International Journal of Emerging Science and Engineering (IJESE)
ISSN: 2319–6378 (Online), Volume-14 Issue-3, February 2026

A Comprehensive Review of Temperature Monitoring and Cold-Chain Integrity Across IoT in Vaccine Storage

Yashwanth L, Ritika S Ghattad, Sinchana Chetan, Sneha S Shrigiri, Narendra Kumar S

Abstract*: *Cold chain monitoring is a system that uses technology to monitor and maintain the temperature required for the storage and preservation of temperature-sensitive goods such as food and medicines. This paper summaries the effects and relation between vaccines and temperature and discuss the wide range of technologies used in the implementation of cold chain monitoring. While vaccines require temperatures between 2°C and 8°C to remain potent, maintaining this temperature throughout the vaccine supply chain is challenging. Technologies such as digital data loggers (DDLs), calibrated thermometers, and wireless sensors are used to monitor temperature by obtaining real-time readings and implementing corrective responses when temperatures exceed the optimal range. Therefore, fluctuations in the measured temperature relative to the optimal temperature directly affect the vaccine and its effectiveness.

Keywords*: *Temperature Monitoring, IoT, Thermal Anomaly Detection, Cold Chain, Machine Learning, Vaccine, Wireless Sensors, Temperature Stability

Nomenclature:
DDLs: Digital Data Loggers
TIR: Thermal Infrared
GUI: Graphical User Interface
ML: Machine Learning
CAE: Convolutional Autoencoder
DTAD: Dynamic Threshold Anomaly Detection

I. INTRODUCTION

A vaccine is a biological preparation that contains a tiny weakened non-dangerous fragment of a bacterium or virus that provides active immunity to your immune system to fight infectious diseases.

The vaccine supply chain is an intricate logistics process that involves the movement of vaccines from manufacturing laboratories to national, subnational, and district stores, and ultimately to the service-delivery point. Across all stages of the vaccine supply chain, it is essential to ensure that the vaccine remains safe for use and retains its efficacy. One of many parameters that can affect a vaccine's efficiency is temperature. Most vaccines require a temperature range of 2°C to 8°C to maintain their potency. Fluctuations in temperature outside this range will degrade vaccine potency and may cause serious health issues in patients. Transportation of vaccines will always be a problem because it involves strict monitoring of the vaccine throughout the supply chain. Cold chain monitoring is a system that utilises technology to monitor and maintain temperature for the storage of temperature-sensitive goods such as food and medicines. Among the many causes of vaccine wastage, such as expiration, packaging issues, and infrastructure limitations, the failure of cold chain monitoring remains the most significant problem, prompting doctors and scientists worldwide to conduct extensive research on the topic. Globally, India averaged approximately 6.3%-6.5% COVID-19 vaccine wastage due to logistical challenges. As a result, a variety of technological solutions have been introduced to overcome these logistical challenges, like Digital Data Loggers (DDLs), calibrated thermometers, and wireless sensors, which give real-time data readings and temperature charts, which will help in preventing the failure of cold chain monitoring not only in vaccine storage but in the storage and preservation of any temperature-sensitive product.

II. BACKGROUND AND THEORETICAL FOUNDATIONS

A. A Vaccine Contains Six Basic Components

- Active ingredients, which include viral or bacterial antigens that directly stimulate the immune system but do not cause any disease
- Adjuvants, which help boost the immune response to the vaccine
- Antibiotics that prevent contamination by bacteria during the vaccine manufacturing process
- Stabilizers that keep the vaccine stable after manufacturing and maintain its effectiveness during storage
- Preservatives to prevent bacterial and fungal growth
- Trace components, which include residual inactivating ingredients such as formaldehyde

Among these six components, Stabilisers play a

Manuscript received on 09 January 2026 | First Revised Manuscript received on 31 January 2026 | Second Revised Manuscript received on 08 February 2026 | Manuscript Accepted on 15 February 2026 | Manuscript published on 28 February 2026.
*Correspondence Author(s)
Yashwanth L, Department of Industrial Engineering and Management, RV College of Engineering, RV College of Engineering, Bengaluru (Karnataka), India. Email ID: yashwanthl.im24@rvce.edu.in
Ritika S Ghattad, Department of Industrial Engineering and Management, RV College of Engineering, RV College of Engineering, Bengaluru (Karnataka), India. Email ID: ritikasghattad.im24@rvce.edu.in
Sinchana Chetan, Department of Industrial Engineering and Management, RV College of Engineering, RV College of Engineering, Bengaluru (Karnataka), India. Email ID: sinchanachetan.im24@rvce.edu.in
Sneha S Shrigiri, Department of Industrial Engineering and Management, RV College of Engineering, RV College of Engineering, Bengaluru (Karnataka), India. Email ID: snehasshrigiri.im24@rvce.edu.in
Dr. Narendra Kumar S*, Associate Professor, Department of Biotechnology, RV College of Engineering, Bengaluru (Karnataka), India. Email ID: narendraks@rvce.edu.in, ORCID ID: 0000-0002-1375-8166

crucial role in maintaining potency, protecting the vaccine against environmental conditions, and improving its shelf life. Stabilizers protect the active ingredients of the vaccine (like virus and bacteria) from breaking down due to heat, light or chemical reactions. Examples of common Stabilizers include glycine, lactose, and Albumin.

When a vaccine is damaged due to cold chain failure, what it means is explicitly that the Stabilizers have lost their ability to protect the active ingredients, leading to denaturation or aggregation of the antigens, therefore reducing its potency.

B. Vaccine Cold Chain Works in 5 Stages

i. Vaccines are sent to the destination country from the manufacturing unit

ii. From there, a refrigerated lorry carries the vaccines to the cold room

iii. From the cold room, the vaccines are distributed to the regional centres in portable ice boxes

iv. The vaccines are then stored in electric fridges between 2°C and 8°C. Vaccines are carried to the local venues in portable ice boxes

As noted earlier, vaccine storage presents logistical challenges throughout the supply chain. These problems include:

- Unstable Power Supply:

Frequent power cuts, especially in developing and rural areas, will cause drastic temperature fluctuations, threatening the cold chain system

- Generator Issues:

Lack of fuel or backup generators will sustain the negative impact of power outages for an extended period of time

- Inadequate Cold Chain Tools:

Lack of cold chain equipment, like freezers and cold boxes, hinders the reliability of vaccine transportation

- High Transportation Costs:

Refrigerated trucks and advanced drone technology are expensive and are rarely affordable by the district health centres

- Limited Storage Infrastructure:

Lack of cold rooms and laboratories in less populated regions or developing regions increases the movement of vaccine transportation in the supply chain

- Climate Change:

Extreme heat conditions, which threaten cold chain monitoring, increase the risk of vaccine spoilage.

III. LITERATURE REVIEW

This review synthesises the literature of the 10 papers across four domains:

i. Freezing as an integral part of the cold chain system

ii. Temperature anomaly analysis

iii. IoT-based real-time temperature fluctuation detection

iv. Thermal anomaly detection

Among 45 studies assessing temperature monitoring in vaccine storage, 29 specifically assess "too cold" temperatures. According to the statistical analyses of this study, vaccine exposure to temperatures below the recommended range was 33% in higher-income countries and 37.1% in lower-income countries. Survey data highlight ongoing issues with vaccine exposure to temperatures outside the optimal range across various stages of the vaccine supply chain [1].

New systems that incorporate intelligent analytical methods to analyse temperature anomaly events have been introduced in countries such as Thailand, Myanmar, and Cambodia. The analytical process involved applying correlation analysis to assess the concordance of temperature variability. The results showed that the temperature variability patterns of the three countries were moderately correlated [3].

DTAD (Dynamic Threshold Anomaly Detection) is a temperature anomaly detection method that sets dynamic thresholds based on the Smoothed Z-score Algorithm rather than fixed thresholds. This method was tested along with four other commonly employed methods. The results showed that DTAD has higher accuracy and time efficiency [4].

A thermal infrared (TIR) camera is one of the many instruments used for Thermal Anomaly Detection. Thermal anomaly detection works on the assumption that a hot region attracts the attention of the human eye in Thermal Infrared images. Thermal anomaly detection safeguards the vaccine cold chain by implementing machine learning to monitor temperature data [10].

With modern technological advancements, IoT-based solutions and Machine Learning (ML) can be implemented to revolutionise the vaccine cold chain. While IoT-based solutions enable real-time Temperature monitoring, ML can be used for predictive analysis and alert systems accordingly.

Based on the literature review of previous studies, IoT-based solutions and Machine learning (ML) will enhance vaccine storage because of:

- Real-Time Monitoring:

IoT-based sensors integrated with a cloud database provide temperature data in real time

- Asset Tracking:

IoT can be used to access precise location tracking, ensuring the vaccine reaches the right place and confirming delivery

- Data Collection:

The IoT cloud database records and maintains the temperature logs, which can be further used for predictive analysis

- Predictive Analysis Using ML:

Using the data recorded in the database, Machine Learning (ML) can be implemented to perform predictive analysis to investigate the regions or errors that cause temperature anomalies throughout the vaccine supply chain

- Alert Mechanisms:

Automated alert systems can be incorporated to provide real-time alerts if the temperature in the vaccine storage exceeds the optimal range for vaccines.

IV. DISCUSSION

In developing rural areas, the delivery of medicines remains highly outdated and lacks modern tools and techniques used in the vaccine supply chain. In smart medicine delivery, IoT is used to implement a system that incorporates a mobile application (user interface), an Arduino, MQTT (Message Queuing Telemetry Transport) for

Retrieval Number:100.1/ijese.C263914030226
DOI:10.35940/ijese.C2639.14030226
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

communication, a temperature sensor, and a mini portable cooling box [9].

MQTT is a light-weight messaging protocol that facilitates efficient and reliable data transfer from IoT devices to cloud platforms and mobile apps. When integrated with IoT-enabled sensors, MQTT provides a reliable and effective cold-chain monitoring system that enables real-time monitoring, secure communication, and efficient tracking throughout the innovative medicine delivery process. Mobile applications provide a user interface for patients, healthcare providers, and logistics personnel to monitor shipments, receive alerts, and manage delivery schedules.

While currently used vaccine carriers offer portability, they lack temperature data loggers and alert systems. As a result, patients or healthcare facilities that receive the vaccines will not be notified of a breach in the cold chain monitoring system until the inspection is conducted after receipt.

A newly proposed prototype of vaccine cold boxes ensures the maintenance of stable temperatures and the storage of large quantities of vaccines. While it may fall behind current vaccine carriers in portability, it enables real-time temperature logging and alert systems. A modular IoT temperature-monitoring and data-logging system is embedded in the proposed prototype, offering features such as a Graphical User Interface (GUI) for user-friendly monitoring, alarm systems, alert signals in the open state, and real-time temperature data from temperature loggers [6].

The alert systems in the cold box prototype can be implemented by following these stages:

A. Using wireless Temperature and Humidity sensors inside the proposed cold box prototype. These sensors, along with DDLs (Digital Data Loggers), continuously measure environmental parameters such as temperature and humidity within the cold box.
B. The sensors transmit the data wirelessly to a central data logger using technologies like Bluetooth, Wi-Fi or cellular networks like 4G and 5G.
C. The central data logger uploads the collected data into a cloud-based platform where the data is secure and can be used for analysis and management. The data can also be used to train Machine Learning models.
D. Integrating the cloud with a Web dashboard or a mobile application user interface allows patients, healthcare facilities and quality assurance personnel to visualise the data in real time, provides audit trails, generates reports, and manages alert configurations.

In addition to Arduino, a simple microcontroller with limited features, other microcontrollers are used to develop innovative IoT-based vaccine refrigeration systems, such as the ESP32, which offers more features (e.g., Wi-Fi module). A deep learning-based vaccine refrigeration system with real-time temperature fault detection is developed, using an ESP32 microcontroller. The system employs a semi-supervised Convolutional Autoencoder (CAE) trained on real-world temperature-sensor data to capture temporal patterns [7].

A longitudinal study was conducted over 9 months, using Temp-mate thermometers, in 27 health facilities in southern Malawi [8]. This study found that, despite being aware of the product specifications and necessary storage conditions, health facilities are failing to ensure pharmaceutical storage. The primary reason is the lack of investment by the government and stakeholders in equipping health facilities with adequate resources.

When medicines are stored in environments exceeding the safe temperature range, they become less potent and lose efficacy. Most storage conditions specify a temperature range of 25°C or less. A study was conducted in a general practice drug cupboard during a British heatwave to assess whether the storage conditions matched the specified conditions. This study showed that the specified criterion was not met, and the temperatures in the drug cupboard exceeded 25°C. The main reasons for this failure were a lack of air conditioning and the Absence of a temperature log. An evidence-based study was conducted to examine the economic and environmental impacts of the vaccine cold chain in Europe, specifically in the UK, Germany, and Spain. Cold chain logistics are energy-intensive, requiring continuous refrigeration. In Europe alone, cold-chain vaccines generate approximately 6.7 million kg of CO_2 emissions per year. Refrigeration relies heavily on electricity, often produced from fossil fuels. Thus, energy consumption becomes a significant constraint in Cold Chain Management [5].

While discussing various reasons for the failure of vaccine and medicine storage, let us examine the effects of medicinal prescriptions exposed to varying temperatures. A study was conducted to evaluate the impact of temperature on respiratory medicinal prescriptions in Spain. The study involved fitting time-series regression models to medical prescriptions and included a distributed-lag nonlinear model with lags up to 14 days for daily mean temperature [2]. In simple terms, the study found that both hot and cold weather increase the number of respiratory medications taken by patients. Therefore, neglecting the storage criterion and exposing medicines to unstable conditions will indirectly affect public health.

V. EXPERIMENTAL SETUP AND METHODOLOGY

A. Overview

To evaluate the temperature stability within household refrigerators and to analyse the temperature curve over a given period, we conducted a simple experiment using IoT and cloud computing.

B. Components

i. *Node-MCU Board:* It is a low-cost developmental microcontroller board used for IoT projects, known for its built-in Wi-Fi module
ii. *DHT22 Sensor:* It is a low-cost digital sensor used for measuring temperature and relative humidity with an accuracy of ±0.5°C and ±2-5%RH
iii. *Jumper Wires:* They are short, flexible electrical connectors used for simple IoT projects

C. Experimental Procedure

We constructed a simple DHT22 circuit by connecting the sensor to the NodeMCU

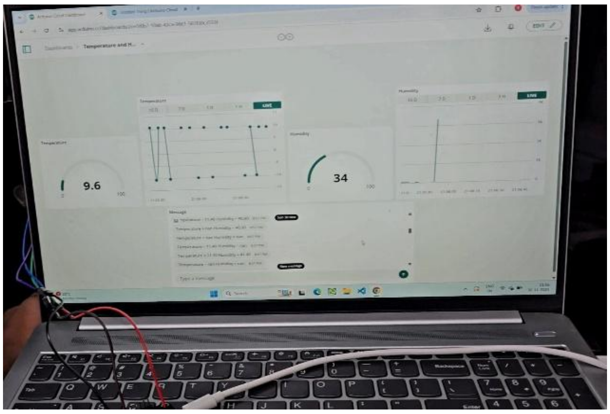
Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

board using jumper wires. Using the Arduino IoT cloud, the sensors were integrated into a dashboard that displayed real-time temperature and Humidity readings as graphs. The DHT22 sensor was then placed in a refrigerator (Fig. 1), and temperatures were recorded while the door was repeatedly opened and closed.

[Fig.1: DHT22 Sensor Inside the Refrigerator]

D. Software Integration

After the circuit was complete, the DHT22 sensor was integrated with the IoT cloud platform provided on the Arduino website. A web dashboard was developed in the cloud to visualise sensor data in real time. Variables for the Temperature gauge, Humidity gauge, Temperature graph, Humidity graph and message box were created to be displayed on the dashboard. The necessary libraries for the dashboard were included in the Arduino code, and each variable was linked with the code. The code was then verified and uploaded to the laptop/PC. The web dashboard was functional and accurately displayed the defined variables (Fig. 2).



[Fig.2: Web-Dashboard Displaying Temperature and Humidity]

E. Key Findings

The experimental data showed that the uncalibrated DHT22 sensor measured the temperature inside the fridge between 7°C and 9.5°C and humidity between 33% and 34% (Fig. 3).

The experiment confirmed that the temperature inside the refrigerator was not constant, varying by 2 °C. The temperature-time curve was not perfectly linear but was nearly linear, with minor deviations.

SL NO.	TIME STAMP (UTC)	TEMPERATURE (°C)	HUMIDITY (%)
1	2025-11-30T15:36:40.626898007Z	Temperature = 9.70	Humidity = 33.70
2	2025-11-30T15:36:41.644765922Z	Temperature = -9.70	Humidity = 33.70
3	2025-11-30T15:36:43.639210542Z	Temperature = nan	Humidity = 33.70
4	2025-11-30T15:36:44.5569043Z	Temperature = nan	Humidity = nan
5	2025-11-30T15:36:45.681368324Z	Temperature = 9.60	Humidity = nan
6	2025-11-30T15:36:46.157895294Z	Temperature = 9.60	Humidity = 33.90
7	2025-11-30T15:36:47.779344505Z	Temperature = nan	Humidity = nan
8	2025-11-30T15:36:49.733493578Z	Temperature = 9.60	Humidity = 34.00
9	2025-11-30T15:36:51.834079895Z	Temperature = nan	Humidity = nan
10	2025-11-30T15:36:57.857632706Z	Temperature = 9.50	Humidity = 34.00
11	2025-11-30T15:36:59.83581841Z	Temperature = nan	Humidity = 34.00
12	2025-11-30T15:37:00.413274096Z	Temperature = nan	Humidity = nan
13	2025-11-30T15:37:07.84745171Z	Temperature = 9.40	Humidity = 34.40
14	2025-11-30T15:37:09.830223359Z	Temperature = nan	Humidity = 34.40
15	2025-11-30T15:37:10.458078213Z	Temperature = nan	Humidity = nan
16	2025-11-30T15:37:17.918888632Z	Temperature = 9.30 x	Humidity = nan
17	2025-11-30T15:37:18.532531325Z	Temperature = 9.30	Humidity = 34.80
18	2025-11-30T15:37:19.885542422Z	Temperature = nan	Humidity = 34.80
19	2025-11-30T15:37:20.409448919Z	Temperature = nan	Humidity = nan
20	2025-11-30T15:37:21.851451325Z	Temperature = -9.30	Humidity = 34.80

[Fig.3: Temperature and Humidity Reading]

VI. CONCLUSION

Insights from studies and experiments on temperature detection and cold chain monitoring have helped enhance Smart Medicine Delivery and Vaccine Supply Chain, particularly in developing rural regions that lack technological advancements in medical storage. Medicine and its storage will continue to be subjects of ever-growing study and research.

Here are a few areas where intense research and a wide range of experiments can lead to discoveries and breakthroughs in the field of Vaccine Supply Chain:

- Utilising renewable sources of energy like solar energy as a backup energy source in case of Main power outages, as it is cheaper, environmentally friendly and highly feasible in relatively hotter regions such as regions lying on the equator
- Multi-sensor fusion, which involves integration of multiple sensors like Humidity sensor, Light sensors to detect door openings, GPS modules for tracking location and Barcode scanners for inventory management
- Intensive data collection and observation of climatic changes over a large span of time to design Machine Learning systems for predictive analysis. These ML models can be used to predict temperature data across different regions of Earth's surface, thereby informing the time required for the vaccine supply chain.

While temperature is the most important and studied parameter to upgrade vaccine storage and Cold chain monitoring, specific steps the government can take to promote safe and trustworthy vaccine supply:

- The government provides effective and updated training to every operator involved in the Vaccine Supply Chain
- Government and Healthcare facilities are spreading awareness among communities about the consequences of taking less potent vaccines or vaccines destroyed due to temperature anomalies.
- Government investing in building adequate Infrastructure for the storage and supply of vaccines.
- The government is investing in ensuring power supply, especially in rural areas where there is either no power supply or an irregular supply. supply of power.

Retrieval Number:100.1/ijese.C263914030226
DOI:10.35940/ijese.C2639.14030226
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

International Journal of Emerging Science and Engineering (IJESE)
ISSN: 2319–6378 (Online), Volume-14 Issue-3, February 2026

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted objectively and free from external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. Celina M. Hanson, Anupa M. George, Adama Sawadogo, Benjamin Schreiber, "Is freezing in the vaccine cold chain an ongoing issue? A literature review". Vaccine 35 (2017) 2127-2133. DOI: http://dx.doi.org/10.1016/j.vaccine.2016.09.070
2. Dominic Roy´e, Aurelio Tobías, Adolfo Figueiras, Santiago Gestal, Margarita Taracido, Ana Santurtun, Carmen Iniguez, "Temperature-related effects on respiratory medical prescriptions in Spain". Environmental Research 202 (2021) 111695. DOI: https://doi.org/10.1016/j.envres.2021.111695
3. Kittisak Kerdprasop, Paradee Chuaybamroong, Nittaya Kerdprasop, "Modelling Method for Temperature Anomaly Analysis". Proceedings of the 10th International Joint Conference on Computational Intelligence (IJCCI 2018), pages 274-280. DOI: https://doi.org/10.5220/0007224902740280
4. Wei Liu, Hongyi Jiang, Dandan Che, Lifei Chen, Qingshan Jiang, "A Real-time Temperature Anomaly Detection Method for IoT Data". Proceedings of the 5th International Conference on Internet of Things, Big Data and Security (IoTBDS 2020), pages 112-118. DOI: https://doi.org/10.5220/0009410001120118
5. Stefun Lutzmayer, Elina Osoianu, Tom Rosenfeld, "Tip of the Iceberg: Economic and Environmental Impact of the Vaccine Cold Chain, White Paper, Europe, Middle East and Africa (EMEA), Jul. 2025. https://www.iqvia.com/-/media/iqvia/pdfs/emea/library/whitepaper/tip-of-the-iceberg-economic-and-environmental-impact-of-the-vaccine-cold-chain.pdf
6. A. Darwin Jose Raju, J.G. Benny Jackson, J. M. Jerlin Priya, P. Lovelin Auguskani, "Smart Cold Chain Monitoring and Alert System for Vaccine Carrier". ISSN: 0369-8963. Volume 91, No. 5, 2022. DOI: https://doi.org/10.37896/pd91.5/91525
7. Mokhtar Harrabi, Abdelaziz Hamdi, Bouraoui Ouni, Jamel Bel Hadj Tahar, "Real-time temperature anomaly detection in vaccine refrigeration systems using deep learning on a resource-constrained microcontroller". Frontiers in Artificial Intelligence. 01 August 2024. DOI: https://doi.org/10.3389/frai.2024.1429602
8. Felix Khuluza, Francis Kachidza Chiumia, Happy Magwaza Nyirongo, Chifundo Kateka, Raphael Abbuh Hosea, Westonie Mkwate, "Temperature variations in pharmaceutical storage facilities and knowledge, attitudes, and practices of personnel on proper storage conditions for medicines in southern Malawi". 22 September 2023. DOI: https://doi.org/10.3389/fpubh.2023.1209903
9. David Samuel Bhatti, Muhammad Mueed Hussain, Beomkyu Suh, Zulfiqar Ali, Ismatov Akobir, Ki-il Kim, "IoT-Enhanced Transport and Monitoring of Medicine Using Sensors, MQTT, and Secure Short Message Service". Volume 12, 2024. DOI: https://doi.org/10.1109/ACCESS.2024.3382508
10. A. Sledz, C. Heipke, "Thermal Anomaly Detection based on Saliency Analysis from Multimodal Imaging Sources". ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume V-1-2021. XXIV ISPRS Congress (2021 edition). DOI: https://doi.org/10.5194/isprs-annals-V-1-2021-55-2021

AUTHOR'S PROFILE

Yashwanth L is a second-year undergraduate engineering student pursuing a Bachelor's degree in Industrial Engineering and Management. His academic interests include work system design, lean manufacturing, productivity improvement, and the application of digital tools in industrial engineering. He is currently focused on developing analytical and web-based solutions to engineering and management problems through coursework and projects. This research represents his first scholarly publication and reflects his interest in research-oriented learning and problem-solving. He aims to explore further interdisciplinary applications of engineering principles in real-world industrial settings.

Ritika S Ghattad is a second-year undergraduate engineering student pursuing a Bachelor's degree in Industrial Engineering and Management. Her academic interests include work system design, lean manufacturing, productivity improvement, and the application of digital tools in industrial engineering. She is currently focused on developing analytical and web-based solutions to engineering and management problems through coursework and projects. This research represents her first scholarly publication and reflects her interest in research-oriented learning and problem-solving. She aims to explore further interdisciplinary applications of engineering principles in real-world industrial settings.

Sinchana Chetan is a second-year undergraduate engineering student pursuing a Bachelor's degree in Industrial Engineering and Management. Her academic interests include work system design, lean manufacturing, productivity improvement, and the application of digital tools in industrial engineering. She is currently focused on developing analytical and web-based solutions to engineering and management problems through coursework and projects. This research represents her first scholarly publication and reflects her interest in research-oriented learning and problem-solving. She aims to explore further interdisciplinary applications of engineering principles in real-world industrial settings.

Sneha S Shrigiri is a second-year undergraduate engineering student pursuing a Bachelor's degree in Industrial Engineering and Management. Her academic interests include work system design, lean manufacturing, productivity improvement, and the application of digital tools in industrial engineering. She is currently focused on developing analytical and web-based solutions to engineering and management problems through coursework and projects. This research represents her first scholarly publication and reflects her interest in research-oriented learning and problem-solving. She aims to explore further interdisciplinary applications of engineering principles in real-world industrial settings.

Dr. Narendra Kumar S is an Associate Professor in RVCE's Biotechnology Department since January 15, 2009. He has 18 years of teaching and 8 years of research experience. Expertise spans Bio-simulations, Bioinformatics, and NGS Technologies. Involved in driving cutting-edge research in genomics, bioinformatics, AI/ML integration, pharmacogenomics, and bioprocess engineering. He has guided 24 undergraduate and 15 postgraduate projects, authored 78 international journal papers and 7 national journal articles, and coordinated 11 National and International conferences. Chaired three Conferences. Notable activities include organizing workshops on LC-MS and bioreactors. Conducted Faculty Development Programmes on NGS and biofuels.