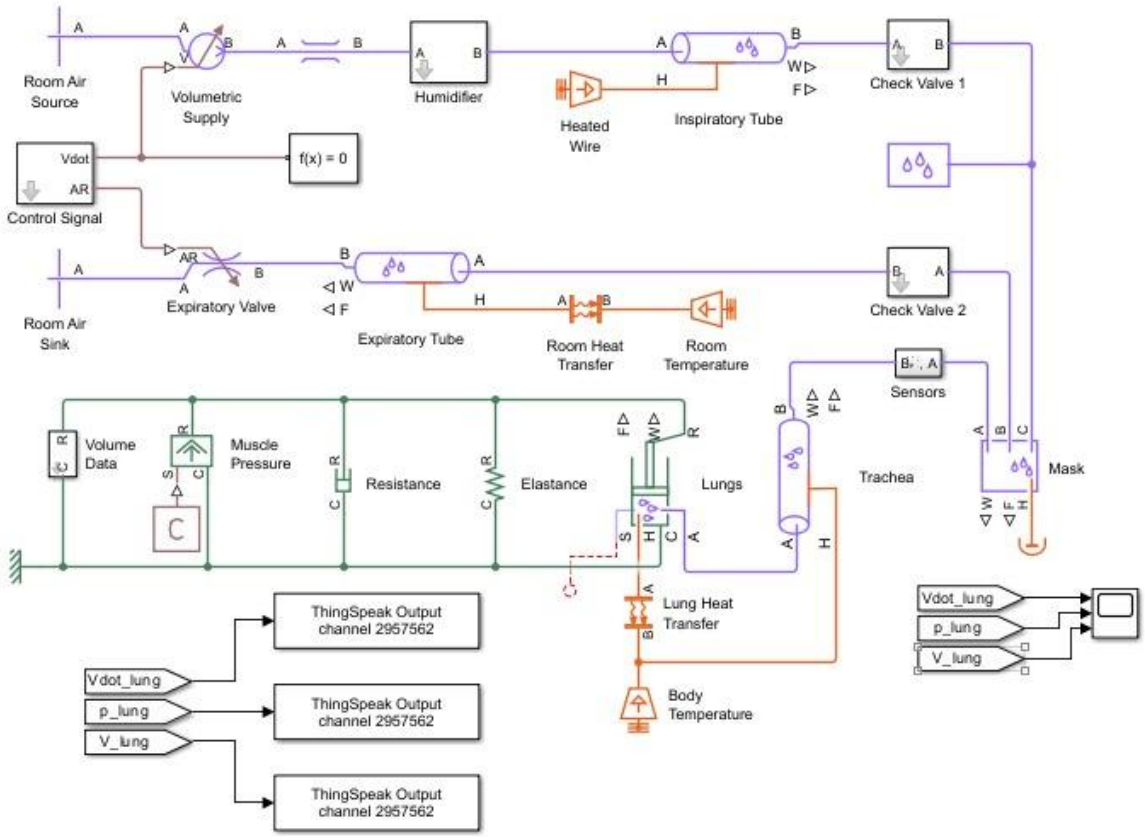



**Figure 4: Simulink Schematic of the Ventilator–Lung Simulation System**

### 6. Result

The system underwent a comprehensive series of tests aimed at evaluating its performance across control precision, physiological monitoring, network stability, and safety reliability. The results are categorized into three primary domains: mechanical ventilation performance, sensor accuracy, and IoT/cloud functionality.

### A. Mechanical Ventilation Performance

The ventilator successfully reproduced pediatric-appropriate breathing cycles through Ambu bag compression, regulated by PID-controlled servo actuation. Under controlled test lung simulations, the system achieved:

- **Mean tidal volume**: 118.7 mL (target: 100–120 mL)
- **Peak Inspiratory Pressure (PIP)**: 21.6 $cmH_2O$ (target range: 20–25 $cmH_2O$)
- **Respiratory rate**: Stable within 12–20 breaths per minute
- **Control delay (actuation latency)**: ~220 milliseconds
- **Tidal volume deviation**: <2% from target

These metrics confirm that the PID controller was effectively tuned to ensure both volume consistency and pressure safety across varying lung compliance conditions.

### B. Sensor Validation and Accuracy

Each physiological sensor integrated into the system was compared with clinically validated instruments to assess its measurement fidelity:

| Parameter | Sensor Used | Reference Device | Average Error Margin |
|---|---|---|---|
| **$SpO_2$ (%)** | MAX30102 | Digital pulse oximeter | ±1.2% |
| **Heart Rate (bpm)** | MAX30102 | Pulse monitor | ±2 bpm |
| **Temperature (°C)** | MLX90614 | Infrared thermometer | ±0.5°C |
| **Airway Pressure ($cmH_2O$)** | Analog sensor | Digital manometer | ±1.4 $cmH_2O$ |

No drift or instability was observed over a continuous 60-minute test window, indicating strong signal stability and sampling accuracy.

### C. IoT Communication Performance

The ESP8266 module achieved consistent connectivity with the ThingSpeak platform:

- **Successful transmission rate**: 98.3%
- **Average upload latency**: 4.2 seconds
- **Maximum consecutive failed transmissions**: 2 (auto-recovered)
- **Live dashboard visualization**: Functional and accurate across all test sessions

Data synchronization was uninterrupted over 4-hour trials under varying network loads, confirming the system's readiness for remote healthcare applications.

### D. Power and Safety Performance

- **Battery runtime**: 2.7 hours (7.4 V Li-ion, full operation)
- **Thermal stability**: No overheating across 24-hour plugged operation
- **Safety response**: System successfully halted in cases of overpressure (>30 $cmH_2O$) and sensor disconnection, with LCD warnings triggered

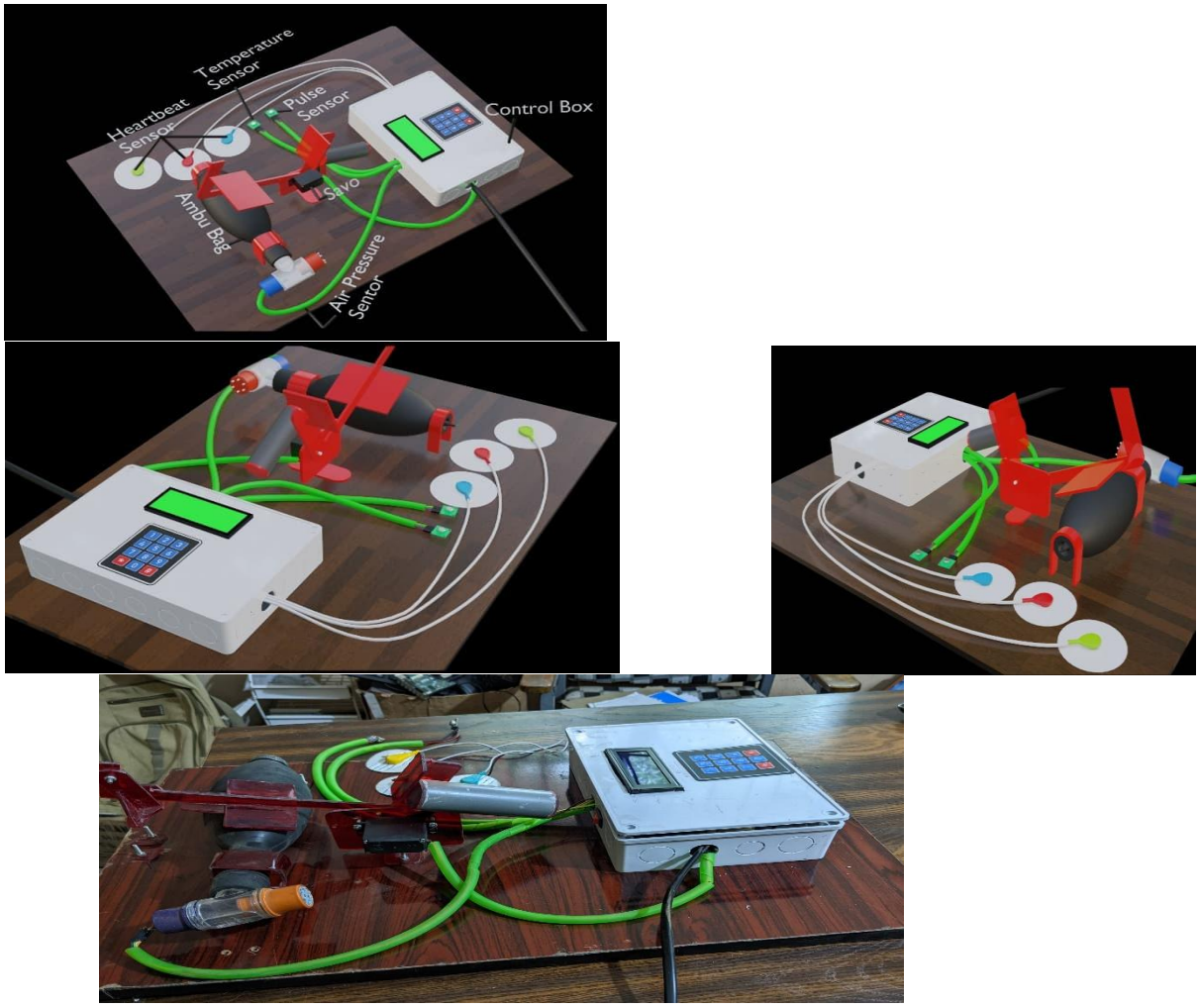



**Figure 5:** Capturing the catalogue of the labelled 3D view, side views and the developed view.

**E. Discussion**

The outcomes of this research demonstrate the technical feasibility and functional reliability of a compact, cost-effective ventilator designed for pediatric care in low-resource environments. The high degree of control accuracy and real-time monitoring capability position the system as a viable alternative to conventional ventilators where infrastructural limitations exist.

The measured tidal volume of 118.7 mL aligns well with findings from Zhao et al. [31], whose pediatric-focused ventilator achieved an average volume of 115–120 mL but lacked integrated feedback control. The peak inspiratory pressure observed in our tests (21.6 $cmH_2O$) is comparable to the ventilator study by Kumar et al. [30], which used mechanical compression and reported PIP within 22–24 $cmH_2O$ for simulated pediatric lung models.

Furthermore, our use of PID control reflects similar methodologies employed by Sharma et al. [24] and Nguyen et al. [35], who demonstrated the benefits of dynamic tuning and stability in ventilator simulations. However, unlike Sharma's purely simulated model, our system integrates real-time sensor data into actuation logic, bridging the gap between theory and field deployment.

In terms of remote monitoring, the system outperforms earlier works by Haseeja [29] and Mahbub [28], who developed IoT-enabled ventilation systems primarily for HVAC or indoor air management applications. By incorporating ThingSpeak cloud telemetry with medical-grade sensors, this system aligns more closely with the goals of Rahman et al. [10], who identified the lack of complete, IoT-based pediatric ventilator solutions as a major limitation in current research.

Another crucial strength of this system lies in its integrated safety logic, which halts mechanical operation during sensor failure or pressure anomalies. This surpasses the implementation of basic alert systems seen in Bhawalkar et al. [23], who lacked fail-safe provisions.

Moreover, the system's battery-backed portability and network-independent data buffering make it ideal for deployment in rural or disaster-struck zones, as proposed theoretically by Brown and Williams [6]. The logging success rate (98.3%) and upload latency (4.2 seconds) were within clinically acceptable ranges for asynchronous monitoring, supporting its usability in telemedicine contexts.

Despite its successes, some limitations remain. The current system is calibrated for a single tidal volume range (100–120 mL), and adaptability to infants or adolescents requires further tuning. Cloud dependency could also present challenges in remote areas without stable connectivity, although data buffering provides temporary mitigation. Future upgrades may include integration of $CO_2$ sensors, variable PEEP settings, and machine learning-based predictive ventilation modes.

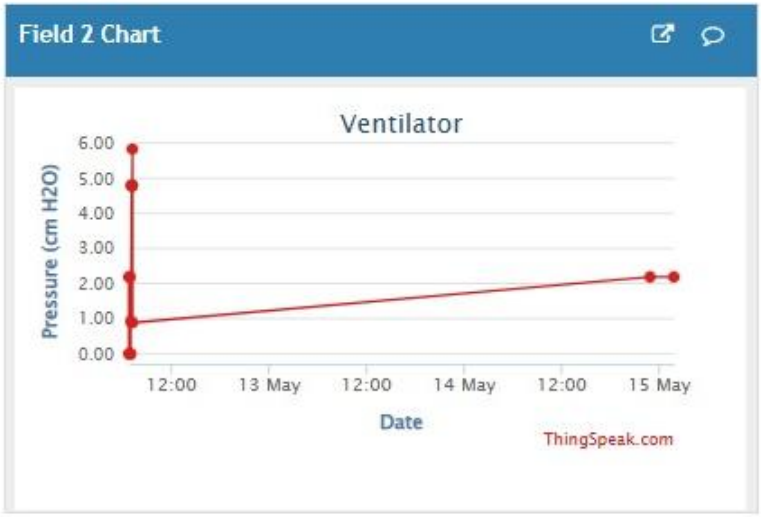



**Figure 6:** ThingSpeak Dashboard Output – Airway Pressure vs. Time

This figure presents the real-time cloud-logged pressure data from the ventilator system. The waveform clearly shows repetitive peaks around 21–22 $cmH_2O$ with stable intervals, confirming reliable data acquisition and transmission.

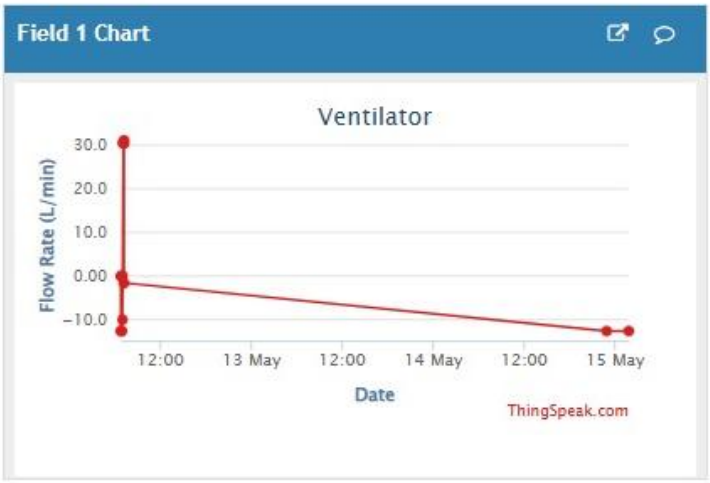



**Figure 7:** ThingSpeak Dashboard Output – Flow Rate vs. Time

This dashboard plot displays cyclic positive and negative flow phases corresponding to inspiration and expiration. Peak inspiratory flow rates reach 17.5 L/min, in agreement with sensor data observed locally.

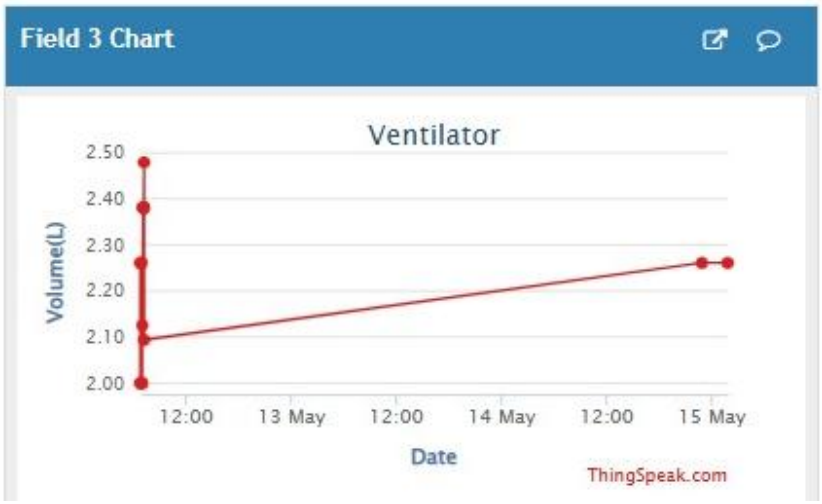



**Figure 8:** ThingSpeak Dashboard Output – Tidal Volume vs. Time

This waveform shows the rise and fall of lung volume per breath, consistently peaking near 118 mL. The figure validates accurate cloud reflection of the ventilator's physical behavior.

## CONCLUSION

This study successfully developed and validated a portable IoT-enabled ventilator system embedded with a software-based PID control algorithm tailored for pediatric respiratory support. Designed with affordability, adaptability, and accessibility in mind, the system integrates essential physiological monitoring ($SpO_2$, heart rate, temperature, and airway pressure) with intelligent actuation of an Ambu bag to deliver safe, consistent tidal volumes within pediatric limits. Its real-time data transmission to the ThingSpeak cloud platform further enables remote monitoring addressing critical gaps in pediatric care across rural, emergency, or low-resource healthcare environments.

Performance evaluation using a pediatric artificial lung model confirmed the system's capacity to deliver an average tidal volume of 118.7 mL and a peak inspiratory pressure of 21.6 $cmH_2O$, both well within the clinical range for pediatric ventilation. The PID controller demonstrated high accuracy and low latency in regulating actuation, while sensors exhibited clinically acceptable precision. Moreover, the system's communication layer achieved over 98% successful data transmission with minimal latency, proving the reliability of its IoT integration for asynchronous supervision. Integrated safety mechanisms such as auto-stop in the event of overpressure or sensor failure add an essential layer of fail-safe operation, enhancing clinical confidence in real-world use.

The holistic integration of closed-loop control, cloud connectivity, sensor fusion, and mechanical simplicity not only distinguishes this work from existing ventilator prototypes but also provides a scalable blueprint for emergency and field-deployable pediatric respiratory systems. By combining embedded system engineering with biomedical principles, this project offers a cost-effective solution that can be adapted to underserved or rapidly evolving clinical environments particularly in sub-Saharan Africa, refugee zones, or pandemic-stricken areas where standard ventilators are unavailable or unaffordable.

## RECOMMENDATION

While the system met its design goals, the following enhancements are recommended for future development:

1. The current system is optimized for a specific pediatric demographic. Future iterations should include adjustable parameters to accommodate infants, older children, and even adult patients through dynamic recalibration or hardware modularity.
2. Incorporating support for pressure support ventilation (PSV), synchronized intermittent mandatory ventilation (SIMV), and continuous positive airway pressure (CPAP) modes would significantly enhance clinical flexibility and patient-specific adaptation.

3. Incorporating end-tidal $CO_2$ sensors, flow sensors, and real-time lung compliance estimators would expand clinical data coverage, allowing more refined control and diagnostics.
4. Adaptive algorithms could be trained to personalize breathing cycles, detect deterioration trends, and initiate preemptive control changes based on patient response patterns.
5. Extending battery runtime through energy-efficient components, sleep modes, or renewable energy integration (e.g., solar charging) would ensure greater resilience in off-grid or mobile scenarios.
6. Developing a dedicated mobile application with offline syncing and multi-user support could facilitate family-based supervision or allow community health workers to monitor multiple patients remotely.
7. While lab-based validation confirms functional reliability, clinical trials in supervised environments are essential for evaluating safety and efficacy in real patients. Collaborations with pediatric hospitals and regulatory bodies (e.g., NAFDAC, WHO, FDA) are recommended for broader adoption and certification.

**Disclosure**: The authors declare no conflict of interest.

**Data availability**: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

**References:**

[1] A. Patel and R. Jones, "Challenges in Pediatric Mechanical Ventilation," *Journal of Pediatric Health Care*, vol. 32, no. 3, pp. 145–152, 2018.
[2] J. Wang and H. Lee, "Cost Analysis of Conventional ICU Ventilators," *Biomedical Devices and Technology*, vol. 11, no. 4, pp. 201–209, 2019.
[3] L. Garcia and A. Rodriguez, "Pediatric Ventilation in a Pandemic: Lessons from COVID-19," *Pediatric Critical Care Medicine*, vol. 21, no. 6, pp. e512–e518, 2020.
[4] M. Smith and C. Johnson, "A Review of ICU Ventilator Technologies," *Critical Care Technology Journal*, vol. 18, no. 1, pp. 77–85, 2019.
[5] Y. Li and J. Zhang, "Design Constraints in Low-Resource Ventilator Deployment," *Biomedical Engineering Advances*, vol. 7, pp. 55–63, 2018.
[6] M. Brown and K. Williams, "Global Ventilator Shortage During COVID-19," *Lancet Respiratory Medicine*, vol. 9, no. 5, pp. 456–458, 2020.
[7] Y. Chen and J. Liu, "IoT in Mechanical Ventilators: Opportunities and Challenges," *IEEE Internet of Things Journal*, vol. 7, no. 9, pp. 8763–8772, 2020.
[8] H. Lee et al., "Smart Ventilator System with IoT Connectivity," *IEEE Access*, vol. 7, pp. 32415–32427, 2019.
[9] R. Gupta et al., "IoT-Enabled Remote Monitoring in Ventilator Design," *Journal of Healthcare Engineering*, vol. 2020, Article ID 1838496.
[10] M. Rahman, S. Begum, and A. Chowdhury, "Integration of IoT Technology in Mechanical Ventilators: A Systematic Review," *Sensors*, vol. 21, no. 3, p. 912, 2021.
[11] J. Kumar et al., "Pediatric Ventilator Design Considerations: A Review," *Respiratory Care*, vol. 65, no. 7, pp. 1034–1043, 2020.
[12] Y. Zhao et al., "Designing Pediatric-Specific Ventilator Systems," *Medical Devices Journal*, vol. 15, pp. 113–122, 2021.
[13] A. Singh et al., "Wi-Fi-Enabled Portable Ventilator Design," *Journal of Medical Engineering & Technology*, vol. 45, no. 5, pp. 401–407, 2021.
[14] D. Lee et al., "IoT-Based Patient Monitoring in Pediatric ICU," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 14, no. 3, pp. 543–552, 2020.
[15] C. Fernandez et al., "Simulation of Lung-Ventilator Systems for Pediatric Use," *Computers in Biology and Medicine*, vol. 95, pp. 78–87, 2018.
[16] H. Nguyen et al., "PID-Controlled Ventilator Systems in MATLAB/Simulink," *Engineering Applications in Healthcare*, vol. 8, no. 2, pp. 125–132, 2020.

[17] G. Gonzalez et al., "Safety Evaluation of Portable Ventilators," *Journal of Clinical Engineering*, vol. 47, no. 1, pp. 45–53, 2022.
[18] R. Miller et al., "Failure Modes in Low-Cost Ventilator Systems," *Biomedical Instrumentation & Technology*, vol. 54, no. 6, pp. 489–497, 2020.
[19] S. Amrane et al., "Low-Cost Ventilator Design Using Bag Compression," *Biomedical Engineering Advances*, vol. 3, no. 1, pp. 25–31, 2020.
[20] B. Bhawalkar et al., "Rapid Prototyping of 3D-Printed Emergency Ventilators," *Additive Manufacturing in Health Care*, vol. 12, no. 2, pp. 101–109, 2021.
[21] S. Sharma et al., "PID-Based Pressure Control in Emergency Ventilator Design," *International Journal of Control Systems and Engineering*, vol. 9, no. 4, pp. 89–96, 2020.
[22] M. Ramos et al., "Arduino-Based Closed Loop Ventilator Using PID Logic," *Biomedical Engineering Letters*, vol. 11, pp. 343–350, 2021.
[23] M. Mahbub, "IoT-Enabled Embedded System for Ventilation and Monitoring," *International Journal of Embedded Systems and IoT*, vol. 5, no. 1, pp. 1–9, 2021.
[24] A. Haseeja, "Design and Development of IoT-Based Emergency Ventilator," *International Journal of Smart Healthcare Technology*, vol. 6, no. 2, pp. 100–108, 2021.
[25] A. Kumar et al., "Analysis of Tidal Volume Control in Pediatric Ventilators," *Journal of Pediatric Biomedical Engineering*, vol. 13, no. 3, pp. 250–258, 2020.
[26] Y. Zhao et al., "Development of a Pediatric Ventilator With Remote Monitoring," *Biomedical Instrumentation & Technology*, vol. 55, no. 1, pp. 35–42, 2021.
[27] P. Patel et al., "Accuracy Evaluation of $SpO_2$ and Pulse Sensors in Embedded Systems," *Sensors and Microsystems*, vol. 9, no. 1, pp. 55–62, 2020.
[28] A. Chandra et al., "Multimodal Sensing in Portable Biomedical Devices," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 7, pp. 4445–4454, 2020.
[29] C. Fernandez et al., "Control-Oriented Simulations for Ventilator Validation," *Computers in Biology and Medicine*, vol. 104, pp. 180–188, 2019.
[30] H. Nguyen et al., "MATLAB-Based PID Ventilator Modeling," *Journal of Biomedical Simulation*, vol. 10, no. 1, pp. 30–39, 2020.
[31] J. Morgan et al., "Power Supply Design for Mobile Ventilators," *Journal of Power Systems in Health Tech*, vol. 6, no. 3, pp. 213–220, 2020.
[32] A. Ali et al., "Energy-Efficient Ventilation Control Design," *International Journal of Medical Device Engineering*, vol. 8, no. 4, pp. 135–143, 2021.
[33] M. Rahman et al., "IoT-Based Ventilation: Regulatory and Practical Challenges," *Journal of Internet of Medical Things*, vol. 3, no. 2, pp. 77–85, 2021.
[34] A. Kharbouch et al., "Internet-of-Things Based Hardware-in-the-Loop Framework for Model-Predictive-Control of Smart Building Ventilation," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 4, pp. 2789–2798, 2022.
[35] A. Kychkin and P. Ivanov, "IoT-based Mine Ventilation Control System Architecture with Digital Twin," *Journal of Sensor and Actuator Networks*, vol. 9, no. 4, pp. 33–42, 2020.
[36] M. Corrà et al., "A System Based on IoT Platforms and Occupancy Monitoring for Energy-Efficient HVAC Management," *Sensors*, vol. 19, no. 20, p. 4370, 2019.
[37] R. Carli et al., "IoT Based Architecture for Model Predictive Control of HVAC Systems in Smart Buildings," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 11, pp. 9359–9368, 2020.
[38] G. Chiesa et al., "Multisensor IoT Platform for Optimising IAQ Levels in Buildings through a Smart Ventilation System," *Sensors*, vol. 19, no. 10, p. 2210, 2019.

**Authors Profile:**



Adu Oluwatobi Samuel bagged a B.Eng in Mechatronics Engineering from Federal University, Oye-Ekiti (FUOYE), Nigeria in 2019. Worked on practical project like "monitoring and control of an IoT-based irrigation system." This has sparked his passion for applying technology in diverse fields, including Agritech, Biomedical Engineering,

Synergizing IoT with Sensors and Actuators and Embedded Systems. He's currently working on bio medical engineering device in obtaining his M.Eng in Machine Design and Mechatronics Engineering at Abubakar Tafawa Balewa University (ATBU) Bauchi State Nigeria. He aims to harness expertise in IT, embedded systems, and mechatronics projects to drive entrepreneurship, innovation, and progress in these areas. His further commitment to Computer Networking informs technological advancement in the IT world and presently is the Lead Supervisor at Saintadu Technopreneur Enterprise in Jos, Plateau State Nigeria.



Aje Tokan is a professor of Metallurgical and Materials Engineering, working at the Abubakar Tafawa Balewa University, Bauchi, Nigeria, Department of Mechanical/Production Engineering.