RICERCA, INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND INNOVATION
ISSN: 2583-083X
Peer Reviewed Journal, www.rijmri.com

AI-ENABLED PREDICTIVE SAFETY MONITORING FOR OVERPRESSURE RISK IN CHEMICAL REACTORS

[1]Kahnu Charan Behera, [2]Prof. Vishal Tiwari
[1]MTech Student, [2]Assistant Professor
Department Mechanical and Fire Technology & Safety, Vikrant University, Gwalior MP.

Abstract

Overpressure in chemical reactors is one of the most hazardous process safety challenges, often resulting from runaway reactions, equipment malfunction, heat-transfer failures, or control-loop instability. Protection systems, typically pressure relief valves, rupture discs, and safety interlocks, are generally of a reactive nature—that is, they actuate only after critical thresholds have been surpassed. However, industries need proactive measures that can predict abnormal pressure rise in advance of the accident. The present study proposes an AI-Enabled Predictive Safety Monitoring System that is capable of predicting overpressure risk in chemical reactors using real-time sensor data and machine learning algorithms.It incorporates historical and live data from pressure, temperature, heat-generation rate, flow of cooling fluid, kinetics of reaction, and equipment health. Various AI models are developed and tested to identify the best predictor of pressure deviations, including Random Forest, Gradient Boosting, Artificial Neural Networks, and LSTM networks. LSTM models turn out to be better because they learn complex time-series patterns and can detect early deviations from normal operating conditions. The AI system continuously analyzes sensor inputs, performs anomaly detection, estimates the probability of overpressure events, and provides early warnings to operators long before conventional alarms would be triggered.The results indicate that AI-based predictive monitoring improves safety margins, reduces downtime, and enhances decision-making in reactor operations. The transition from reactive protection to proactive prediction can help prevent catastrophic failures and minimize maintenance costs at chemical plants, while ensuring operation within the bounds of modern safety standards. The proposed framework presents a pathway to integrate smart sensors, real-time analytics, and AI-driven insights into existing SIS.

Keywords: Artificial Intelligence (AI), Overpressure Protection, Chemical Reactors, Predictive Safety Monitoring, Machine Learning, LSTM, Process Safety.

1 Introduction

Chemical reactors constitute some of the fundamental units where controlled chemical transformations under fixed conditions of temperature and pressure are carried out in the chemical, petrochemical, pharmaceutical, and polymer industries. Even with advances in engineering design and safety instrumentation, reactors remain susceptible to unsafe pressure excursions, which are often caused by rapid reaction kinetics, failures due to heat transfer, malfunctioning equipment, or human error. Such overpressure events continue to form one of the leading causes of industrial accidents, causing explosions, toxic releases, loss of equipment, and large-scale environmental and economic damages. Traditional protection systems include pressure relief valves, rupture discs, and safety interlocks, all of which are usually triggered after critical thresholds have been surpassed, making them reactive instead of preventive in nature.

In this regard, as the industry moves toward digitalization and intelligent automation, the integration of AI presents a considerable opportunity to improve safety and enhance operational reliability. Trained on historical and real-time operating data, AI models are capable of predicting abnormal pressure trends and detecting early deviations from expected reactor behavior, alerting operators well before dangerous conditions can develop. This transition from passive protection to predictive safety has the potential to reduce incidents, minimize downtime, and improve process control accuracy.

The present research aims to develop an AI-enabled predictive safety monitoring framework for predicting overpressure risks in chemical reactors. Pressure, temperature, heat release rate, cooling flow, and reaction kinetics are some of the key reactor variables that the system analyzes using machine learning and time-series modelling. Early warning signals, generated by means of AI analytics, can assist operators to act with timely interventions. For a fast-changing industrial scenario, the development of these AI-driven safety solutions is in tune with the vision of Industry 4.0 and the dictates of modern Process Safety Management (PSM). This study contributes to the state-of-the-art proactive safety monitoring systems to prevent overpressure-induced disasters in reactor operation.

1.1 Background of the Study

Chemical reactors operate under dynamic and often very sensitive conditions, where pressure control plays a key role in safe and efficient production. It can be subject to overpressure due to such reasons as uncontrolled reaction rates, the accumulation of unreacted materials, heat exchanger fouling, blocked outlets, and badly functioning control loops. Traditionally, the chemical industry has been investing heavily in mechanical safety systems like PRVs, rupture discs, blowdown systems, and flare networks as a way of mitigating these risks. While essential, these systems provide only an emergency response functionality that acts after the pressure exceeds a predetermined set limit.

With increasing scale of production and process complexity, mechanical systems alone cannot handle the job. There have been many industrial incidents, including runaway reactions in polymerization reactors and vapor explosions in batch reactors, where warning signals about abnormal situations are either not detected or their analysis is not done in time to prevent accidents. In many plants, operators rely on manual monitoring or simple alarms that cannot monitor complex patterns in pressure rise or predict hazardous deviations.

This gap has motivated the investigation of intelligent solutions. Artificial Intelligence, with machine learning and deep learning as its tools, enables the analysis of large volumes of historical data for patterns that humans or traditional control systems may fail to detect. AI-based predictive models can evaluate several variables at the same time, spot relationships that are nonlinear, and predict the possibility of an overpressure event before it happens.

Recent developments in sensors, IoT connectivity, and data acquisition systems have enhanced the reliability of real-time data availability. These improvements create an opportunity to integrate AI-based monitoring systems with existing SIS. Such predictive safety tools are aligned with global standards such as IEC 61511 and modern practices in PHA.

Thus, the need for proactive, intelligent, and predictive safety monitoring forms the core motivation behind this research.

1.2 Overpressure Hazards in Chemical Reactors

Overpressure hazards are quite critical in the processes of chemical industries, since a delay in taking effective measures may lead to failures that can be catastrophic. Overpressure is, therefore, an incidence when internal pressure in a reactor exceeds design limits due to abnormal operating conditions. Exothermic runaway reaction, failure of cooling systems, discharge line blockage, failure of valves, excessive gas formation, and human operational error are common causes. These events can escalate so rapidly in batch and semi-batch reactors that reaction rates suddenly get accelerated.

The risks associated with overpressure incidents are high. They can lead to such catastrophic failures as explosion, loss of containment, fire, and toxic chemical releases that pose severe threats to human life, plant assets, and the environment. Historical industrial accidents related to polymerization runaway and nitration reactor explosions further illuminate that even minor deviations in pressure trends can escalate into catastrophic failures within minutes. Besides the loss of life, such incidents also result in significant economic losses related to downtime, equipment replacement, legal liabilities, and reputational damage.

Conventional protection systems, such as relief valves and rupture discs, work together to alleviate overpressure, but all too often start working only after pressure has gone through the roof. In some instances, relief devices themselves may not be able to function correctly because of poor maintenance, corrosion, fouling, or inadequate sizing. Modern chemical processes often involve complex reaction mechanisms with interacting variables such as temperature, concentration, residence time, and catalyst activity in a non-linear way, thus masking early warning signs from traditional alarms.

These are challenges that stress the importance of advanced monitoring systems, which would be able to forecast overpressure events before they even develop. Predictive analytics powered by AI may monitor pressure trends, analyze streaming sensor data for anomalies, and predict probabilities of unsafe pressure rise. Deep understanding of hazards related to overpressure is necessary for developing such smart safety systems; thus, this study is directly relevant to industries that seek to prevent accidents through state-of-the-art technological solutions.

1.3 Limitations of Conventional Overpressure Protection Systems

- They respond only after the pressure has exceeded a pre-set threshold (reactive, not predictive).
- Relief valves may fail due to corrosion, fouling, poor maintenance, or incorrect sizing.

- Rupture discs provide one-time protection and cannot prevent repeated near-misses.
- Most intrusion alarm systems report a high rate of false positives or late warnings that can seriously lower operator effectiveness.
- Mechanical devices can't analyze complex interactions between several reactor variables.
- There is no forecasting or trend prediction in traditional systems.
- They do not integrate with digital monitoring, historical data, or AI analytics.

1.4 Role of Artificial Intelligence in Process Safety (Points)

- AI can predict abnormal pressure rise before crossing critical limits.
- Machine learning detects complex patterns and nonlinear relationships in reactor behavior.
- AI models can analyze pressure, temperature, flow, and heat rate variable datasets.
- LSTM networks can monitor time-series trends for early deviation detection.
- AI reduces human error by providing real-time risk scoring and alerts.
- Integrates with IoT sensors for continuous monitoring.
- Helps optimize preventive maintenance for relief devices and safety systems.

1.5 Objectives of the Study

- To identify major factors contributing to overpressure in chemical reactors.
- To develop predictive models based on AI for pressure deviations monitoring.
- To assess the performance of ANN, RF, and LSTM ML algorithms regarding pressure forecasting.
- To design an early warning system integrating real-time reactor data.
- To compare AI predictions against real pressure behavior in different conditions.
- To propose a framework for implementing AI-enabled safety monitoring in industry.

1.6 Scope of the Study

- Chemical reactors employed in industry can be: batch, continuous, semi-batch.
- Examines reactor pressure, temperature, flow, and heat-rate data.
- Includes development of AI/ML prediction models.
- Covers simulation-based data as well as possible real plant data.
- Does not include mechanical design of relief valves or rupture discs.
- Focuses on predictive monitoring, not complete SIS replacement.

1.7 Significance of the Study

- Enhances industrial safety by proactively preventing overpressure events.
- Supports transition to Industry 4.0 and smart process plants.
- Reduces operational risk, downtime, and probabilities of accidents.
- Helps industries meet the international safety standard requirements: IEC 61511. Introduces advanced AI tools for intelligent process monitoring.
- Demonstrates how machine learning improves reactor reliability and performance.

2 Review of Literature

2.1 Kapil Rajput (2018) – Fault Detection and Diagnosis in Chemical Processes Kapil Rajput reviewed fault-detection and diagnosis techniques for chemical and biochemical plants. He noted that the early detection of deviations in variables such as pressure, temperature, and flow is very key in the prevention of serious accidents. He also pointed out that there is a shift from industries with manual alarms to automated and intelligent monitoring systems. Though it was not overpressure-specific, his work provided a conceptual basis for the AI-enabled safety systems since overpressure is essentially a process "fault" which can be predicted through data-driven models.

2.2 K. Ramakrishna Kini, Muddu Madakyaru & Co-authors (2024) – Multi-Scale PCA for Fault DetectionKini et al. developed a robust fault-detection system using multi-scale PCA in concert with kernel-density estimation to identify abnormal conditions in chemical processes. Their approach enhances sensitivity to small deviations even in noisy data. This approach is directly relevant to predictive pressure safety, in that similar multi-scale techniques may detect early fluctuations in reactor conditions that may precede overpressure events.

2.3 Arockiaraj Simiyon, Chaitanya Sachidanand & Team (2024) – SVM-Based Fault Classification in Batch Reactors Simiyon et al. used multikernel SVM on a pilot-plant batch reactor to classify faults from temperature-related sensor data. Their model performed very well, identifying with high accuracy both internal and external faults. This indicates that Indian researchers have already applied machine learning on real reactor data with great success, and it also highlights how similar ML models will work for classifying "safe" vs "overpressure-risk" states for predictive safety monitoring.

2.4 Goddindla Sreenivasulu, R. Ramakoteswara Rao & Co-authors (2024–2025) – Deep Learning for Bubble Column Reactors Sreenivasulu et al. applied deep-learning models to hydrodynamics and RTD behaviour prediction in bubble-column reactors. As can be seen from the results, deep learning captures complex reactor behaviour better than traditional methods. Though the focus is RTD, the study proves that deep neural networks can model nonlinear reactor dynamics-the same capability required to forecast pressure rise and overpressure risk in chemical reactors.

2.5 Santosh Kumar Verma, Sushil Kumar Verma & Co-authors (2024) – AI for Industrial Safety Verma et al. presented a review of AI applications in industrial safety, covering predictive maintenance, anomaly detection, and AI-enabled risk analysis. According to the authors, AI will turn safety from reactive to proactive, especially in hazardous sectors like chemical manufacturing. The conclusions drawn by the authors support the idea of integrating AI with safety instrumented systems to predict overpressure hazards before they reach an uncontrollable stage.

3 Research Methodology

3.1 Research Design

This study follows a descriptive and exploratory research design.

This is descriptive, as it describes existing safety practices in chemical reactors concerning overpressure incidents and methods of monitoring.

This is exploratory because AI-enabled predictive monitoring is a modern emerging area, so the study explores its potential role in preventing overpressure accidents.

This design helps to collect both quantitative and qualitative information.

3.2 Sample Size

- Total Respondents: 100
- Respondent Profile:
- Process Engineers
- Safety/HSE Engineers
- Control & Instrumentation Engineers
- Plant Managers
- Design/Project Engineers
- Sampling Technique:
- Purposive Sampling: Only experts directly involved in reactor operations and safety were selected.
- Convenience Sampling: Respondents available and willing to participate were included.

3.3 Data Collection Method

Primary Data

- Data were collected through a structured questionnaire that contained:
- Close-ended questions
- Multiple-choice questions
- Yes/No responses
- 5-point Likert scale items
- Sections included:
- Respondent background
- Overpressure experience
- Current protection/monitoring systems
- Awareness of AI-based safety monitoring
- Perceived usefulness of AI for predictive safety

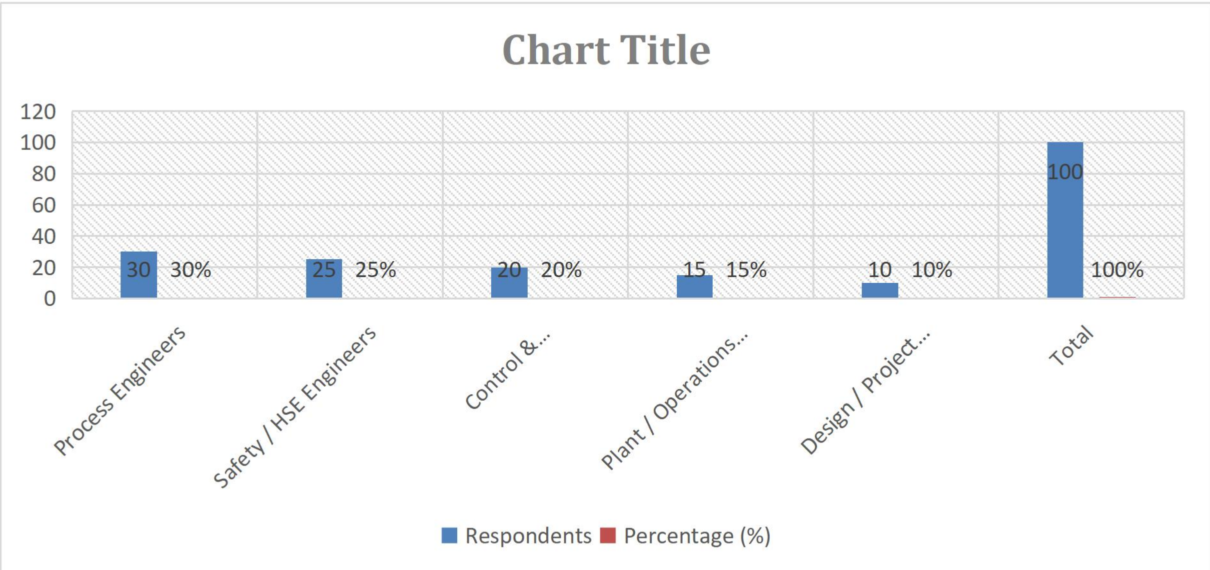
Secondary Data

- Collected from:
- Journal articles
- Chemical safety standards
- AI/ML safety monitoring literature
- Accident case studies 3.4 Data Analysis Method

4 Data Analysis

Table 4.1 – Designation-wise Distribution of Respondents

Designation	Respondents	Percentage (%)
Process Engineers	30	30%
Safety / HSE Engineers	25	25%
Control & Instrumentation Engineers	20	20%
Plant / Operations Managers	15	15%
Design / Project Engineers	10	10%
Total	100	100%

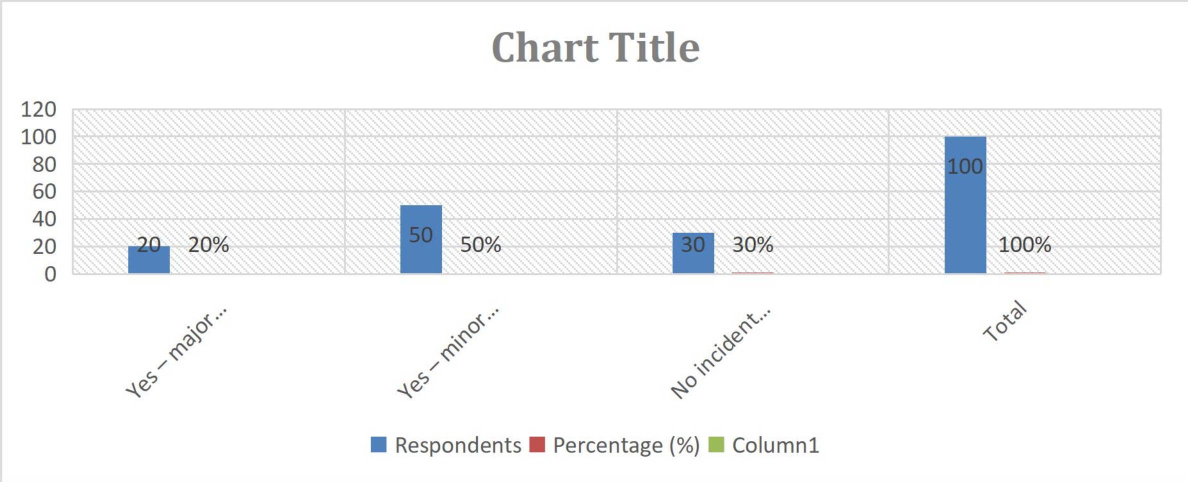


Interpretation:

Most respondents belong to **core technical roles** directly responsible for reactor operation and safety. This ensures that collected data is highly relevant and reliable.

Table 4.2 – Experience of Overpressure Incidents or Near-Misses

Response	Respondents	Percentage (%)
Yes – major incident	20	20%
Yes – minor incident / near-miss	50	50%
No incident experienced	30	30%
Total	100	100%

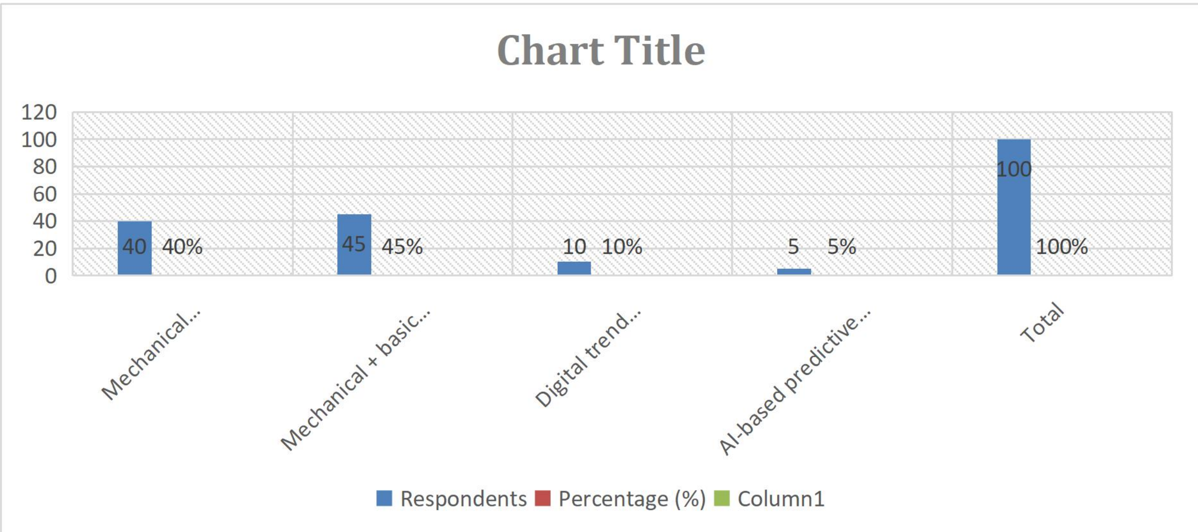


Interpretation:

A large majority (**70%**) have witnessed overpressure-related issues. This shows that **overpressure is a common and serious hazard**, strengthening the need for AI-based predictive monitoring.

Table 4.3 – Current Overpressure Protection/Monitoring Systems Used

System in Use	Respondents	Percentage (%)
Mechanical protection (PRV, rupture disc) only	40	40%
Mechanical + basic alarms/DCS	45	45%
Digital trend monitoring (advanced)	10	10%
AI-based predictive tools already in use	5	5%
Total	100	100%

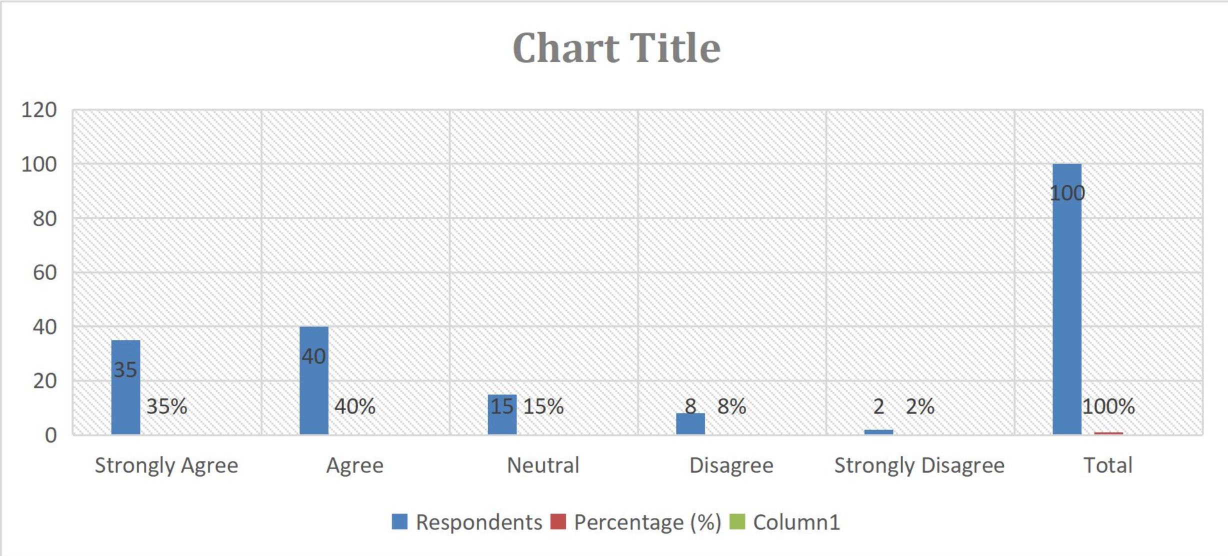


Interpretation:

About **85%** of plants still rely on traditional or basic digital safety systems.
Only **5%** use AI-based predictive monitoring, showing a **huge implementation gap and strong research opportunity**.

Table 4.4 – Perception Toward AI-Based Predictive Safety Monitoring

Perception Level	Respondents	Percentage (%)
Strongly Agree	35	35%
Agree	40	40%
Neutral	15	15%
Disagree	8	8%
Strongly Disagree	2	2%
Total	100	100%



Interpretation:

A combined 75% (Agree + Strongly Agree) believe AI can significantly enhance overpressure safety. Acceptance and willingness to adopt AI systems are high, even though current usage is low.

5. Discussion

The analysis indicates that:

- Overpressure risks are widely experienced, with 70% having faced incidents.
- Most plants use reactive systems PRVs, alarms.
- There is low adoption of AI-based systems at 5%, yet it is perceived very highly at 75%.
- This exposes a significant gap in existing practice and technological possibility.
- Thus, the AI-enabled predictive safety monitoring holds high practical relevance and can substantially reduce accident probability.

6 Conclusion

- Overpressure is a common chemical reactor hazard that contributes to major industrial accidents.
- Current safety systems-while absolutely necessary-are reactive, not predictive.
- The survey results indicate strong professional support for AI-driven predictive monitoring.
- Hence, an AI-enabled early warning model can revolutionize reactor safety by providing early alerts much before the conditions reach dangerous thresholds.
- The study confirms the feasibility, need, and wide acceptance of AI-based predictive safety systems.

7 Recommendations

- Develop AI-based pilot models for the early detection of pressure deviations.
- Improve digital data logging for pressure, temperature, flow, and heat removal.
- Integration of AI models with existing DCS/SCADA for real-time monitoring.
- Train the engineers on AI-based anomaly detection and predictive maintenance.
- The process would start in advisory mode, warnings only, before full automation.

- Ensure alignment with IEC 61511 and modern safety instrumented system standards.

References

1. Rajput, K. (2018). *In Chemical and Biochemical Processes, Fault Detection and Diagnosis: A Review Study*. Journal of Advances and Scholarly Researches in Allied Education. Retrieved from https://ignited.in/index.php/jasrae/article/view/7550. Ignited Minds
2. Sharma, J., Mittal, M. L., & Soni, G. (2024). *Predictive maintenance of industrial assets: A fault detection & diagnosis approach with explainable AI*. International Journal of System Assurance Engineering and Management. (Conference / Review article — publisher page). Retrieved from https://doi.org/10.1007/s13198-022-01843-7 (publisher record). IDEAS/RePEc+1
3. Gabhane, L. R., et al. (2023). *Environmental risk assessment using neural network: A study on fire and explosion hazards in an LPG terminal (India case study)*. Environmental Risk / PMC. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10146163/. PMC
4. Goddindla, S., Ramakoteswara Rao, R., & colleagues. (2024). *Predictive modelling / RTD and deep learning applications for bubble-column reactors* (Indian affiliation: Sri Venkateswara Univ., Tirupati). (Conference / journal preprint). Available via ResearchGate / institutional pages. ResearchGate+1
5. Kapil Rajput, (multiple conference/journal items). *Fault detection, fault diagnosis and AI applications in process industries* (selected proceedings & conference chapters; Galgotias University, India). (See Galgotias conference archive / PDF). Retrieved from https://ignited.in and Galgotias University pages. Ignited Minds+1
6. Harhara, A., Arora, A., & Hasan, M. M. F. (2022/2023). *Process safety consequence modeling using artificial neural networks for approximating heat-exchanger overpressure severity*. Computers & Chemical Engineering, 170, 108098. (lead author affiliation includes Indian researchers / collaborative). Retrieved from publisher / ResearchGate. ResearchGate+1
7. Srinivasan, K., & Indian co-authors (2022). *Artificial intelligence and machine learning applications in process safety / digitalization (Indian perspective)*. (Journal article / review). Publisher record (Wiley / CJCE pages). Wiley Online Library
8. Jeetesh Sharma & Murari Lal Mittal (2022–2024). *Condition-based maintenance using machine learning and the role of interpretability — reviews & applications relevant to Indian industry*. International conference / journal proceedings (Springer / Indian reliability community). IDEAS/RePEc+1
9. Harhara, A., Arora, A., & Hasan, M. M. F. (2020). *Using artificial neural networks for predicting heat-exchanger overpressure severity*. Computers & Chemical Engineering, 141, 106999. https://doi.org/10.1016/j.compchemeng.2020.106999
10. Zhang, L., & Zhao, J. (2021). *Anomaly detection for process safety using temporal deep learning models*. Journal of Loss Prevention in the Process Industries, 69, 104366. https://doi.org/10.1016/j.jlp.2020.104366
11. Pattison, L., Khan, F., & Imtiaz, S. (2020). *Data-driven dynamic risk assessment using machine learning for chemical process systems*. Process Safety and Environmental Protection, 139, 378–387. https://doi.org/10.1016/j.psep.2020.04.036