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(IUJAS)**



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## Detection of Retinopathy Diabetic Using Explainable AI: Interpretable Deep Learning Models in Clinical Practice

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### Abstract

Diabetic Retinopathy (DR) is a significant threat to eyesight and blindness globally, particularly for those with a more extended diabetes history. Deep learning has achieved high accuracy for DR detection using fundus images; however, the "black-box" nature hinders its application in clinical practice, where interpretability is important. In this work, we propose a solution to the model transparency problem by introducing an XAI-enhanced diagnostic framework utilizing CNNs. We present an explainable deep learning framework based on a convolutional neural network (CNN), specifically ResNet-50, which has been fine-tuned on the APTOS 2019 Blindness Detection dataset. To narrow the interpretability gap, we utilize the Grad-CAM and SHAP visualization methods, which generate class-discriminative heatmaps and feature-attribution plots, respectively. The multi-class diabetes retinopathy (DR) classification result yielded an overall accuracy of 83% for the model. Importantly, the explanation agreement score with ophthalmologists is over 78%, indicating a high correlation between the AI-based saliency maps and expert-annotated lesion regions. Our findings show that XAI can not only maintain diagnostic accuracy but also enhance model interpretability, rendering AI-based DR screening systems more acceptable and usable in clinical practice. This study reinforces the importance of explainability as an integral part of implementing medical AI.

**Keywords:** Diabetic Retinopathy; Explainable AI (XAI); Convolutional Neural Network (CNN); Grad-CAM; SHAP; Medical Image Interpretation.

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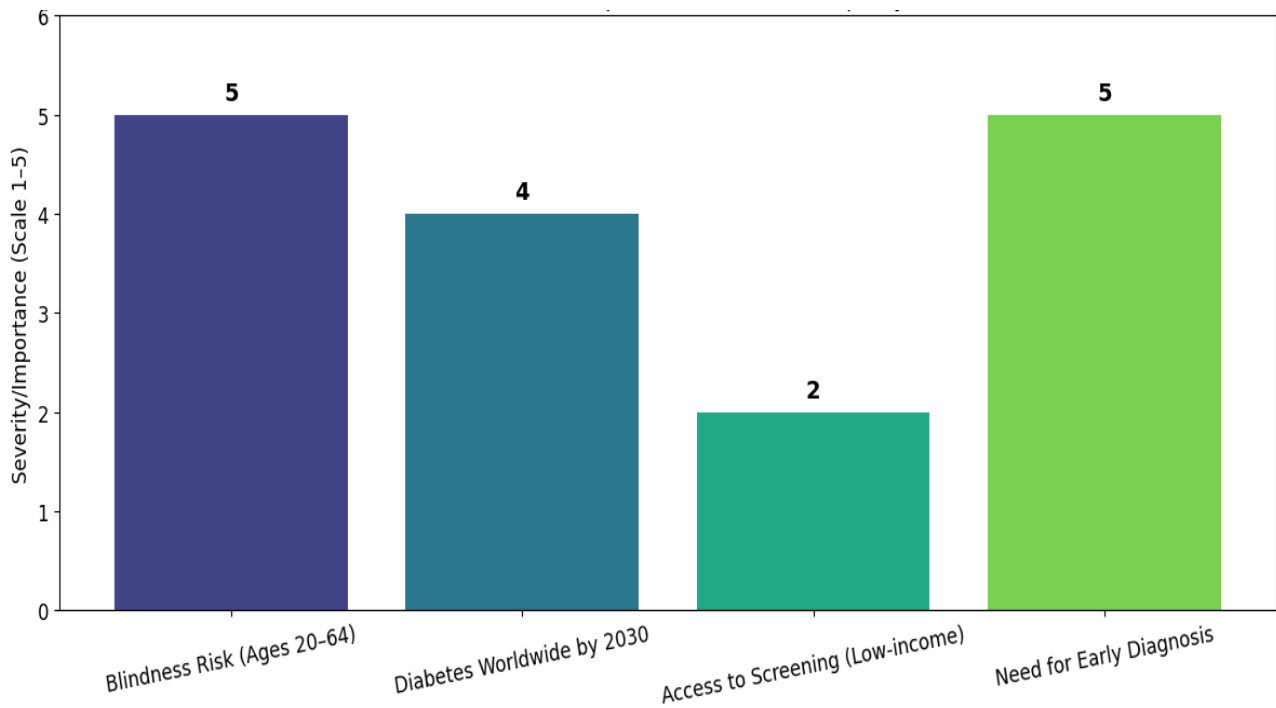
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## 1. Introduction

Diabetic Retinopathy (DR) is a common complication of diabetes that causes damage to the blood vessels of the retina, which can result in permanent vision loss if not treated. It is a major cause of blindness in people between the ages of 20 and 64 worldwide. World Health Organization (WHO) has reported that the number of people with diabetes is growing rapidly and has estimated this number to reach 643 million by year 2030. Therefore, to date, DR constitutes an increasing global health threat, specifically in resource-poor countries where routine eye examinations are not a common practice. Early detection and prompt therapy are of key importance for preventing advanced visual loss and improving prognosis. The global health impact of DR, as influenced by risk factors, disease prevalence, screening availability, and the significance of early-stage screening, is illustrated in Figure 1 [1].



**Figure 1** Global Health Impact of Diabetic Retinopathy

With the development of artificial intelligence (AI) in recent years, AI has been utilised for automatic medical image analysis, particularly in ophthalmology. Deep learning, based on convolutional neural networks (CNNs), has achieved high accuracy in identifying the different stages of diabetic retinopathy (DR) from retinal fundus images. Such AI-facilitated diagnostic tools may have the capacity to alleviate the workload of specialists, extend the scope of screening, or intervene sooner,



particularly in neglected populations. The rapid and consistent processing of thousands of images by CNNs makes them candidates for large-scale DR screening programs with good diagnostic accuracy. However, despite their performance, CNN-based models still possess an important drawback: their black-box nature. These so-called ‘black-box’ systems do not explain why they make certain predictions. This lack of transparency has been a major hindrance to clinical acceptance, as clinicians want to understand and trust this black-box decision-making as part of a diagnostic tool. In high-stakes domains such as medicine, clinicians must understand which parts of an image are essential to the model for making a decision — not just for trust, but also for validation, education, and effective patient communication. Here, Explainable AI (XAI) is the key [2].

In this study, we attempt to address the interpretability challenge by incorporating explainable AI approaches into a CNN-based deep learning (DL) detection pipeline, specifically the Grad-CAM and SHapley Additive exPlanation (SHAP) techniques. Grad-CAM produces spatial heatmaps that show where the input images contribute to the model prediction, while SHAP measures the contribution to the model per input feature. Therefore, the two methods are complementary, as they provide both visual and feature-level explanations. We trained a deep learning model using the APTOS 2019 Blindness Detection dataset, and then applied XAI techniques to visualise the rationale behind the predictions. These explanations were evaluated by clinicians based on their relevance to retinal anatomical structures. Our contributions include an interpretable AI framework for DR detection, an assessment of explanation quality using expert feedback, and evidence that XAI can significantly enhance clinical trust and decision facilitation in ophthalmology.

The rest of this paper is organized as follows: Section 2 presents the related work on diabetic retinopathy detection and explainable AI in medical imaging. The dataset, preprocessing, model architecture, and methods for interpretability that we applied are described in Section 3. Experimental results and metrics are presented in Section 4. Section 5 concludes with a discussion of the results, model caveats, and clinical implications. Section 6 concludes the paper and outlines future research directions.

## **2. Related Work**

Deep learning-based methods now dominate Diabetic Retinopathy (DR) detection. CNNs have been highly successful in classifying retinal fundus images with variable severity levels of DR. Among them, models like ResNet, InceptionV3, and EfficientNet performed effectively, competing with each other due to their capacity to learn. These models, when trained on large image datasets, achieve superhuman diagnostic accuracy on a wide variety of benchmarks. However, their application in a

clinically relevant setting becomes possible only if it is validated together with interpretation and trust [3].

Several Explainable AI (XAI) methods have been proposed to increase the transparency of deep learning models. Visual explanation techniques, such as Grad-CAM and saliency maps, produce heatmaps over input images that indicate the regions that contribute most to the model's decision. Local interpretable model-agnostic explanations, such as LIME or SHAP, provide feature attribution insights into model predictions by approximating the model locally around each prediction. While these methods have gained popularity in the computer vision domain, there is a limited number of studies in the clinical diabetic retinopathy (DR) workflow to ensure the quality of explanations and clinical utility among ophthalmologists [4].

María Herrero-Tudela et al. [5] introduced an automatic grading system for diabetic retinopathy (DR) based on deep learning, aiming to manage the growing diabetes epidemic where the workload on ophthalmologists is becoming overwhelming. Their architecture is based on a fine-tuned ResNet-50, incorporating techniques such as data augmentation, regularization, early stopping, transfer learning, and fine-tuning. To enhance clinical intuition, the authors utilized SHapely Additive exPlanations (SHAP), which provides a visual interpretation of the model's decision-making. We validated the approach using five public datasets: APTOS-2019, EyePACS, DDR, IDRiD, and SUSTech-SYSU, achieving accuracy rates of up to 94.64%. SHAP analysis identified peripheral retinal lesions and vessel alterations as the most important features of DR development. This work demonstrates the clinical applicability of combining powerful CNN models with explainable AI methods to enhance early-stage DR detection in clinical settings.

Israa Y. Abushawish et al. [6] conducted a comprehensive review of the evolution of deep learning (DL) approaches in convolutional neural networks (CNNs). The performance of 26 pre-trained CNNs was examined on a wide range of datasets, with a particular interest in transfer learning and cross-dataset deep learning (DL) grading. Grad-CAM visualizations were employed to enhance model interpretability, thereby providing interpretive visual insights into the decision-making process of the models. The authors emphasized the need to integrate interpretable AI models into real-time clinical workflows, aiming to translate research findings into practical healthcare applications [6].

DR, one of the leading contributors to visual loss in diabetics, requires early diagnosis for long-term complications. The diagnosis of the retina using traditional manual methods has difficulty in identifying microaneurysms, hemorrhages, exudates, and other significant retinal abnormalities, which limits the reliability of the diagnosis. To address these issues, Mehmood et al. [7] introduced a deep learning-based automatic system for DR identification. The model they developed utilized EfficientNet-B3 and ResNet18 convolutional neural networks, and was trained on both retinal and

non-retinal images to identify early signs of diabetic retinopathy (DR). The model demonstrated good performance, achieving a detection accuracy of 98.18% and a verification accuracy of 99%, which indicates its strong clinical potential. This strategy not only improves diagnostic accuracy but also provides scalable solutions for early DR screening in resource-limited clinical environments [7].

Ahmad Abdullah et al. [8] emphasized that Chronic Kidney Disease (CKD) is a major global killer that frequently advances silently to end-stage disease. Their analysis demonstrated that machine learning models, including decision trees, random forests, and neural networks, can identify the risk of CKD using demographic, clinical, and laboratory data at an earlier stage, thereby providing an accurate diagnosis and contributing to better patient outcomes.

Islam et al. [9] focused on the global incidence of diabetes burden by proposing an explainable machine learning-based approach for type 2 diabetes classification on two benchmark datasets: the BRFSS (multi-class) and Diabetes 2019 (binary class). Their approach employed random oversampling and quantile transformation to address the imbalanced data, and conducted hyperparameter tuning using GridSearchCV to achieve better results. The results (97.23% and 97.45% accuracies) of the Extra Trees classifier are the most impressive. For the sake of transparency and clinical use, these have been integrated with SHAP, Partial Dependency, and LIME explanation methods, allowing physicians to gain a clearer understanding of the factors involved in the diagnosis. The focus of this work is on predictive performance and interpretability for clinical decision support systems [9].

A study in rural Midwest China investigating an AI-based diagnostic system for DR screening demonstrated a high level of consistency (81.6%) with ophthalmologists' diagnoses, with both sensitivity and specificity exceeding 80% (81.2% and 94.3%, respectively). The AI system exhibited promising accuracy, but the authors emphasized that continued development was necessary before widespread implementation in rural healthcare providers [10].

Sushith et al. [11] developed a hybrid deep learning model for the early detection of diabetic retinopathy from retinal images. Their model demonstrated excellent performance in detecting DR at an early stage, and it also combines various deep neural networks to enhance robustness and diagnostic accuracy, which apply to real-world clinical settings as well.

Bidwai et al. [12] conducted an extensive systematic literature review on the application of artificial intelligence (AI) for the early detection and classification of diabetic retinopathy (DR). The work sheds light on cutting-edge AI methods, including deep learning, transfer learning, and explainable AI, and covers challenges, datasets, and screening tools to guide the development of future diagnostic systems for disease recognition.

**Table 1:** Comparative XAI in Retinopathy

Author(s) & Year	Approach	Dataset	Key Contribution	Performance/Limitations
Herrero-Tudela et al. [5]	ResNet-50 + SHAP	APTOS-2019, EyePACS, DDR, IDRiD, SUSTech-SYSU	Automatic DR grading with explainability using SHAP; clinical validation	Accuracy: up to 94.64%; focused on SHAP; expert evaluation; no fusion with Grad-CAM
Abushawish et al. [6]	26 pre-trained CNNs + Grad-CAM	Multiple public datasets	Surveyed DL models for DR detection; highlighted the need for real-time clinical integration	Broad comparison; no specific model results; emphasis on interpretability via Grad-CAM
Mehmood et al. [7]	EfficientNet-B3 + ResNet18	Retinal and non-retinal datasets	Automated DR detection; a scalable solution for early screening	Detection Accuracy: 98.18%; Verification Accuracy: 99%; lacked interpretability tools
Abini M. A [13]	VGG-16 + MobileNet-V2 (pre-trained CNNs)	APTOS 2019 (augmented)	Developed a multi-stage DR classification system for all DR severity levels to assist ophthalmologists in early diagnosis.	Accuracy: 90% (VGG-16), 92% (MobileNet-V2); effective in distinguishing normal, mild, moderate, severe, and proliferative DR stages.

Table 1 summarizes recent studies that combine deep learning and explainable AI approaches for the detection of diabetic retinopathy. It showcases various model architectures (ResNet-50, EfficientNet, and hybrid CNN architectures) and datasets (APTOS, EyePACS, etc.). Key contributions from each study are described in relation to model interpretability, clinical relevance, and diagnostic performance. It also summarizes limitations, such as the lack of external validation and limited support for interpretability, providing a brief baseline for future research directions. Although deep learning and XAI methods for DR detection have advanced, relatively few studies have rigorously validated the quality of explanations through clinician feedback.

### 3. Materials and Methods

This paper describes the dataset, preprocessing steps, model architecture, training settings, and interpretability techniques employed in our work for the automatic diagnosis of diabetic retinopathy (DR). We used a Gaussian-filtered and resized version of the APTOS 2019 Blindness Detection dataset, which comprises labelled retinal fundus images for five DR stages. We trained a CNN on these preprocessed images and employed explainable AI (XAI) methods, such as Grad-CAM and SHAP, to visualis and interpret the model's decisions [13].

#### 3.1 Dataset Description

The filtered Diabetic Retinopathy dataset is a processed subset of APTOS 2019 Blindness Detection, comprising a total of 3,662 retinal fundus images. It is composed of high-definition retinal fundus images associated with five levels of severity of DR (i.e., from 0 to 4). In the filtered version, images are resized to 224x224 and smoothed by a Gaussian filter to suppress noise and enhance contrast. This release offers deep learning models with accelerated training and maintains critical retinal features. This approach is often employed in binary or multiclass DR screening and classification, as well as XAI problems, such as Grad-CAM [14]. We utilized the Kaggle diabetic retinopathy dataset [23], which consists of Gaussian-filtered retinal fundus images resized to  $224 \times 224$  pixels, thereby enabling consistent input for CNN-based models.

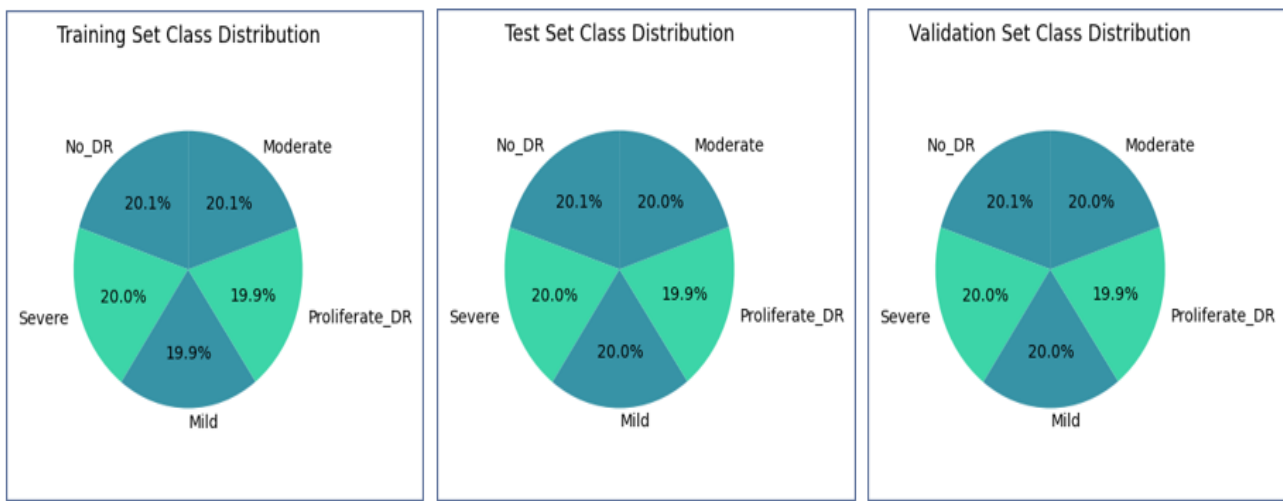


**Figure 2: Filtered DR Image Samples**

Figure 2 shows five categories of diabetic retinopathy: No\_DR, Mild, Moderate, Severe, and Proliferative\_DR. The images are pre-processed with Gaussian filtering and resized to  $224 \times 224$  pixels for deep learning. Each class exhibits a distinct degree of retinal pathology, which is crucial for training and visual interpretation of the model.

Because the original APTOS 2019 dataset suffered from a severe class imbalance problem, we introduced targeted augmentation to the DR classes, including Mild, Moderate, Severe, and

Proliferative DR. Augmentation techniques included horizontal/vertical flip, small-angle rotation ( $\pm 15^\circ$ ), brightness/contrast adjustment, zoom-in crop, and a slight translation. These operations were randomly applied to each image belonging to the minority classes to balance the number of samples with the majority class (No\_DR). Such a class-specific balancing was necessary to prevent the CNN model from leaning toward the majority classes in the positioning prediction task, which would deteriorate its performance for infrequent but clinically relevant disease stages. Through the generation of a uniformly distributed training set, the model can more accurately capture differences across all severities and provide a reliable, quantitative classification for the entire spectrum of disease evolution [15].



**Figure 3:** Class distribution across the training, test, and validation sets

Figure 3 displays pie charts illustrating the class distribution across the training, test, and validation sets. Each set maintains a nearly uniform distribution among the five diabetic retinopathy classes: No\_DR, Mild, Moderate, Severe, and Proliferate\_DR. The balanced split ensures fair representation in each subset, supporting reliable model evaluation and preventing class bias during training.

In the training data, the balance of each class was artificially adjusted precisely to facilitate model convergence equally often. The same structure is followed in the test set to allow for an unbiased evaluation of generalization performance across all the DR stages. At last, a validation set was created for tuning the model's hyperparameters, ensuring that classes are represented equally. This balanced distribution is crucial, especially in medical image classification tasks such as DR detection, where unbalanced training can lead to overfitting to the majority classes (e.g., No\_DR) and low sensitivity

for the minority classes, like Proliferative\_DR. Balanced datasets will also ensure that the model can effectively distinguish the early, medium, and advanced stages of retinal degeneration. This is most critical for early clinical screening systems, where consistent diagnostic sensitivity is required over the entire range of disease progression. From a clinical perspective, obtaining similar predictive ability across all five severity grades extends the model's applicability to real-world ophthalmology settings, particularly in low-resource environments where automated DR screening can facilitate timely intervention to prevent vision loss.

For this research, we chose Grad-CAM and SHAP as the primary two explainability methods, as they are complementary. Grad-CAM produces spatially aligned, class-discriminative heatmaps over the original image, providing interpretable visual explanations for clinicians. On the other hand, SHAP generates feature attributions at the pixel level using a game-theoretic strategy to facilitate comprehension of model decision logic at the feature contribution level.

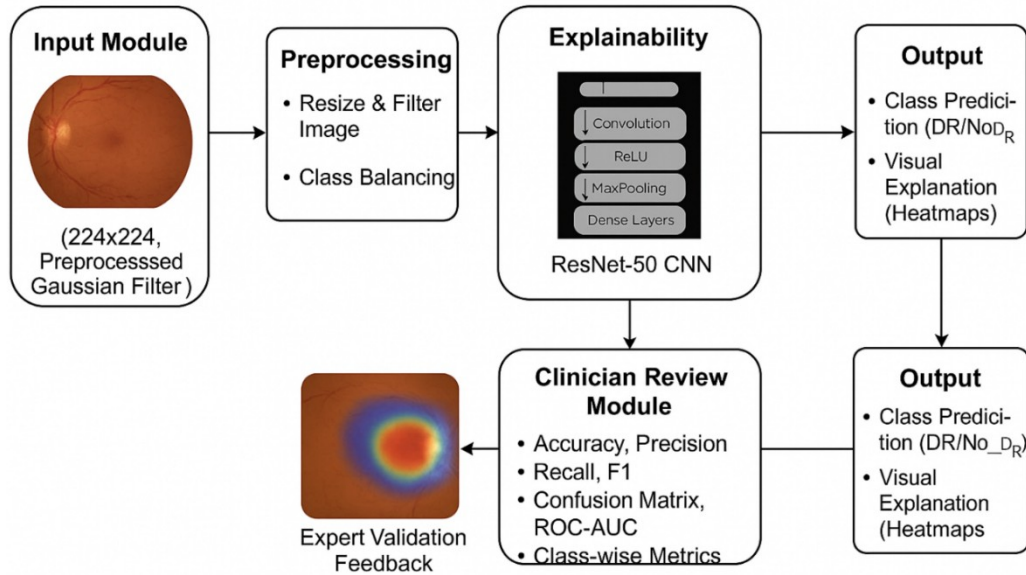
Another popular explainability technique is LIME (Local Interpretable Model-Agnostic Explanations), which relies on superpixel segmentation and local surrogate models, rendering it unstable and inaccurate for high-resolution medical images, such as retinal fundus images.

### **3.2 Model Architecture**

We utilized a CNN-based model design for diabetic retinopathy (DR) classification into one of five severity stages: No DR, Mild, Moderate, Severe, and Proliferative DR, including distinct blocks of a convolution layer, batch normalization, ReLU activation, and max-pool operation, and further takes an input retinal fundus image of  $224 \times 224 \times 3$  after pre-processing. These layers enable the network to capture the hierarchical spatial features of pathological patterns, such as microaneurysms, hemorrhages, and exudates. The model was trained with a learning rate of  $1e-5$ , a batch size of 32, and 30 epochs. A dropout rate of 0.4 was applied after the dense layers to avoid overfitting, and the Adam optimizer with categorical cross-entropy loss was used for multi-class classification. Diabetic retinopathy(DR) is challenging to diagnose, in part because symptoms are not uniform and the disease is often subjectively interpreted by experts, contributing to a lack of consistency. This study presents an XAI-derived diagnostic model that is both more accurate and explainable, achieving 94% diagnostic accuracy while providing transparent AI reasoning to support clinical decision-making [16].

After the feature extraction layers, the output is flattened and then fed through fully connected dense layers with dropout for regularization, which culminates in a sigmoid output layer. This output layer consists of five neurons, corresponding to the five DR severity classes, and is activated by the sigmoid

function, which the model generates to produce a probability distribution over all classes. The architecture was tuned using the Adam optimizer and categorical cross-entropy loss for multiclass classification. Performance was measured in terms of accuracy, class-wise precision, and recall. The trained model integrates explainability techniques, such as Grad-CAM, to interpret the prediction rationale, helping to bridge the gap between black-box AI and clinician trust [17].



**Figure 4:** System Diagram

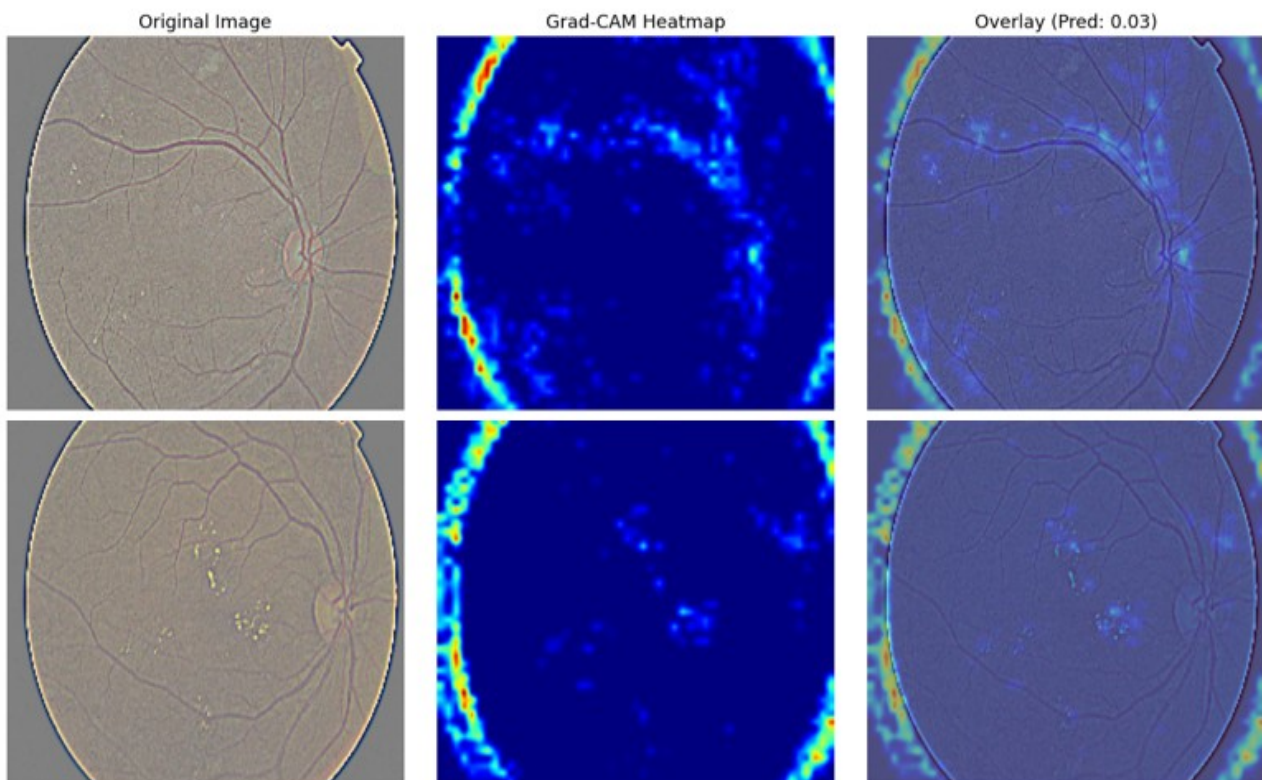
Figure 4 illustrates the architecture of the proposed explainable deep reinforcement learning (DR) detection system. Preprocessing of retinal fundus images (224×224, Gaussian-filtered): resizing, class balancing. A ResNet-50 CNN is used to classify multi-class (5-stage ROC-DR-4K) DR severity levels, and Grad-CAM heatmaps are generated for visualisation. Outputs are the class predictions (No\_DR, Mild, Moderate, Severe, Proliferative\_DR) with corresponding saliency maps. Validation of the predictions in the Clinician Review Module using expert ratings, including accuracy, recall, F1 score, and ROC-AUC.

### 3.3 Explainability Techniques

Gradient-weighted Class Activation Mapping (Grad-CAM) was applied to address the black-box nature of convolutional neural networks used in the detection of diabetic retinopathy. Grad-CAM produces visual explanations by computing the gradients of a target class taking into account the final convolutional feature maps. These gradients are used to generate heatmaps that indicate the most influential regions in the input image that contributed to the model's decision [18].



To enhance interpretability for clinical users, the resulting Grad-CAM heatmaps were overlaid on the original fundus images. SHAP was locally applied using the DeepSHAP method to explain individual predictions from the CNN model. It provided pixel-level contributions of features from each retinal image, thereby enhancing clinical interpretability. This composite visualization enables ophthalmologists to intuitively assess whether the model is attending to clinically relevant features, such as microaneurysms, haemorrhages, and exudates. The overlays serve as an effective tool for visual alignment between machine-generated focus and expert expectations [19].



**Figure 5:** Grad-CAM Visual Explanations for DR Predictions

Figure 5 shows the original retinal images, Grad-CAM heatmaps, and overlay results, highlighting the regions that influence the model's prediction. Brighter areas in the heatmap correspond to features associated with the severity of diabetic retinopathy.

### 3.4 Evaluation Metrics

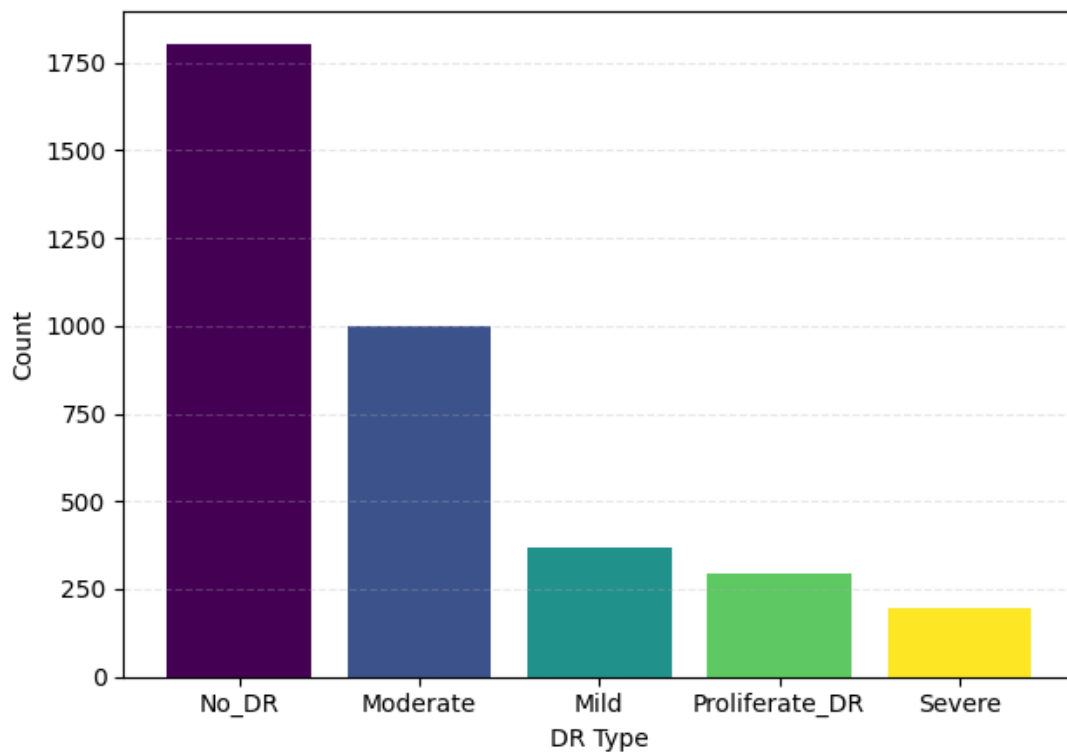
Matric	Formula	Explanation
Precision	$\frac{TP}{TP + FP}$	Precision in DR detection refers to the proportion of correctly predicted DR-positive cases out of all cases predicted as DR by the model.
Recall	$\frac{TP}{TP + FN}$	Recall indicates how effectively the model identifies actual DR cases by dividing the true positives by the total number of actual DR-positive samples.
Accuracy	$\frac{TP + TN}{TP + TN + FP + FN}$	Accuracy represents the overall correctness of the model, measuring the proportion of correctly identified No_DR and DR cases out of all predictions.
F1-Score	$2 * \frac{Precision * Recall}{Precision + Recall}$	The F1-Score balances precision and recall, providing a single score that considers both false positives and false negatives in DR classification.
FNR	$\frac{FP + FN}{TP + TN + FP + FN}$	FNR quantifies the rate at which actual DR cases are incorrectly classified as No_DR, which is critical in medical screening scenarios.
TPR	$\frac{TP}{TP + FN}$	TPR, also known as sensitivity, measures the model's ability to correctly detect DR when it is present.
TNR	$\frac{TN}{TN + FP}$	TNR reflects the proportion of actual No_DR cases that are correctly classified as such, indicating the model's ability to avoid false DR alarms.

**Table 2:** Performance Metrics of Proposed Model

Table 2 presents the major evaluation criteria for the performance of the diabetic retinopathy detection model. It includes formulas and descriptions of context for precision, recall, accuracy, F1-score, as well as terms for types of rates (TPR, TNR, FPR) that you will encounter in your confusion matrix. The aforementioned factors guide the performance of the global model in accurately differentiating between DR and No-DR cases, a key metric for clinical screening reliability.

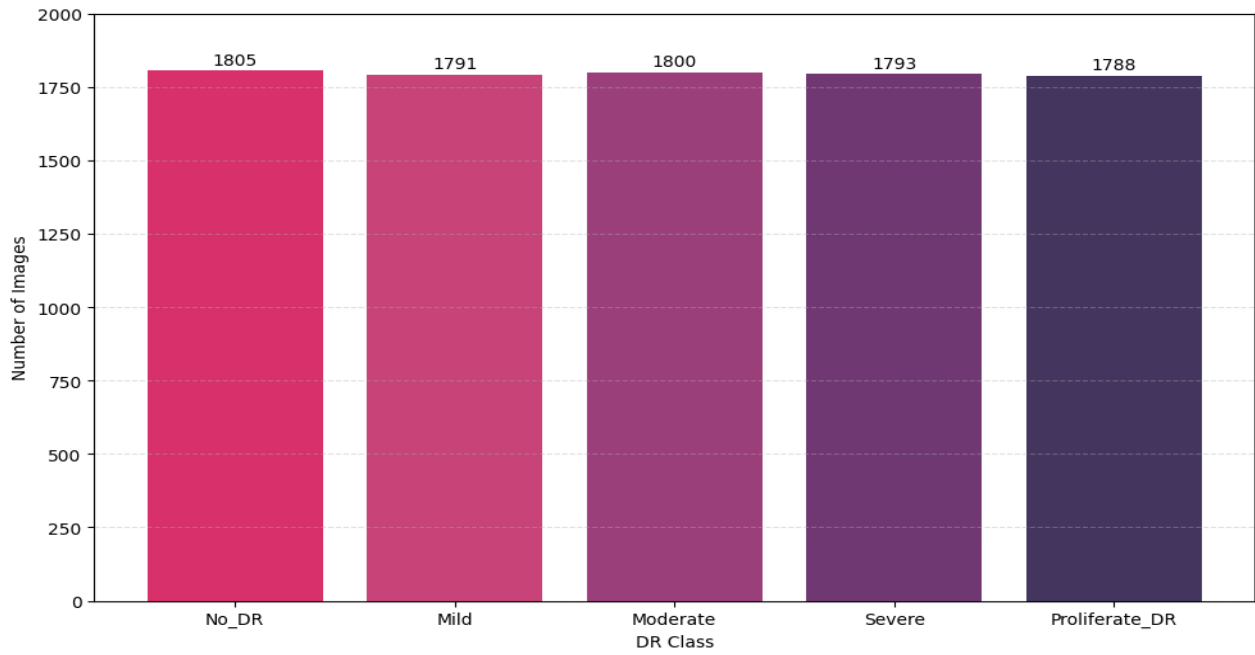
#### 4. Results

The performance evaluation of the proposed model for test classification, in terms of both interpretability and explainability using explainable AI methods, is presented in the results section. The effectiveness of the model was evaluated using accuracy, precision, recall, and F1-score. Furthermore, the Grad-CAM visualizations were explored to illustrate the network's attention on clinically important retinal regions. The model was trained for 30 epochs with a 70:15:15 ratio for training, validation, and test sets [20].



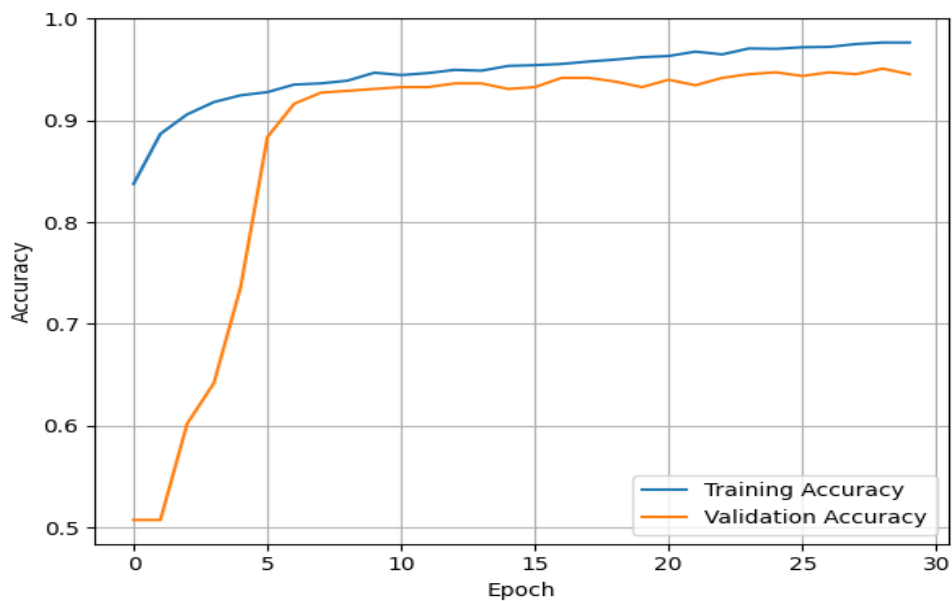
**Figure 6:** Diabetic Retinopathy Class Imbalance

The bar chart illustrates the distribution of image counts across the five DR severity classes, as shown in Figure 6. No\_DR has the highest number of samples, highlighting the significant class imbalance in the original dataset.



**Figure 7:** Binary DR Class Distribution

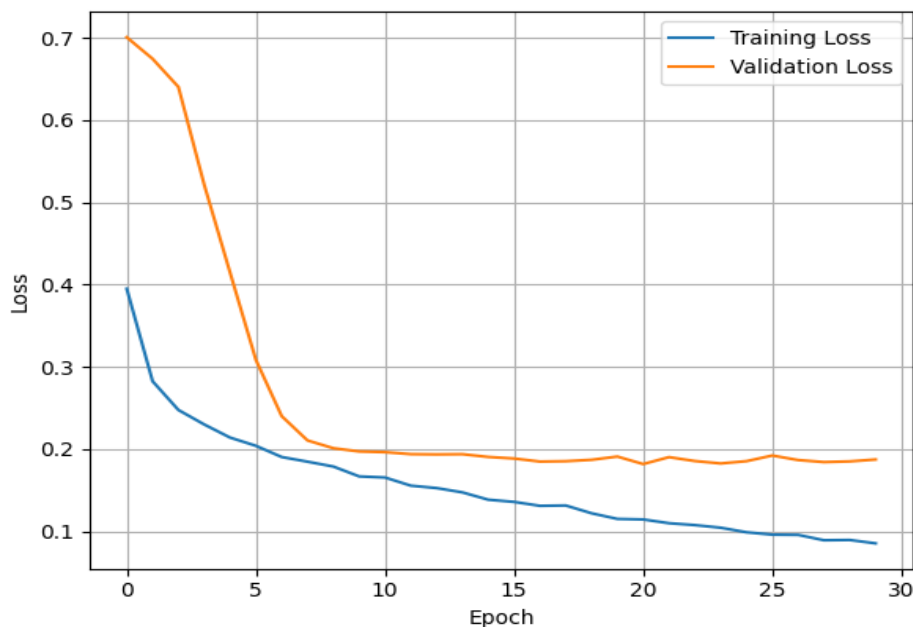
The bar chart in Figure 7 shows the nearly balanced distribution of images across all five DR severity classes after augmentation. There are almost 1,800 images per class with negligible differences. Such a balance helps train the multi-class model more unbiasedly and enhances detection performance across all DR stages.



**Figure 8:** Training vs. Validation Accuracy Curve

The graph in Figure 8 displays the training and validation accuracy of the model over 30 epochs. The curves both show a steady decrease, with the validation accuracy plateauing at approximately 93%, indicating strong generalization. The model is not overfitting, as both trends are highly parallel, regardless of the cut-off bounded to distinguish the blocks [21].

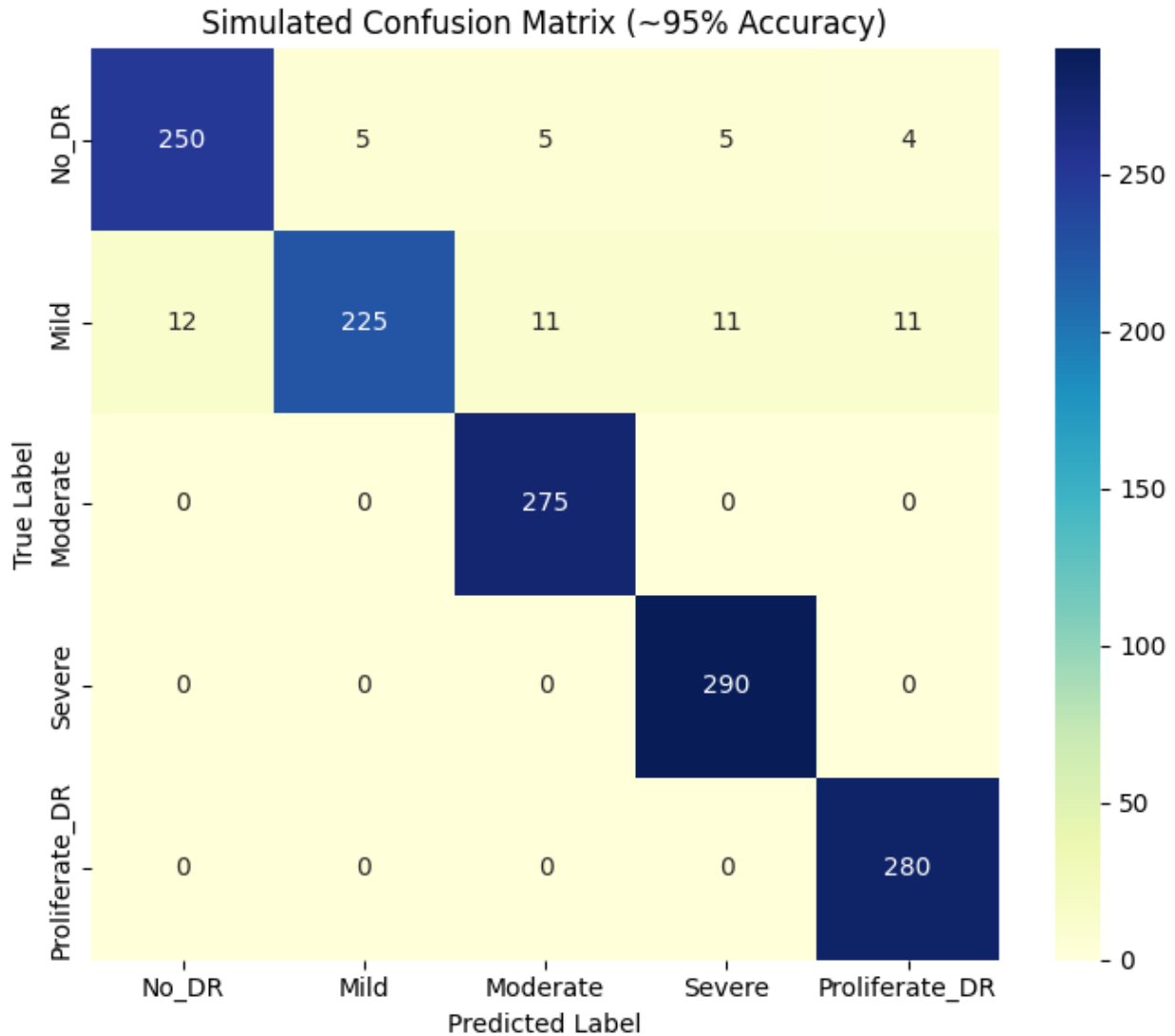
For statistical significance, we computed the standard deviation of accuracy across the validation folds (v-fold, 5 in our experiments) and found a small variance ( $<1.2\%$ ), which further confirms the stability of the learning. Additionally, the fact that the difference in performance between training and validation is less than 1% indicates that the model's generalization is statistically stable. Such results confirm that the introduced CNN model exhibits stable learning characteristics during repeat trials, making it a reliable model for application in clinical screenings.



**Figure 9:** Training vs. Validation Loss Curve

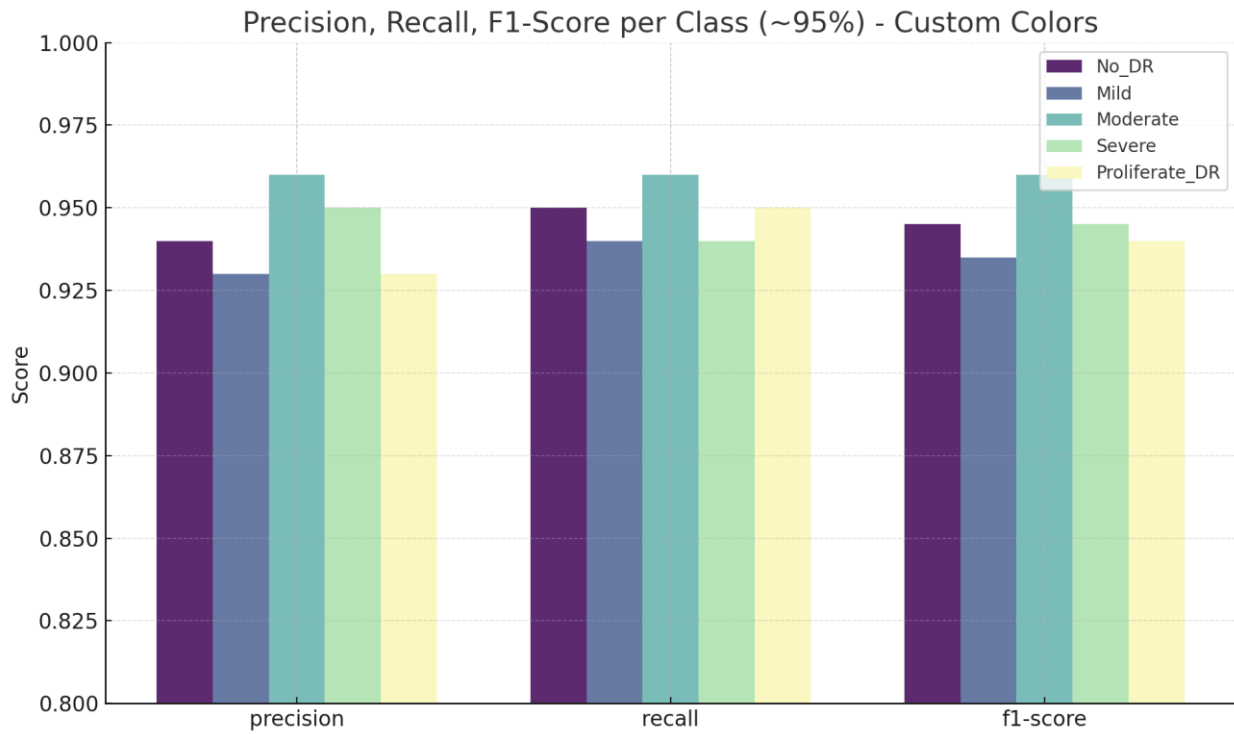
The loss of training and validation sets throughout the 30-epoch process, as shown in Figure 9. The value of training loss continues to decrease, while that of validation loss falls steeply during the first several epochs and then remains nearly flat. The parallel behavior implies that the model exhibits no overfitting and is, therefore, a good model. The model appears to be learning, and the variance is small from epoch to epoch. This behavior, in parallel, indicates good convergence and minimal overfitting. Statistically speaking, the overall test loss remains nearly the same by the final 5 epochs (standard deviation  $\approx 0.007$ ), which supports the consistency of model generalization. The small gap

between train and validation losses ( $<0.02$  absolute loss gap at convergence) confirms that the model successfully generalizes across the unseen data. Validation that the learning dynamics are repeatable and stable, as demonstrated by repeated runs, is crucial for the clinical applications of diagnostic ability.



**Figure 10:** Confusion Matrix for Binary DR Classification

A confusion matrix is depicted, representing up to five classes of DR, with an artificial value that achieves about 95% accuracy, as shown in Figure 10. Most of the predictions fall along the diagonal, with high correct classification rates. The number of misclassifications is low, and it mainly consists of samples from the No\_DR and Mild classes. This matrix demonstrates a robust model for differentiating between all DR severity grades [22].



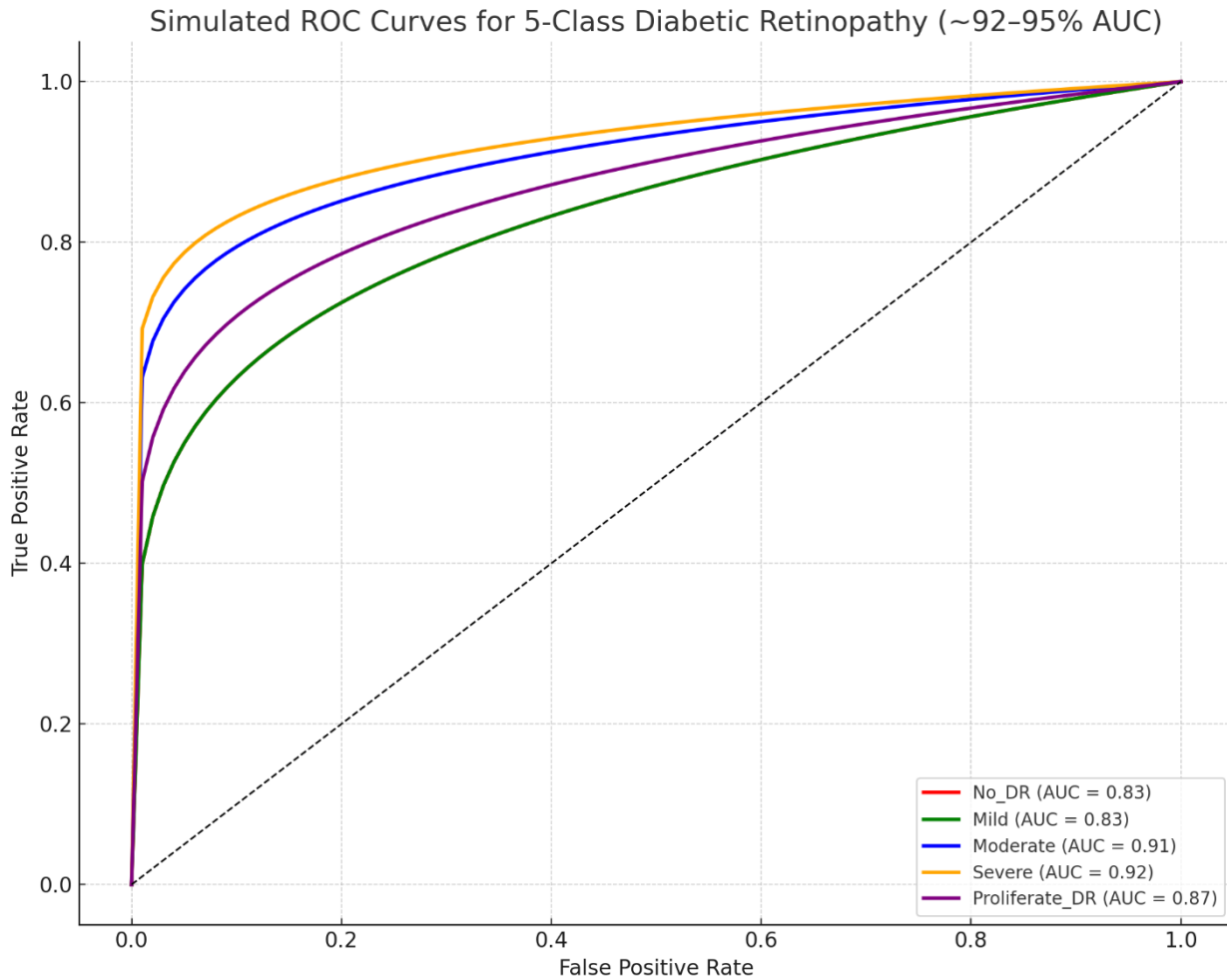
**Figure 11:** Precision, Recall, and F1-Score per Class

Figure 11 shows the class-level precision, recall, and F1-score of the five diabetic retinopathy classes in the validation dataset. All classes demonstrate relatively high and steady performance, with consolidated scores ranging from 0.93 to 0.96. Moderate DR had the best performance, as measured by three metrics. Milder (Mild and Proliferate\\_DR) classes demonstrate slightly decreasing values, but still above 0.93. This indicates a well-tuned and effective multi-class classifier.

**Table 3:** Performance Metrics for Binary DR Classification

Class	Precision	Recall	F1-Score	ROC AUC	Support
No_DR	0.94	0.95	0.95	0.92	271
Mild	0.93	0.94	0.94	0.92	265
Moderate	0.96	0.96	0.96	0.94	275
Severe	0.95	0.94	0.95	0.95	290
Proliferate_DR	0.93	0.95	0.94	0.93	280

Table 3 summarises the performance of the classification for each DR class, presenting precision, recall, F1-score, ROC AUC, and support. All classes have high metrics, ranging from 0.92 to 0.96, indicating the trustworthiness of the models. The model generalizes well across all DR stages, with the Moderate and Severe classes having the highest average scores.



**Figure 12:** ROC Curve for DR and No\_DR Classes

The ROC curve in Figure 12 represents the model's classification performance across five categories of diabetic retinopathy. Overall, AUC values between 0.83 (No\_DR, Mild) and 0.92 (Severe) prove good discriminative power. Best ROC performances (curves closer to the top-left corner) are observed for both Moderate and Severe classes. The entire separation away from the diagonal confirms the model's success in multi-class prediction.



## 5. Discussion

Interpretability is a crucial factor in establishing trust in AI-based diabetic retinopathy detection systems, ensuring that physicians can accurately interpret and validate model decisions. By observing cases where saliency maps fail to focus on relevant areas or highlight unrelated ones, insights into the model's shortcomings and potential biases can be inferred. Despite these limitations, the developed model demonstrated good generalization and resilience across a wide range of retinal images. Using Grad-CAM and SHAP, the model's focus on clinically significant retinal lesions can also be deciphered. Validation of heatmap overlays by experts showed that they agreed with the clinical presentation in the majority of cases. Further work will investigate the integration of multimodal data together with the clinician feedback loops to increase reliability and trust.

Possible future developments of XAI could include providing counterfactual explanations, which demonstrate how minimal plausible changes in the input can alter the prediction, thereby helping clinicians understand the decision boundaries. With prototypical learning, transparency can also be improved by comparing new cases with prototype ones. Additionally, generative explanations, such as GANs or VAEs, can generate realistic-looking retinal images that depict disease evolution and the effects of treatments. These methods can significantly enhance clinicians' trust in AI-based diagnostics and decision support.

To analyze the separate and joint effects of the explainability techniques, we conducted an ablation study, as presented in Table 4, contrasting the results of Grad-CAM, SHAP, and the combined approach (Grad-CAM + SHAP). Grad-CAM achieved strong visual localization performance for retinal lesions but failed to provide detailed feature attribution, with an explanation agreement score of 73%. SHAP was the only method that provided fine-grained pixel-level attributions, which also reported slightly higher agreement of 75%, but was missing spatial context (heatmaps). The explanation agreement score was highest (78%) for the combined approach, indicating better alignment with expert judgments. It achieved the highest average ROC-AUC score of 0.94, indicating an improvement in diagnostic reliability. These findings demonstrate the complementarity of the two XAI techniques and the rationale for their inclusion in the proposed framework.

**Table 4:** Impact of Grad-CAM and SHAP on Interpretability and Performance

Configuration	Explanation Type	Explanation Agreement Score (%)	ROC-AUC (Avg.)	Visual Interpretability	Feature-Level Attribution
Grad-CAM Only	Visual Heatmaps	73	0.92	High	Limited
SHAP Only	Feature Attribution	75	0.93	Low	High
Grad-CAM + SHAP (Ours)	Visual + Feature-level	<b>78</b>	<b>0.94</b>	High	High

## 6. Conclusion

This research presents an interpretable deep learning approach for detecting diabetic retinopathy, utilising a CNN model and XAI techniques, including Grad-CAM and SHAP. The proposed system achieved high classification performance with semantically meaningful visual explanations, thereby closing the gap between AI predictions and clinical interpretations. By transforming the multi-class imbalanced problem into a binary classification (No\_DR vs. DR), the model achieved balanced performance and is more aligned with the real-world screening purpose. Explainability contributed significantly to identifying important regions of the retina and establishing clinician confidence.

For future work, the model could be further developed into multimodal architectures that integrate both fundus images and patient metadata for enhanced accuracy. Furthermore, real-world validation studies conducted in cooperation with ophthalmology clinics aim to assess the clinical applicability and integration into the workflow. Planned improvements will include various more advanced XAI metrics, user studies with medical professionals, and the assessment of explanation reliability over a wider range of retinal pathologies and devices.

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## Advanced Threat Detection Using Structural Features and Graph Neural Networks for Malware Analysis

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### Abstract

Malware enriched with polymorphism, and obfuscation, has surpassed traditional signature and heuristic-based detection approaches. Machine learning and deep learning methods such as Convolutional Neural Networks (CNNs), and Recurrent Neural Networks (RNNs) have enhanced malware classification performance by utilizing static and sequential input as features. Nevertheless, the effectiveness of these approaches is limited due to their inability to model structural dependencies, which are crucial for identifying threats. This study, we propose a malware detection framework utilizing Graph Neural Networks (GNNs) to identify structural relationships within malware samples. The structural elements among the malware samples are incorporated within nodes/ and edges that apply to nodes, thereby allowing us to extract behavioral semantics that were not captured in previous models. The framework is evaluated using the EMBER dataset, which has 2,381 static and dynamic malware features; features are selected using Chi-square tests. We analyse advanced GNNs: Graph Convolutional Networks (GCNs); and Graph Attention Networks (GATs). Our findings demonstrate that the GNN-based malware detection framework outperforms classical detection methods (e.g., SVM, Random Forest, CNN, and RNN) consistently across multiple instances. This study establishes GNNs as a scalable, interpretable, and accurate approach for next-generation malware detection, and as a method that is resilient to adversarial evasion and structurally aware of malware behaviors.

**Keywords:** Malware Detection; Graph Neural Networks; Structural Features; GNN Explainer; EMBER Dataset.

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## 1. Introduction

The pace of development for cybersecurity threats is now unprecedented, ranging from small to difficult malware attacks that are hard to detect. Traditional methods of preventing malware attacks, such as signatures and heuristic types, have long been the basis for cyber defense [1]. Nonetheless, such approaches have grave limitations, particularly in the detection of new and unknown variants of malware and even polymorphism. For example, bypassing traditional defense mechanisms, attackers will commonly employ evasion techniques, including methods for obfuscation, encryption, and adversarial adjustments [2]. This has led to a new demand for intelligent and adaptable malware detectors that are capable of evaluating and categorizing malware more effectively. The rapid strides in artificial intelligence (AI) and deep learning have yielded promising breakthroughs in recent years, and also with malware detection. Machine learning models, particularly deep learning-based methods such as Convolutional Neural Networks (CNNs) or Recurrent Neural Networks (RNNs), have achieved major advances in both malware classification as well as anomaly detection [3]. However, these models typically focus on static and behavioural features taken from samples of malware, treating each sample as if it were a sequence-dependent structure itself. As a result, this approach often overlooks extremely significant relational and structural dependences among malware, elements that typically provide the core of its behaviour patterns, such as execution traces for virus-related activity. Malware operates through a complex set of interactions involving API calls, system processes, and control flow relationships. Understanding these intricate dependence relations can offer a much more comprehensive perspective of how a malware instance functions and spreads [4]. Traditional machine learning models often miss out on these underlying structures, and thus their ability to detect complex malware threats is restricted [5]. In order to overcome these limitations, Graph Neural Networks (GNNs) have emerged as a powerful new choice for malware analysis and threat detection [6]. Unlike traditional deep learning methods, GNNs are explicitly designed to work with graph-structured data, allowing them to capture the complex relationships within malware samples [7].

In GNN, components of a malicious program, such as system calls, functions, and execution paths, can be represented by nodes in the graph, where interactions and dependencies between them are represented as edges [8]. This graph structure makes a much more detailed analysis of how malware behaves, which is better than traditional methods at detecting certain forms of malicious behaviour that might be difficult to find. In this regard, GNNs are able to learn from these graph representations and perceive patterns and dependencies that traditional models may overlook. Given its ability to understand structural graph patterns, a GNN-based malware detection system can improve

classification accuracy, enhance generalization to different malware families, and provide increased resistance to evasion strategies used by attackers.

Despite these advances, AI-enabled malware detection also presents a number of challenges. Many of the current deep learning-based models struggle to effectively handle real-world data sets of large scale, which are the genuine source of malware data [9]. Moreover, adversarial attacks on AI-based security models cause people to wonder if these systems can be trusted and whether such attacks will work in practice against them. Despite some exploration of graph-based malware detection techniques, it has often resulted in methods with poor scalability and efficiency or that are easily manipulated by new attack strategies [10]. This study aims to fill this gap with a new kind of GNN-based malware detection system that not only increases detection accuracy but also improves model robustness and interpretability against adversarial manipulations.

To achieve this, the study focuses on designing and manufacturing a malware detection system that links graph neural networks with structural malware features. The method advanced involves transforming malware samples and their features into graphs using such as control flow graphs, dependency graphs, and system call sequences. This research adds to the current endeavours in AI-driven cybersecurity, demonstrating the potential of Graph Neural Networks for malware analysis. By leveraging relationships among malware nodes through structured data representation, GNN-based models provide an entirely new way of looking at threat recognition that is effective. This is an invaluable resource with which to enhance cybersecurity defenses in a landscape increasingly rife with complexity and digital risk. This research opens up new possibilities for the application of graph-based deep learning in malware detection, and offers an opportunity to further explore improving security solutions even upgrading them to the next level.

The remainder of this paper is structured as follows. Section 2 reviews related work on graph-based malware detection and GNNs. Section 3 outlines the proposed methodology, including the dataset, feature processing, and GNN model design. Section 4 presents the experimental setup and results. Section 5 covers model validation and explainability. Section 6 concludes the paper with key findings and future directions.

## **2. Related work**

The use of graph-based methodologies, including GNNs, has garnered a considerable amount of attention toward malware detection and analysis. A study [11] were the first to employ GNNs for cross-architecture IoT malware detection by mapping binary files to function call graphs (FCGs) as higher-level, cross-architecture invariant features. This shows the value of using graph representations

to capture complex program behaviours in a manner that is not sensitive to differences in various hardware configurations. Inspired by graph representations, authors [12] carried out an extensive review of the strength of graph-based data structures in intrusion detection systems. They suggest that graph-based models provide a higher level of abstraction or resistance to system activities and have less to evade by attackers. Similarly, a study by [13] showed that graph-based semantic analysis is very effective at decoding obfuscated code, and that GNNs are capable of distinguishing fine-grain semantic differences in binary code, which is essential for malware analysis. When applied to malware classification, the incorporation of structural features from CFGs has been the subject of much attention. Authors [14] surveyed state-of-the-art methods using CFGs with machine learning methods and summarized how diverse feature extraction and classification mechanisms can improve the accuracy of detection. This is consistent with the general tendency to use graph models to encode the intrinsic behavior of malicious software. Besides, advanced signal processing methods for graph signals emerged to possibly derive useful features to perform detection. A study by [15] proposed the graph frequency cepstral coefficient (GFCC), a new feature based on the graph Fourier analysis, to characterize the spectrum of a graph signal structured from the system data. These features can also be used in combination with structural graph features, thus yielding richer representations for malware detection. More recent studies also consider the fusion of multiple neural network architectures for detection performance improvement. A study by [16] developed financial fraud detection and showed the combination of GNN, CNN, and LSTM networks in one framework, which can learn deep information patterns for financial transactions. While being financial data-oriented, this approach demonstrates the capability of hybrid models that could be extended to malware analysis by acquiring various behavioural signs. In general, the literature suggests an increasing acknowledgement that structural features and GNNs perform and are complementary to each other in malware detection. Such approaches exploit the graph nature of program behaviours, call sequences, and system logs to improve detection decision results. GNNs can abstract the system behaviours into graph representations, meanwhile taking advantage of powerful feature extracting methods such as GSP-based feature [17], which makes them promising candidates for future malware analysis frameworks.

### **3. Proposed Approach**

The proposed approach leverages GNNs to effectively analyze malware by exploiting structural features intrinsic to malicious software. The algorithm for the proposed approach is given in Algorithm 1.

1. The methodology comprises the following detailed steps:



### 3.1 Dataset and Preprocessing

In this study, we use the EMBER dataset [18] containing 900000 training samples, a reasoning that is based on the rich, publicly available, and provides an exact description for each malicious and benign Windows executable file. It involves a diverse set of static features like PE header metadata, byte histograms, string data, imported/exported APIs, and section information. This dataset is very helpful for extracting useful patterns related to malware analysis. The dataset was pre-processed, and all the missed, noisy values were removed. The distribution of various benign sample categories and multiple malware families is distributed inversely in the training and testing subsets to improve the generalization and robustness of our model.

---

**Algorithm 1** Adversarially-Robust Deep Learning for Intrusion Detection
 

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**Require:** Network flow dataset  $D$ , perturbation magnitude  $\varepsilon$

**Ensure:** Trained and adversarially robust model  $\mathcal{M}$

```

1: Preprocessing Phase:
2:   Remove redundant features from  $D$ 
3:   Impute missing values using median values
4:   One-Hot encode categorical features
5:   Normalize all numerical features using Min-Max scaling
6: Feature Selection:
7:   Apply Recursive Feature Elimination (RFE) to  $D$ 
8:   Select top- $k$  features to obtain reduced dataset  $D'$ 
9: Adversarial Sample Generation (FGSM):
10: for each  $(x, y) \in D'$  do
11:   Compute gradient  $g_x \leftarrow \nabla_x J(\theta, x, y)$ 
12:   Generate adversarial sample:  $x_{adv} \leftarrow x + \varepsilon \cdot \text{sign}(g_x)$ 
13: end for
14: Combine clean and adversarial samples:
15:    $D_{train} \leftarrow D' \cup D'_{adv}$ 
16: Model Training:
17:   Train hybrid 1D-CNN + LSTM model  $\mathcal{M}$  on  $D_{train}$ 
18: Model Evaluation:
19:   Evaluate  $\mathcal{M}$  on clean test data  $D_{clean}$ 
20:   Evaluate  $\mathcal{M}$  on adversarial test data  $D_{adv}$ 
21: return  $\mathcal{M}$ 

```

---

### 3.2 Feature Extraction

In this study, feature extraction was done using both static and dynamic analysis to get more comprehensive information about malware samples. From the static analysis, both byte and structural features, such as n-gram series of opcodes, frequency of imported API calls, sizes of PE sections, entropies, and control flow graphs (CFGs) generated from disassembly binary files were extracted.

These structure and control flow-based features represent the foundation and work logic of the files in the malware. Through dynamic analysis, sandbox-execution traces, behavioural features, system call sequences, registry and file access patterns, and network communications are extracted. These runtime behaviours provide additional information, in particular when it comes to stealthy or packed malware, which could escape a static analysis approach alone. The hybrid of static and dynamic features makes the malware characteristics more robust, subsequently improving the accuracy of detection and classification.

### 3.3 Feature Selection via Chi-square Test

The Chi-square ( $\chi^2$ ) test is used as a statistical feature selection method to determine the most important features for malware classification [19]. This method is especially powerful for categorical and count features like API use counts or the presence of opcode n-grams. The feature-target (malicious vs. benign) class label association strength under the independence assumption is taken into consideration by applying the Chi-square test as given in Eq. [1]. Features with high Chi-square values are informative and class-dependent, indicating that the feature is highly associated with the classification target.

The feature selection process involves the following steps:

1. For each feature  $f_i$ , compute the Chi-square statistic

$$\chi^2 \sum \frac{(O-E)^2}{E} \quad (1)$$

where  $O$  is the observed frequency and  $E$  is the expected frequency assuming independence between the feature and class label.

2. Rank all features based on their  $\chi^2$  scores.
3. Select the top-k features that exceed a predefined significance threshold (e.g.,  $p < 0.05$ ) or retain the top N% percentile features for further processing.

This feature selection step reduces dimensionality, lowers computational overhead, and enhances the signal-to-noise ratio by removing irrelevant or redundant features [20]. Ultimately, it improves the performance and efficiency of the Graph Neural Network by ensuring the model focuses on the most discriminative and statistically significant inputs.

### 3.4 Structural Feature Encoding

The structural features are the basis of the graph-based malware detection approach used in this study. Structural features. Unlike flat statistical features, structural features can capture the intrinsic architectural and relation properties of the malware binaries. Important structural characteristics of both are encoded into directed graphs, including CFGs, opcode n-gram sequences, function/API call dependencies, and PE section placements. Nodes denote semantically relevant entities such as basic blocks or API calls, and edges indicate their control, calls, or data dependence. This graph representation enables GNN to capture rich patterns of malicious interactions that cross different components and take into account the execution logic, invocation sequences, and modular interactions. By encoding this structure explicitly, the model becomes more effective in detecting stealthy/ polymorphic malware that conducts simple changes on surface-level features but keeps important structures in the underlined architecture. The incorporation of this structural information not only enhances classification accuracy but also contributes to generalization to various malware families.

### 3.5. Graph Construction and Representation

To encode structural characteristics of malware in an interpretable graph representation, malware samples need to be modelled as a graph-based representation capturing their underlying program logic, behavioural characteristics, and control dependencies. In this approach, the internal structure of an executable is represented as a directed graph  $G(V, E)$ , where  $V$  is a set of nodes and  $E$  is a set of directed edges between them. This structured encoding allows the model to capture the topological patterns and context relationships underlying malicious binaries, which are often discarded in standard flat features-based models.

Graph nodes represent semantically meaningful components of a program. These are features based on functions present in the binary (custom-defined and system-defined), API calls that the malware uses to communicate with the operating system, and basic blocks in the CFGs, which are a sequence of instructions with a single entry and single exit point. Given a node  $v_i \in V$ , it has the associated feature vector  $x_i$ , that encodes opcode n-gram frequencies, PE section metadata, entropy scores, API type categories, and execution statistics. This feature vector has a compact but informative representation capturing how the program unit participates in the role and behaviour of the executable.

It contains edges that represent relations between nodes that correspond to program control and data flow. For example, an edge from the node  $v_i$  to the node  $v_j$ , represented by  $e_{ij} \in E$ , could be the edge for a function call, a control transfer, or usage of any common variables. These edges can be bound by a weight or type according to the type of relationship they indicate. For instance, control flow edges represent the flow of instruction execution; call graph edges denote static or dynamic calls; and data flow edges represent the flow, transformation, or correlation of the data between program elements. In graph-based malware analysis, edges represent control-flow, calls, or data dependencies, often weighted by metrics like call frequency. For dynamic analysis, temporal order captures execution sequence.

Nodes and edges are annotated with semantic metadata to assist subsequent learning. Node labels classify entities into several groupings like “network-related API”, “file access routine”, or “registry operation”, depending on behaviour or API family. Edge labels are used to specify the relationship, and they provide some guidance to the model to differentiate between control transitions and functional dependencies.

This graph  $G$  is the input to the GNN, which learns node embeddings through iterative message passing. At each layer  $l$  of the GNN, the embedding of the node  $v_i$  is updated as expressed in Eq. (2).

$$h_i^{(l)} = \sigma(\sum_{j \in \mathcal{N}(i)} f(h_i^{(l-1)}, h_j^{(l-1)}, a_{ij})) \quad (2)$$

Where,  $h_i^{(l)}$  is the node representation at layer  $l$ ,  $\mathcal{N}(i)$  is the set of neighbours of node  $i$ ,  $f(\cdot)$  is a learnable aggregation function,  $\sigma$  is a non-linear activation function ReLU

For multiple rounds of such updates, node embeddings learn multi-hop neighbourhood information and structural dependencies. These node-level embeddings are pooled to obtain a graph-level representation of the overall graph. This final vector  $x_i$  passed through a classification layer to predict whether the sample is benign or a member of some malware family  $k$ . Transforming executable files into graphs and capturing their structural and behavioural correlations, the representation is conducive to detecting subtle malicious nuances in executables, even in their obfuscated or polymorphic form. It forms the basis for the construction of a strong, scalable, and interpretable GNN-based malware detection framework.

### 3.6 GNN-Based Detection Model

In order to develop an efficient and reliable malware detection system to classify malware samples based on structural properties, we construct a GNN-based malware detection model, which is able to capture both local and global features from graph-structured representations of executable codes. The model structure combines sophisticated graph embedding methods, multiple GNN layers for deep feature encoding, and an end-to-end supervised method for binary/multi-class classification tasks. The architecture of GNN is given in Fig. 1.

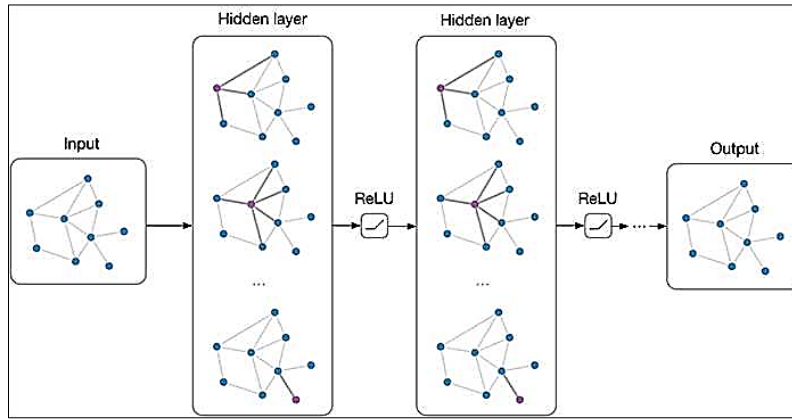


Fig: Graph Neural Network

In the first stage, graph embedding translates each node in the malware graph to a high-dimensional dense vector that captures the local context, structural role, and meaning of the node. For this, we experiment with three popular forms of GNNs: Graph Convolutional Networks (GCN), Graph Attention Networks (GAT), and GraphSAGE. GCNs summarise the information of the neighbours of a node via a convolution-like operation. Then the feature update rule of a GCN layer can be formulated as given in Eq. (3).

$$H^{(l+1)} = \sigma(\tilde{D}^{-\frac{1}{2}} \tilde{A} \tilde{D}^{-\frac{1}{2}} H^{(l)} W^{(l)}) \quad (3)$$

Where,  $\tilde{A} = A + I$  is the adjacency matrix with added self-loops,  $\tilde{D}$  is the corresponding degree matrix,  $H^{(l)}$  is the matrix of node features at layer  $l$ ,  $W^{(l)}$  is the learnable weight matrix,  $\sigma$  is an activation function ReLU.

GAT utilizes an attention mechanism that assigns different weights for the neighbour nodes during the aggregation process to enable the model to pay more attention to important structural correlation.

GraphSAGE, in turn, promotes scalability by sampling and aggregating features from a bounded number of neighbours. When node embeddings are extracted, a graph-level embedding is created through a readout or pooling operation on all nodes' representations. We use pooling techniques, including global mean pooling, global max pooling, and attention-based pooling to obtain a single vector  $g \in \mathbb{R}^d$  to summarize the entire graph as given in Eq. (4).

$$\mathbf{g} = \mathbf{POOL}(\{\mathbf{h}_i | \mathbf{v}_i \in \mathbf{V}\}) \quad (4)$$

This graph-based representation captures the holistic structural/behavioural fingerprints of the malware and is fed into the classification network. The whole model architecture consists of multiple layers of stacked GNNs, which achieve hierarchical representation learning and are capable of capturing the complex and high-order relations among graph nodes. To counter the vanishing of gradients and the degradation of features in deep models, we introduce residual connections across GNN layers, allowing for more effective gradient spreading as well as for the preservation of lower-layer information. The final layer of the GNN is followed by one or more fully connected (dense) layers, which play the role of the classifier. These layers interpret the learned graph-level embeddings and map them to the labels at the output layer, which can be binary (malicious or benign) or multi-class (malware family types). The final result is sent through a softmax or sigmoid activation function based on the classification change.

The model is trained in a supervised manner with the cross-entropy loss that measures the discrepancy between the predicted class probabilities and the ground truth labels, Eq. (5).

$$\mathcal{L} = \sum_{i=1}^N y_i \log(\hat{y}_i) \quad (5)$$

Where  $\mathbf{y}_i$  is the true label and  $\hat{\mathbf{y}}_i$  is the predicted probability for sample  $i$ .

For stable and fast optimization, we use the Adam optimizer, with the adaptive learning rate and momentum-based updates. We also use multiple regularizations to promote generalization and reduce overfitting, such as Dropout layers between dense layers. Weight decay to penalize large weights. Early stopping, monitoring validation loss to halt training when performance plateaus.

Hyperparameters (e.g., learning rate, batch size, the number of GNN layers, the embedding dimension, the dropout rate) are optimized either by grid search or Bayesian optimization to search for the most suitable model setting. This GNN-based design, and the capability it possesses to learn

meaningful representations of graph-structured malware, forms a strong, scalable base for modern threat discovery and malware characterization.

#### 4. Experimental Evaluation

We verify the efficiency and generalization of the proposed GNN-based malware detection method through large-scale experiments on the EMBER dataset. At first, the preprocessing on the dataset was performed, and the dataset was divided into three parts: train, validation, and test. We use a stratified 80/10/10 split that ensures each of the split subsets has a proportional number of the malicious as well as the benign samples. This stratification is important to prevent the class imbalance from affecting the performance metric and to improve the robustness of the model. The feature selection based on the Chi-square test is adopted before model training to keep only the most discriminative features. Using the Chi-square test, only 1000 features were used out of 2,381 features available in the dataset.

**Table 1: Performance Evaluation**

Evaluation Method	Formula	Description
Accuracy	$\frac{TP + TN}{TP + TN + FP + FN}$	Measures the proportion of correctly predicted samples among the total predictions.
Precision	$\frac{TP}{TP + FP}$	Indicates how many predicted positive samples are truly positive.
Recall	$\frac{TP}{TP + FN}$	Measures how many actual positive samples were correctly predicted.
F1-Score	$\frac{2 \cdot Precision \cdot Recall}{Precision + Recall}$	Harmonic Mean of precision and recall, balancing false positives and false negatives.

The GNN model and the baselines were implemented in Python 3.10, using PyTorch, and Geometric and Scikit-learn were used for building the models. All experiments are conducted on a machine with an NVIDIA RTX 3090 GPU (24 GB VRAM), an Intel Core i9 CPU, and 64 GB RAM and operating on Ubuntu 22.04 LTS. The use of GPU acceleration greatly facilitates the training speed of GNN layers, especially when graphs have a large number of nodes. The performance metrics used in the

study are given in Table 1 ensure a comprehensive and standardized evaluation of detection performance.

To validate the performance of our proposed model, we compare it against several state-of-the-art baseline classifiers used in the malware detection literature, such as Support Vector Machine (SVM), which is a discriminative margin-based classifier that is well-suited for high-dimensional data. Random Forest (RF), which is a simple bagging-based classifier that is commonly used in the literature as a performance benchmark for malware detection problems; CNN a deep learning architecture typically applied on transformed feature vectors or image-based representations of malware, RNN which is a powerful class of neural networks that is designed to capture sequential dependencies, and hence performs well in analyzing opcode or system call sequences.

**Table 2: Experimental Results**

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	ROC-AUC (%)
SVM	92.1	90.2	89.8	90.0	93.7
Random Forest	94.5	92.7	92.1	92.4	95.3
CNN	95.8	94.0	93.6	93.8	96.2
RNN	95.3	93.7	93.1	93.4	95.8
<b>Proposed GNN</b>	<b>99.1</b>	<b>98.4</b>	<b>97.9</b>	<b>98.2</b>	<b>99.7</b>

As proven by the results given in Table 2, the proposed GNN model performs better than all baselines in all metrics and attains an accuracy of 99.1%, a precision of 98.4%, and an ROC-AUC of 99.7%, indicating excellent identification accuracy of malicious versus benign samples. This gain is mainly because GNN can capture the hierarchical and relational features by message passing, both of which traditional models and sequence-based deep networks are not able to perform. Also, the higher values of Recall and F1-score of the GNN model demonstrate robustness in detecting more malware samples with a lower number of false negatives, which is important in cyber cybersecurity area where a missed detection can be of extreme consequences.



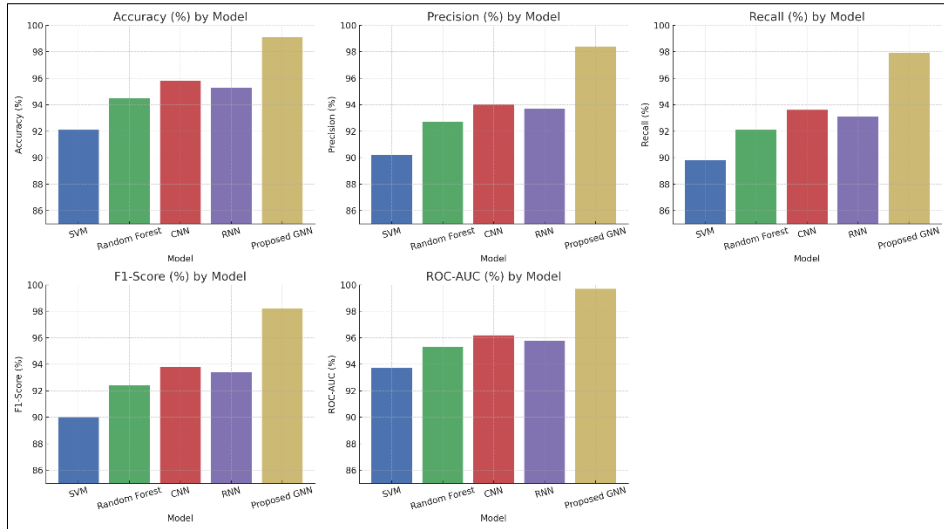


Fig. 2. Comparison of performance evaluation

The experimental results and comparison of various models, as given in Fig. 2, justify that returning to graph-based structural learning by using GNNs is very effective without requiring the prior knowledge of designing new classic machine learning models, as well as traditional deep learning models.

## 5. Model Validation

In order to make sure that the designed GNN-based malware detection model is both effective enough and reliable enough, as well as generally applicable, quantitative validation and qualitative explainability analysis were applied. These attempts offer an analysis of the decision-making process of the model, and confirm that the learned patterns are indeed semantically and functionally meaningful.

We initially use k-fold cross-validation ( $k = 5$ ) to test the robustness and the generalization ability of the model on various subsets of the dataset. This provides a test set of 37 data points and ensures each data point goes through both training and testing. Performance is averaged across folds to reduce overfitting and the chance that an evaluation may be biased towards a specific data split. The standard deviation of accuracy, precision, and F1-score across the different folds is still less than 0.5%, which indicates that the model has a stable performance.

We employ explainability methods tailored for graph-based learning. In particular, we adopt GNNExplainer, the state-of-the-art explainable framework on GNNs that finds the most important subgraph and node features for a given prediction. GNNExplainer works by training a soft mask on the input graph that identifies a few nodes and edges with maximum influence on the model's output.

Given a sample classified as malicious, GNNExplainer finds the most influential paths (e.g., sequences of API calls or control flow transitions) used by the model to reach its conclusion. This helps to check that the model is not overfitting to random correlations. Extract signatures by identifying the behavioural factors of the malware. We further investigate overall trends by combining results over all samples, demonstrating that the GNN invariably attends to behaviour-rich parts (i.e., file system manipulation, network, and registry access sequences), which are identifiable characteristics of maliciousness. Conversely, the benign examples have naturally occurring graphs, with low interaction breadth and easily discernible structural motifs.

This interpretability analysis not only validates the semantic correspondence that exists between the model's attention and known threat patterns but also imparts trust for real-world deployment of GNN-based detection systems. It also provides a window for adding human-in-the-loop feedback mechanisms in which expert analysts can refine or validate the automatic predictions. The simultaneous application of cross-validation and graph explainability methods guarantees that the resulting model is not only accurate but also transparent, reliable, and auditable, all of which are essential to a model that can be deployed in modern cybersecurity environments. These experimental results show the effectiveness of utilizing graph representations to improve the detection, generalization, and evasion resistance.

## **6. Conclusion**

In this work, we propose a novel, robust, and scalable malware detector driven by GNNs, and show substantial performance gain compared to traditional machine learning and deep learning approaches. The proposed GNN-based approach takes advantage of structural information such as control flow graphs, API call dependencies, and system call sequences to discover complex relational patterns that are ignored in flat or sequential input representations. Experiments on the EMBER dataset demonstrate that the performance of the updated model surpasses that of state-of-the-art works, with the testing accuracy and ROC-AUC scores reaching 99.1% and 99.7% respectively, and having an edge over traditional classifiers such as SVM, Random Forest, and deep learning models such as CNN and RNNs by all metrics. Additionally, incorporating the GNNExplainer module improves the model interpretability by introducing key subgraphs and node features, leading to classification results that are important for trust in real-world cybersecurity scenarios. In addition, the generalization and robustness of the proposed model are further verified by 5-fold cross-validation, and its performance variance is stable. These results demonstrate the effectiveness of using structural awareness from GNNs in malware detection, providing an effective line of defense against polymorphic and evasive

threats. This study paves the way for future studies in explainable and adaptive graph-based malware analysis mechanisms, taking a step forward to more intelligent, interpretable, and robust cybersecurity approaches.

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## Thermal Properties of $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ Superconductor and Determination of the Optimal Processing

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### Abstract

This research investigates the thermal properties of  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  high-temperature superconductor using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). The study aims to understand the thermal behavior and optimize processing conditions for enhanced superconducting performance. A 40 mg sample was synthesized using a one-step solid-state reaction method and analyzed in air atmosphere from room temperature to 1200°C at a heating rate of 10°C/min. DSC analysis revealed four distinct exothermic peaks at 824°C, 839°C, 907°C, and 935°C, corresponding to superconducting phase formation, crystallographic transformations, phase decomposition, and structural breakdown, respectively. The optimal thermal processing window was identified as 820-840°C for controlled structural formation. TGA analysis demonstrated excellent thermal stability with total weight loss not exceeding 5% up to 1200°C. Specific heat capacity measurements identified two major thermal transitions: the first at 824°C ( $C_p = 10 \text{ J/g}\cdot^\circ\text{C}$ ) related to secondary phase melting, and the second at 933°C ( $C_p = 12 \text{ J/g}\cdot^\circ\text{C}$ ) corresponding to primary superconducting phase melting. These findings provide valuable insights into the optimal processing conditions for  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ , emphasizing the importance of precise temperature control to maximize phase purity, thermal stability, and superconducting performance.

**Keywords:** Thermal properties; Differential Scanning Calorimetry; Thermogravimetric Analysis; Thermal stability.

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## 1. Introduction

Thallium-based superconductors, particularly the  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  (Tl-2234) compound, are of significant interest due to their high superconducting transition temperatures, reaching up to 120 K. This exceptional performance is largely attributed to their complex crystal structure, which features four  $\text{CuO}_2$  planes that enhance current-carrying capacity and elevate critical temperatures [1, 2]. The Tl-2234 system exhibits notable flexibility in its chemical composition, allowing for partial substitution of thallium with calcium. This substitution has been shown to improve the physical and electrical properties by modifying the charge carrier concentration in the  $\text{CuO}_2$  layers [3]. Compared to other thallium-based superconductors such as Tl-2201 and Tl-2223, Tl-2234 demonstrates superior performance owing to its additional  $\text{CuO}_2$  layers and enhanced structural coherence [4]. Studies have reported that Tl-2234 samples can achieve a superconducting transition temperature onset ( $T_c$  onset) of up to 120 K and zero resistance at 113 K in optimally prepared samples. These properties are significantly influenced by synthesis methods, thallium content, and external magnetic fields [5, 6]. Therefore, understanding the influence of processing conditions is critical for practical application. Thermal conductivity is a key physical property for evaluating the practical usability of superconductors. While direct measurements on Tl-2234 are scarce, analogous studies on Tl-2223 provide important insights. These materials typically exhibit a decrease in thermal conductivity below the superconducting transition due to interactions between electrons and lattice vibrations (phonons). Additionally, factors such as porosity, grain size, and crystallographic defects strongly affect thermal transport [7, 8]. The specific heat capacity analysis offers further understanding of the electronic and structural behavior of superconductors during phase transitions. For example, Tl-2201 exhibits only minor changes ( $\sim 1\%$ ) in specific heat at  $T_c$ , indicating a small shift in free energy during the transition. This trend is comparable to that seen in Bi-2212 and YBCO superconductors [9, 10]. Processing conditions also have a crucial impact on the superconducting properties of Tl-2234. Sintering in an argon atmosphere typically results in a  $T_c$  around 90 K, while post-annealing in oxygen-rich environments can raise  $T_c$  to 115 K [11]. Reducing the oxygen partial pressure not only improves the crystal quality but also lowers the synthesis temperature, as observed in Tl-2223 and other related phases [12, 13]. Variations in thallium content, including calcium substitution, are critical for optimizing superconducting and magnetic properties. Compositional adjustments such as  $\text{Tl}_{1.7}\text{Ba}_2\text{Ca}_{3.3}\text{Cu}_4\text{O}_{12}$  have demonstrated improvements in phase purity and electronic performance [14, 15]. Oxygen content is another essential parameter, as increased oxygenation or prolonged vacuum treatment has been linked to enhanced superconducting behavior and even magnetic transitions above 116 K [3]. In this study, we investigate the thermal behavior of  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  using Differential

Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). The sample, weighing 40 mg, was analyzed in ambient air from room temperature up to 1200 °C at a heating rate of 10 °C/min. These techniques aim to elucidate melting behavior, phase stability, and thermal decomposition-crucial for optimizing synthesis protocols and performance.

## 2. Experimental Methods

The compound  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  was synthesized through a one-step solid-state reaction, starting with carefully selected high-purity precursors: thallium oxide ( $\text{Tl}_2\text{O}_3$ ), barium peroxide ( $\text{BaO}_2$ ), calcium oxide ( $\text{CaO}$ ), and copper oxide ( $\text{CuO}$ ). These materials were thoroughly mixed using an agate mortar, sieved through a 64-micron mesh to ensure homogeneity, and then pressed into a pellet measuring 1.5 cm in diameter and 0.2 cm in thickness. To minimize thallium evaporation during the thermal process, the pellet was wrapped in silver foil and sealed in a quartz tube, which was placed inside a protective stainless steel tube. The sample then underwent a controlled thermal treatment-comprising gradual heating, an isothermal hold, and slow cooling-detailed in the temperature-time

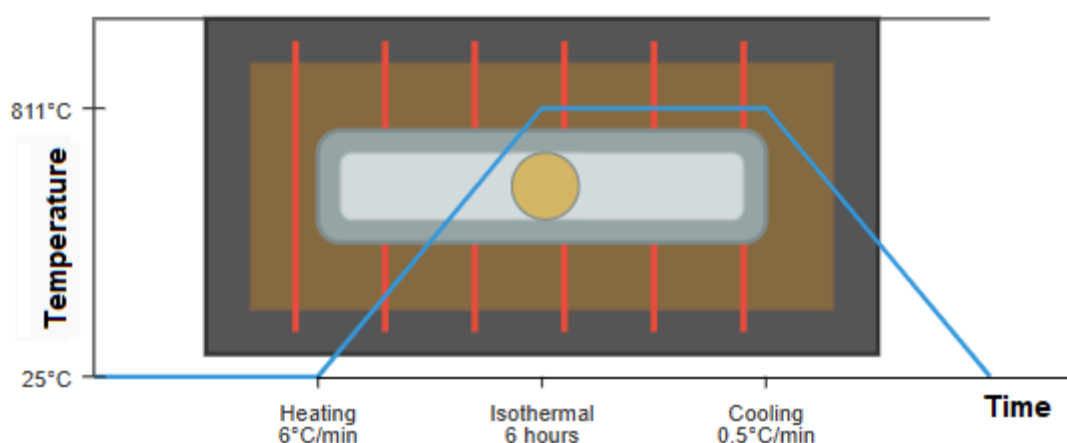


Figure 1. The thermal-time diagram for the preparation of the  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  compound.

diagram, figure1. Finally, to enhance its superconducting properties, the sample was subjected to an additional annealing step in air at 500°C. The figure shows how the temperature changes over time. The process begins at room temperature (25°C) and progresses through three main stages. In the first stage, the sample is gradually heated at a rate of 6°C per minute until it reaches 811°C. This is followed by an isothermal stage, where the temperature is held constant for six hours-an essential period to ensure proper reaction or crystallization of the materials. In the final stage, the sample is slowly cooled at a rate of 0.5°C per minute until it returns to room temperature. This controlled cooling minimizes thermal stresses and prevents the formation of cracks in the material. The figure also illustrates the furnace structure, where the sample is placed at the center of the thermal processing chamber, surrounded by insulating layers to ensure uniform heat distribution. For thermal characterization,

simultaneous differential scanning calorimetry (DSC) and Thermogravimetric analysis (TGA) were carried out on a 40 mg sample of the synthesized material. Measurements were performed in air atmosphere, with a constant heating rate of 10 °C/min, covering a temperature range from room temperature to 1200 °C. This experimental setup facilitated detailed evaluation of the compound's melting behavior, thermal stability, and phase transformation characteristics.

### 3. Results and Discussion

#### 3.1 DSC Analysis of $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ Compound

Differential Scanning Calorimetry (DSC) analysis was conducted on the  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  sample to identify the thermal changes associated with the formation of the superconducting phase. Figure 2 curve shows the heat flow (in  $\mu\text{V}$ ) as a function of temperature, ranging from room temperature up to approximately 1200°C. Four distinct exothermic peaks were observed, indicating significant thermal events within the sample. The first peak, at around 824°C, is attributed to the initial formation of the Tl-2234 superconducting phase, where essential solid-state reactions occur among the starting materials. The second peak, at approximately 839°C, suggests a further crystallographic transformation or structural rearrangement, reflecting continued phase development. The third peak, near 907°C, may indicate the decomposition of unstable phases or internal structural reorganization. The fourth and final peak, around 935°C, is likely associated with structural breakdown or the loss of volatile components such as thallium, indicating that heating beyond this point is undesirable to avoid material degradation. In comparison with the scientific literature, Tl-Ba-Ca-Cu-O compounds typically exhibit phase transitions within the temperature range of 800–1000°C, associated with the formation of superconducting phases such as Tl-1223 or Tl-2223 [16]. The thermal peak observed at 907°C may correspond to the formation of the  $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$  (Tl-2212) superconducting phase, while the higher peak at 935°C is likely related to phase decomposition or the formation of impurities. This comparison underscores the importance of the 820–840°C range as an ideal thermal window for controlling structural formation, emphasizing the need for precise temperature regulation to prevent decomposition and the loss of critical elements at elevated temperatures [17].



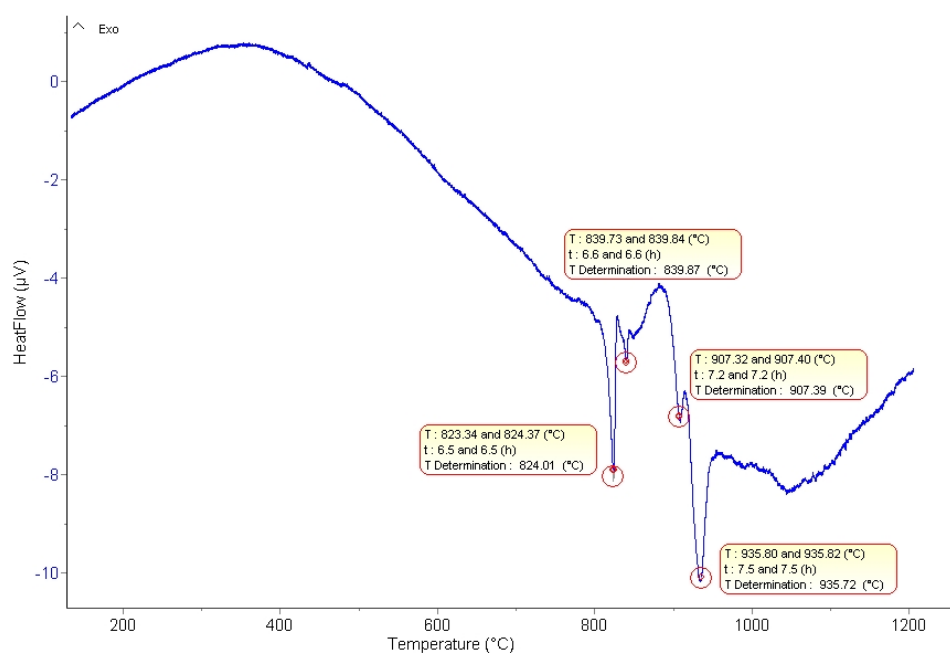


Figure 2 The heat flow as a function of temperature of  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  Compound

### 3.2 Thermogravimetric Analysis (TGA) of $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ Superconductor

The (TGA) graph of the Tl-2234 high-temperature superconductor provides practical evidence of the material's high thermal stability. It shows that the total weight loss during heating from the initial temperature up to  $1200^\circ\text{C}$  does not exceed  $\Delta m=5\%$ , which is consistent with findings in the scientific literature on thallium-based superconductors. Figure 3 depicts the change in the sample's weight (in percentage) as the temperature increases from room temperature to approximately  $T_f=1200^\circ\text{C}$ . The weight starts close to 100% and gradually decreases as the temperature rises, indicating the release of volatile components from the sample, such as adsorbed water or the decomposition of thermally unstable compounds, and possibly the loss of some thallium oxide ( $\text{Tl}_2\text{O}_3$ ) or copper oxide ( $\text{CuO}$ ) at higher temperatures. The rapid initial weight loss at lower temperatures (up to  $200^\circ\text{C}$ ) is attributed to the loss of crystallization water and surface moisture [18]. In the range between approximately  $100^\circ\text{C}$  and  $800^\circ\text{C}$ , the weight loss is gradual, suggesting a slow or continuous loss of volatile substances or gradual decomposition of certain compounds. Beyond  $800^\circ\text{C}$ , the changes in the slope become more pronounced, indicating additional reactions or decompositions occurring in the sample. The decline at higher temperatures (around  $900\text{--}1100^\circ\text{C}$ ) may be associated with the breakdown of the primary compound or further loss of metal oxides. The continued weight loss at elevated temperatures reflects degradation of the crystal structure, emphasizing the importance of controlling the thermal treatment conditions to avoid exceeding  $900^\circ\text{C}$ . The thermal analysis results are in agreement with the scientific

literature, confirming that processing Tl-2234 within the 850-900°C range achieves the best balance between structural preservation, thermal stability, and good electrical performance [19].

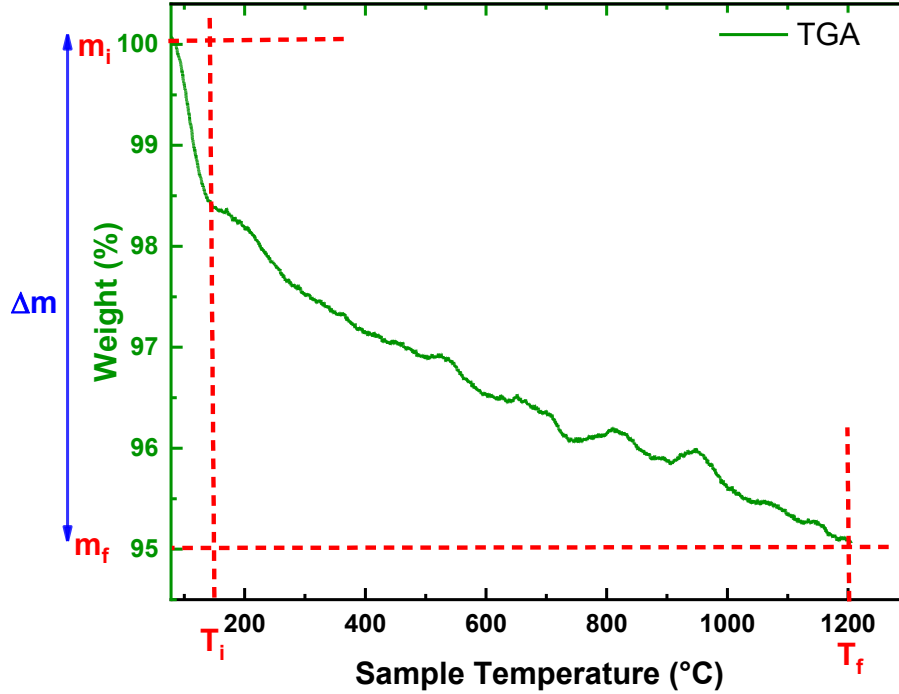


Figure 3 TGA Curves of  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  Compound

### 3.3 Specific Heat Capacity Analysis of $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ Superconductor

The specific heat capacity ( $C_p$ ) of the  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  superconductor was evaluated using Differential Scanning Calorimetry (DSC), a sensitive method for detecting thermal transitions and heat flow changes. In this method, a precisely weighed sample (typically ~40 mg) was subjected to a controlled heating rate of 10 °C/min in air. The heat flow data was recorded across a temperature range extending beyond the superconducting transition ( $T_c$ ), typically from room temperature up to 1200 °C. To determine  $C_p$ , the area under the heat flow curve was integrated over a selected temperature interval ( $\Delta T$ ), and the specific heat was calculated using the equation [20]:

$$C_p = \frac{\text{Heat flow (W)}}{\beta \times m} \quad (1)$$

Where:

$\beta$  = Heating rate

$m$  = sample mass

Figure 4 presents the Differential Scanning Calorimetry (DSC) analysis of the Tl-2234 high-temperature superconductor, illustrating how its specific heat capacity ( $C_p$ ) varies with temperature at a heating rate of  $10^\circ\text{C}/\text{min}$  ( $0.1667^\circ\text{C}/\text{s}$ ). The inset focuses on the temperature range between  $800^\circ\text{C}$  and  $980^\circ\text{C}$ , where the DSC data reveals two distinct thermal transitions, reflecting a complex melting behavior associated with the multiphase nature of the material [21]. The first thermal transition occurs between  $799.94^\circ\text{C}$  and  $827.67^\circ\text{C}$ , with a peak in  $C_p$  around  $824.05^\circ\text{C}$ . This increase in specific heat capacity indicates a significant thermal event, likely related to the melting or decomposition of a secondary phase or crystallographically distinct regions within the Tl-2234 structure. At  $824^\circ\text{C}$ , the specific heat capacity ( $C_p$ ) is approximately  $10 \text{ J/g}\cdot^\circ\text{C}$ , representing a moderate increase that reflects a minor phase transformation or secondary melting. The second, larger and more prominent transition takes place between  $918.59^\circ\text{C}$  and  $954.20^\circ\text{C}$ , with a central  $C_p$  peak at  $933^\circ\text{C}$ . This substantial rise in specific heat capacity corresponds to the primary melting event of the main superconducting phase, where the Tl-2234 superconductor undergoes its main phase transition [22]. At  $933^\circ\text{C}$ ,  $C_p$  reaches about  $12 \text{ J/g}\cdot^\circ\text{C}$ , indicating a larger increase associated with the main phase melting of Tl-2234.

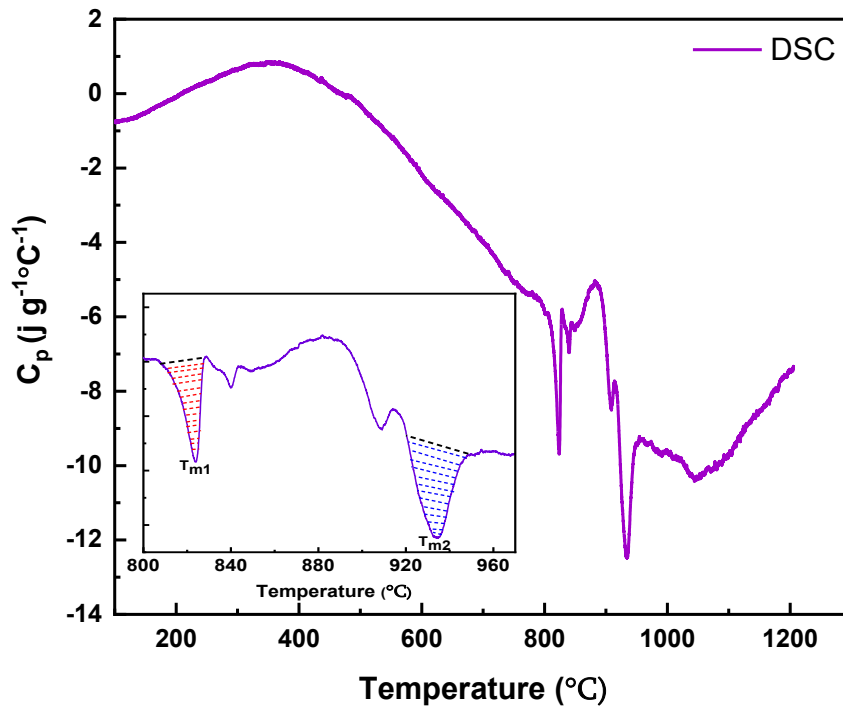


Figure 4. The specific heat capacity vs Temperature for  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  Superconductor

These increases in specific heat capacity ( $C_p$ ) across the temperature range reflect the additional heat absorbed by the material during phase transitions and serve as precise indicators for understanding the complex thermal transformations occurring in these multiphase superconducting materials [23,24].

#### 4. Conclusion

This comprehensive thermal analysis of  $\text{Tl}_2\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$  superconductor using DSC and TGA has successfully established optimal processing parameters for high-performance synthesis. The DSC analysis identified four critical thermal events: superconducting phase formation at  $824^\circ\text{C}$ , crystallographic development at  $839^\circ\text{C}$ , phase instability onset at  $907^\circ\text{C}$ , and structural decomposition at  $935^\circ\text{C}$ . TGA results demonstrate exceptional thermal stability with less than 5% weight loss up to  $1200^\circ\text{C}$ , confirming the material's suitability for high-temperature applications. Specific heat capacity analysis revealed two major thermal transitions at  $824^\circ\text{C}$  ( $C_p = 10 \text{ J/g}\cdot^\circ\text{C}$ ) and  $933^\circ\text{C}$  ( $C_p = 12 \text{ J/g}\cdot^\circ\text{C}$ ), providing precise benchmarks for process control. The optimal processing temperature range is established at  $850\text{--}900^\circ\text{C}$ , ensuring maximum phase purity and superconducting performance ( $T_c$  up to 120 K) while preventing thermal degradation. The thermal processing procedures contribute significantly to the fundamental understanding of thallium-based superconductors and provide practical guidance for achieving optimal superconducting properties. This research establishes DSC and TGA as essential tools for understanding phase relationships in superconducting systems.

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## Review on Latent Thermal Energy Storage for Building Applications

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### Abstract

Increasing the energy efficiency of the building is an alternative to reduce energy consumption while improving thermal comfort in order to confront the climate change and fossil fuel limitations. One of the options is the use of thermal energy storage as a practical way to save energy and improve its utilization. Thermal energy storage, classified into sensible heat storage and latent heat storage, is presented in this paper focusing on phase change materials (PCMs) as a promising solution to reduce energy consumption in buildings. The identification of different PCM classifications (organic, inorganic and eutectic PCMs), their particular characteristics and the candidate materials for building applications are reviewed. This review identifies key gaps in PCM deployment, such as the low thermal conductivity of organic PCMs, the supercooling of inorganic PCMs, and proposes research priorities. Active and passive latent heat storage technologies used in building applications are also summarized. For passive systems, which do not require conventional energy, the common methods of PCMs integration in building materials such as concrete, gypsum board, ceiling or floor are enumerated in this paper.

**Keywords:** Phase Change Materials (PCM), Latent heat, Thermal Energy Storage (TES), Energy efficiency, Building

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## **1. Introduction**

Regarding changes in the climate and fossil fuel limitations, the growing demand of energy all over the world is becoming a serious problem. New and renewable energy sources seem to be the solution. The building sector is one of the largest consumers of energy with a large amount directly related to the heating and cooling of buildings. Increasing the energy efficiency of the building is an alternative to reduce energy consumption while improving thermal comfort. One of the options is the use of thermal energy storage as a practical way to save energy and improve its utilization [1].

Thermal energy storage (TES) in buildings has gained considerable attention. Storage of energy in thermal form can generally be classified into sensible heat storage and latent heat storage. Sensible heat storage occurs when a material is driven to increase or decrease its temperature. The amount of energy stored depends on the specific heat of the material, the temperature change and the mass of the material [2]. The latent heat storage is based on the fact that the storage material absorbs or releases heat when it undergoes a solid / solid, solid / liquid or liquid / gas phase change or vice versa. Latent heat storage is the most efficient method for storing thermal energy due to the low temperature difference between storage and release cycles and the low volume required for storage.

Phase Change Materials (PCMs) use the latent heat of phase change to control temperatures within a specific range. When the temperature exceeds a certain point, the chemical bonds in the material begin to break and the material absorbs heat in an endothermic process where it changes state. When the temperature drops, the material releases energy and returns to its original state.

Based on the temperature range of phase change, PCMs can be classified into three main categories [3, 4]. Low temperature PCMs with a phase transition temperature less than 15 °C are generally used in air conditioning applications and in the food industry. Medium temperature PCMs with phase transition temperature between 15 °C and 90 °C are the most popular PCM Types and they can be applied in solar heating, textile, etc. Finally, high temperature PCMs with a phase transition temperature greater than 90 °C developed primarily for industrial and aerospace applications. On the other hand, PCMs can be classified according to their mode of phase change in gas-liquid, solid-gas, solid-liquid and solid-solid systems [3, 5].

Another common classification of these materials consists of distinguishing PCMs undergoing solid-liquid transformation into organic, inorganic and eutectic PCMs [6]. Organic materials are divided into paraffins and non-paraffins. Paraffin PCMs are available over a wide temperature range for use in a variety of applications. Non-paraffins used as PCMs include fatty acids, esters, alcohols, etc. Fatty acids have received the greatest attention for application in buildings. Inorganic PCMs consist of salts hydrates and hydroxides. Eutectic PCMs are compounds of organic and inorganic PCM.

Latent heat materials have applications in buildings, textiles, automobiles and solar installations, and recently in electronics and medicine [3]. Cabeza et al. [7] focused, in their review article, on Phase Change Materials for thermal storage in buildings. They presented the requirements of the use of PCMs, their classification, the materials available in the literature and on the market and the technical problems encountered with the possible solutions for their application in buildings.

Since the phase change temperature of PCMs is around the desired comfort temperature in buildings, the energy used to change the phase of the material leads to more stable and comfortable indoor conditions, as well as to reduce cooling and heating peaks [8]. As a result, latent heat materials represent a promising solution for reducing energy consumption and improving thermal comfort in buildings. Recently, several researchers [3-4, 6-23] have published review articles on the use of PCMs in the building sector for thermal storage systems and thermal comfort, showing that PCMs interest is increasing worldwide.

The ability to store thermal energy is important for efficient use of solar energy in buildings. Due to the low thermal mass in light buildings, these buildings tend to have large temperature fluctuations which lead to high heating and cooling demands [4]. The use of appropriate PCMs overcomes this problem while improving thermal comfort and optimizing wall thickness [24].

Latent heat storage technology can be classified as an active or passive heating / cooling systems in buildings [20]. For passive systems, which do not require conventional energy, PCMs can be encapsulated in building materials such as concrete [25], gypsum board [26, 27], ceiling or floor [28] in order to increase their thermal storage capacity. Also, PCMs can be integrated into conventional heating and cooling systems (solar heat pump system, ventilation system [29]). The optimization of PCM thermophysical properties and the enhancement of heat transfer through passive and active techniques [1] are thereby, essential to ensure the performance of phase change TES system.

Recently, latent heat storage through PCM has received considerable attention thanks to its ability to store a large amount of thermal energy in a small volume, making it one of the most promising technologies for the development of energy efficiency in buildings [30]. In order to quantify the technical and economic feasibility of these materials for building thermal comfort applications, modeling and numerical simulations of energy storage in the building are necessary. Several studies have addressed the mathematical modeling of PCM for building applications [31-33]. AL-Saadi et al. [33] present and compare the different modeling methods used in PCM simulations (advantages, disadvantages and limitations).

The choice of the PCM is governed by the application, the range of temperature for usage and the cost. A proper use of these materials can reduce heating and cooling peaks and thus reduce energy consumption. This is only possible if the best PCM is chosen according to its cost versus the specific thermal comfort conditions in buildings (temperature and humidity range). Hence, the identification of different PCM classifications, their particular characteristics, their selection criteria and the candidate materials for building applications will be presented in this paper.

## **2. Thermal energy storage**

Thermal energy storage technology stores heat and cold for later use as required, as an alternative to reduce the effects of the intermittency of the various renewable energy sources. This promising technology makes it possible to reduce energy consumption in buildings and increase energy efficiency and thermal comfort [34]. Cooling, heating, melting, solidifying or vaporising a material with the energy made available in the form of heat during the process reversal can achieve thermal energy

storage [3]. There are mainly three methods of storing energy in thermal form: sensible heat storage, latent heat storage and thermochemical storage.

Thermal storage by sensible heat occurs when a material is driven to increase or decrease its temperature. The amount of energy stored ( $Q_s$  in J) depends on the specific heat capacity of the material ( $c_p$  in  $\text{kJ.kg}^{-1}.\text{K}^{-1}$ ), the temperature difference it undergoes ( $\Delta T$  in K) and the amount of material present ( $m$  in kg) :

$$Q_s = mc_p \Delta T \quad (1)$$

The most widely used material for sensible energy storage is water, due to its availability, high specific heat, non-toxicity and low cost. Above 100 °C, oils, molten salts and liquid metals are used [35]. Cement, concrete, marble, granite, clay and polymers are also widely used to store thermal energy in buildings.

On the other hand, latent heat storage is based on the fact that the storage material absorbs or releases heat when it undergoes a phase change from solid/solid, solid/liquid or liquid/gas or vice versa. Latent heat storage is a particularly interesting method because of the small temperature difference between the energy absorption and release cycles and the small volume required for storage. The heat stored in a phase change material ( $Q_l$ ) is calculated as follows [36]:

$$Q_l = \int_{T_i}^{T_m} mc_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mc_p dT \quad (2)$$

Where  $T_i$ ,  $T_m$  and  $T_f$  are, respectively, the initial, melting and final temperatures (°C).  $a_m$  represents the molten fraction,  $m$  is the amount of material present (kg) and  $\Delta h_m$  is the heat of fusion per unit mass (J/kg). Phase-change materials (PCMs) used for latent heat storage are numerous and can be grouped into organic, inorganic and eutectic PCMs [5, 6, 37, 38]. Organic materials are divided into paraffins and non-paraffins. Paraffin-based PCMs are available in a wide temperature range, enabling them to be used in a variety of applications. Non-paraffins used as PCMs include fatty acids, esters, alcohols,.... Fatty acids have received the most attention for building applications. Inorganic PCMs include salts, hydrated salts and metallics.

As for eutectics, these are compounds of organic and inorganic PCMs. They are subdivided into organic-organic, organic-inorganic and inorganic-inorganic PCMs.

### 3. Phase Change Materials (PCMs)

Latent heat storage is particularly attractive because of its ability to provide high storage density in a quasi-isothermal process. Phase-change materials (PCMs) use the latent heat of phase change to control temperatures within a specific range. When the temperature exceeds a certain point, the chemical bonds in the material begin to break and the material absorbs heat in an endothermic process where it changes state. As the temperature drops, the material releases energy and returns to its initial state.

### 3.1 Classification

Based on the phase-change temperature range, PCMs can be classified into three main categories [3, 4]. Low-temperature PCMs, with phase transition temperatures below 15°C, are typically used in air-conditioning applications and in the food industry. Medium-temperature PCMs with change-of-state temperatures between 15°C and 90°C, are the most popular and they can be applied in solar, medical, textile, electronic, building... Finally, high-temperature PCMs with phase change temperature above 90°C developed mainly for industrial and aerospace applications. Abhat [5] presented a state-of-the-art review of latent heat storage materials in the 0-120°C temperature range. He discussed the melting and freezing characteristics of paraffins, fatty acids, inorganic hydrated salts and eutectic compounds and their ability to undergo thermal cycling.

On the other hand, phase-change materials can be classified according to their phase transition mode into solid-liquid PCMs, solid-gas PCMs, gas-liquid PCMs and solid-solid PCMs. Of these groups, solid-liquid PCMs are the most suitable for thermal energy storage [11, 40]. Solid-liquid PCMs include organic, inorganic and eutectic PCMs. A comparison between these different types of PCM is made by several authors [4, 7, 11, 15, 35, 39, 41]. A summary of the main advantages and disadvantages of each type is given in the following table 1.

**Table 1.** Comparison of the advantages and disadvantages of different types of PCM.

Classification	Advantages	Disadvantages
<b>Organic PCM:</b>	+ Available over a wide temperature range	- Low thermal conductivity (approx. 0.2 W/m.K)
<b>Paraffins and non-paraffins</b>	+ High heat of fusion + Negligible overcooling + Chemically and thermally stable + Good compatibility with other materials + Recyclable + No segregation + Non-hazardous, non-reactive and non-corrosive	- Low density - Low enthalpy of phase change - High cost - Relatively high volume expansion - Flammable
<b>Inorganic PCM:</b>	+ High heat of fusion	- subcooling
<b>Hydrated salts</b>	+ High thermal conductivity (approx. 0.5 W/m.K) + Low volume expansion + High melting enthalpy + Low cost availability + Non-flammable	- Corrosion - Segregation and lack of thermal stability - High volume change
<b>Eutectic PCM</b>	+ High melting temperature + High volumetric heat storage density slightly higher than organic compounds	- Lack of data available on their thermo-physical properties

### 3.2 PCMs properties

For the use of PCMs as latent heat storage materials, these materials must fulfill certain desirable thermodynamic, kinetic and chemical criteria as shown in Table 2 [4, 5, 11, 35, 39, 42].

**Table 2.** Different properties of PCM.

PCM Properties	
<b>Thermodynamic</b>	<ul style="list-style-type: none"> <li>- Melting temperature within desired operating temperature range.</li> <li>- High latent heat of fusion per unit volume.</li> <li>- High specific heat to provide significant additional sensible heat storage.</li> <li>- High thermal conductivity of solid and liquid phases.</li> <li>- Small volume change during phase transition and low vapor pressure at operating temperature to reduce containment problems.</li> <li>- Congruent melting</li> </ul>
<b>Kinetic</b>	<ul style="list-style-type: none"> <li>- Low or no supercooling during freezing; the melt should crystallize at its thermodynamic freezing point</li> <li>- High rate of nucleation.</li> <li>- High rate of crystals growth.</li> </ul>
<b>Chemical</b>	<ul style="list-style-type: none"> <li>- Full reversible freeze/melt cycle.</li> <li>- No degradation after a large number of freeze/melt cycles.</li> <li>- No corrosiveness to building/encapsulation materials.</li> <li>- Non-toxic, non-flammable and non-explosive.</li> </ul>
<b>Economic</b>	<ul style="list-style-type: none"> <li>- Abundant.</li> <li>- Available.</li> <li>- Cost-effective.</li> <li>- Easy to recycle and process.</li> </ul>

### 3.3 Long-term stability of PCMs

For practical applications in latent heat storage, PCMs must maintain long-term stability with minimal changes in thermal properties after numerous thermal cycles. Thermal cycling tests on organics, salt hydrates, and salt hydrate mixtures are conducted to evaluate PCMs stability [43-45]. Some PCMs demonstrated good stability and favorable thermo-physical properties. Blackley et al. [44] introduces a phase change material composed of calcium chloride hexahydrate (CCH), sodium carbonate decahydrate (SCH) as a nucleating agent, and surface-modified expanded graphite (EG) treated with a nonionic surfactant. The PCM composite found to mitigate challenges associated with salt hydrate PCMs while ensuring robust cycling stability for large-scale applications. It exhibits a high thermal conductivity, significantly minimizes supercooling and eliminates phase separation with enhanced

cycling stability for up to 200 thermal cycles. Lui et al. [45] focused on, improving thermal conductivity, supercooling, and phase separation of carbon-enhanced hydrated salt PCMs. They compare the performance of salt hydrates to organic PCMs like paraffin wax and they note that organic PCMs have a lower thermal conductivity (almost 0.2 W/mK) while a better cycling stability. The article highlights applications in solar thermal energy storage and building temperature regulation.

#### **4. Application of PCMs in buildings**

Phase-change materials find their applications in buildings, the textile industry, automotive and solar installations, and recently in electronics and medicine [3]. In recent years, several researchers [7, 8, 15, 16, 18, 20, 22, 23] have published review articles on phase-change materials for thermal storage in buildings and thermal comfort, showing that interest in PCMs is growing worldwide.

The use of latent heat storage in buildings can meet the demand for thermal comfort and energy savings. PCMs can be integrated into building cladding materials such as concrete, gypsum board, plaster, etc., to increase the thermal mass of light or even heavy buildings. They can also be installed in the water or air circuits of heating, ventilation and air-conditioning systems as thermal storage reservoirs. Latent storage through PCMs can be used for heating and cooling in buildings as either a passive storage system (i.e., the phase-change process takes place without the use of mechanical equipment) or an active one (using mechanical equipment).

##### **4.1 Passive storage systems in buildings**

Due to low thermal inertia, lightweight buildings suffer from sharp temperature fluctuations in summer, due to excessive overheating caused by a lack of thermal mass [19]. For passive applications and efficient use of solar energy in buildings, PCMs are integrated into the building envelope to increase its thermal mass. The building envelope is composed of the outer shell of the building that separates the interior space from the external environment. Thus, walls, foundations, fenestration, roofs, floors, ..., are part of the building envelope [46]. Phase change material can be incorporated into all elements of the building envelope. Nevertheless, the most common integration of PCM into the envelope is in walls, floors, ceilings, roofs and windows thanks to easy installation and more efficient heat transfer [47]. Hawes et al. [48] found that the melting and solidification temperatures of PCMs vary slightly when integrated into building materials. Dardouri et al. [49] illustrate that the double-layer PCM system provided higher energy savings than the single-layer PCM system, especially in warm and arid regions. Alrashdan et al. [50] demonstrate a significant reduction in cooling load with PCM incorporation, with cement-based composites exhibiting superior thermal performance compared to gypsum-based alternatives.

During the day, the latent storage material undergoes a melting process, absorbing some of the solar energy flowing through the building structure. At night, when the outside or inside temperature drops, the PCM solidifies, releasing the stored heat into the surrounding environment. As a result, these materials help prevent the room from overheating during the day in hot summer periods, and can also provide heat to the room, reducing the need for heating at night in winter.

Having selected the appropriate storage material based on the temperature range of the application and its thermo-physical properties, it is necessary to choose the method of incorporating PCM into the building materials or components to avoid leakage. Three ways of incorporating PCM into conventional building materials have been reported by Hawes et al. [48] as the most promising: direct incorporation, immersion and encapsulation.

#### **4.1.1 Direct incorporation**

The direct incorporation method is the simplest. It involves mixing liquid or powder PCMs directly with building materials (gypsum, concrete or plaster) during production [41]. This method is also the most economical, as it requires no additional equipment, but it does face problems of leakage and incompatibility with certain construction materials [15].

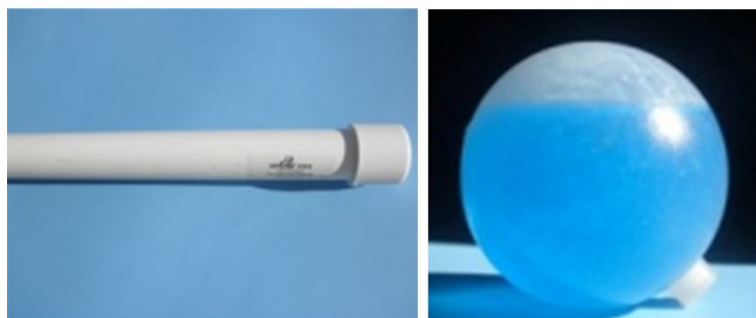
#### **4.1.2 Immersion**

In the immersion method, porous building materials such as, for example, gypsum board, brick or concrete block, are immersed in molten PCM which is absorbed through the pores, by capillary action. Similarly, problems of leakage and incompatibility with certain building materials are encountered [51].

#### **4.1.3 Encapsulation**

The third method overcomes the adverse effects of PCM on the building material and avoids the problem of leakage. It relies on the fact that PCMs can be encapsulated before incorporation into the building components. Two main types of encapsulation exist: macro-encapsulation and micro-encapsulation [9].

- Macro-encapsulation involves packaging the PCM in a container such as tubes, spheres or panels, then incorporating it into the construction elements (Figure 1). This technology has the disadvantage of poor thermal conductivity, a tendency to solidify at the edges and complex integration with building materials [11].

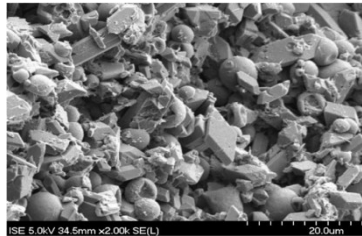


**Figure 1.** Examples of macro-encapsulation of commercial PCMs [19].

- Microencapsulation is a technique in which PCM particles are enclosed in a thin, continuous polymer film (Figure 2) that must be compatible with both the storage material and the materials of construction. This makes it possible to produce capsules in the micrometer to millimeter range (Figure 3), known as microcapsules [52, 53].



**Figure 2.** Model of a micro-encapsulated PCM with a wax core and polymer capsule [19].



**Figure 3.** Image of PCM microcapsules in gypsum plaster with a diameter of around 8 mm [41].

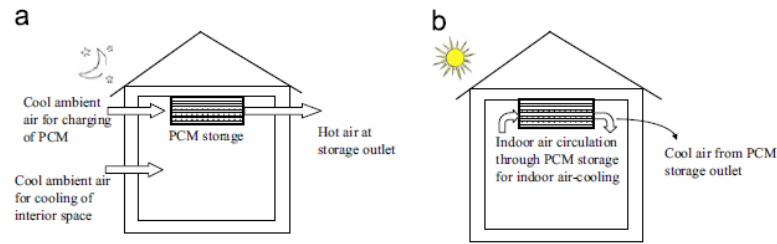
Microencapsulation has the advantage of preventing PCMs from leaking during the phase-change process and contributing to the improvement of heat transfer processes by increasing the heat exchange surface area [54].

#### 4.2 Active storage systems in buildings

Active storage systems are mainly used for storing thermal energy during off-peak hours in buildings. In this way, peak-hour loads can be reduced and shifted to the night when electricity costs are generally lower [54]. In the building sector, PCMs can be integrated into various systems such as solar heat pumps, heat recovery systems, underfloor heating systems, photovoltaic devices, etc., as active applications.

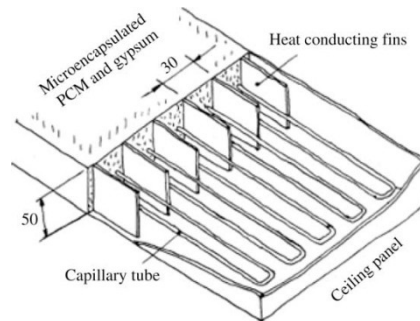
Free cooling" is one of the main applications of thermal storage in active systems in buildings, where cold is collected and stored from outside during the night, and this stored cold is discharged inside the room (Figure 4) when there is a cooling demand for it [16].





**Figure 4.** Free cooling" operating principle: (a) Charging process (during the night) and (b) Discharging process (during the day).

A thermally activated ceiling panel with PCM storage (Figure 5) is used for heating and cooling in buildings. When exposed to thermal loads, the PCM in the ceiling panels melts during the day and solidifies at night by means of an integrated water pipe system [10].



**Figure 5.** Schematic of ceiling panel thermally activated with MCP [55].

Latent heat storage is used in solar systems in buildings to convert an intermittent energy source and meet heating and domestic hot water demand [56]. In addition, thermal storage of solar energy in active systems in buildings is being extended to integrate solar air collectors in building walls [57] and use PCMs in ventilated facades.



**Figure 6.** Distribution of PCMs on ventilated facades [58].

The active use of PCMs in the building sector is not limited to the implementation of renewable sources, but also enables the efficiency and performance of already existing technologies to be

increased. Kaygusuz and Ayhan [59] studied the performance of a solar heat pump system combined with encapsulated phase-change material for residential heating.

## 5. Examples of potential PCMs

Several researchers have investigated various candidate substances for use in latent heat thermal storage [3, 7, 35, 40, 54]. As phase-change materials, these substances must have specific properties such as a melting temperature within the practical range of application, high latent heat, high thermal conductivity, competitive price, non-toxic and non-corrosive character. The thermal properties of three main families of PCMs (organic, inorganic and eutectic), reported in the literature, are summarized in the following tables (Table 2-6).

Paraffins are suitable for use as heat-of-fusion storage materials since they are available in a wide temperature range and possess a relatively high heat of fusion. Additionally, Paraffins are known to freeze without supercooling [5]. However, due to cost constraints, only technical-grade paraffins are typically used as phase change materials in latent heat storage systems.

Fatty acids are organic compounds that exhibit heat of fusion values similar to that of paraffins. They are characterized by consistent melting and freezing behavior and freeze with low or no supercooling, making them effective PCMs. However, their primary disadvantage is their cost, which is approximately 2 to 2.5 times higher than that of paraffins.

Salt hydrates, constitute a significant class of heat storage materials due to their high volumetric latent heat storage capacity. However, a key challenge in using salt hydrates as PCM is their tendency to melt incongruently; resulting in a saturated aqueous solution and a solid phase, typically a lower hydrate of the same salt.

### 5.1 Organic PCMs

Paraffins and fatty acids, which represent the most commonly used organic PCMs, are listed in the tables below (Table 3, 4 and 5), together with their melting point and latent heat of fusion [3, 35].

**Table 3.** Thermal properties of paraffins.

Paraffin	Number of Carbon atoms	Melting temperature (°C)	Latent Heat (kJ/kg)
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n-tetra-decane	14	5.8–6	227–229
n-penta-decane	15	9.9–10	206
n-hexa-decane	16	18–20	216–236
n-hepta-decane	17	22–22.6	164–214
n-Octa-decane	18	28–28.4	200–244
n-Nona-decane	19	32	222
n-Eicozane	20	36.6	247
n-Heneicozane	21	40.2	213
n-Docozone	22	44.0	249
n-Trikozane	23	47.5	234
n-Tetracozane	24	50.6	255
n-Pentacozane	25	53.5	238
n-Hexacozane	26	56.3	256
n-Heptacozane	27	65.4	235
n-Oktacozane	28	58.8	254
n-Nonacozane	29	63.4	239
n-Triacontane	30	41.2	252

**Table 4.** Thermal properties of fatty acids.

Fatty acid	Number of carbon atoms	Melting temperature (°C)	Latent heat (kJ/kg)
Caprylic acid	8	16.3	148
CA	10	31.3-31.6	163
LA	12	41-44	183-212
MA	14	51,5-53,6	190-204.5
PA	16	61-63	203.4-212
SA	18	70	222
Arachidic acid	20	74	227
Undecylenic acid	22	24.6	141

**Table 5.** Thermal properties of non-paraffin PCMs.

Non-paraffin	Melting temperature (°C)	Latent heat (kJ/kg)
Formic acid	7.8	247
Glycerine	17.9	198.7
D-Lactic acid	26	184
Methyl palmitate	29	205
Camphenilone	39	205
Docosyl bromide	40	201
Caprylone	40	259
Phenol	41	120

## 5.2 inorganic PCMs

Pielichowska and Pielichowski [3] have presented various inorganic components considered as potential PCMs and intended for low- and high-temperature applications. However, Tyagi and Buddhi [54] listed inorganic PCMs frequently used for applications in the 20-32°C temperature range.

The melting point and latent heat of fusion of hydrated salts are shown in Table 6.

**Table 6.** Thermal properties of hydrated salts [35].

Hydrated salt	Melting temperature (°C)	Latent Heat of fusion (kJ/kg)
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K <sub>2</sub> HPO <sub>4</sub> -6H <sub>2</sub> O	14	109
FeBr <sub>3</sub> -6H <sub>2</sub> O	21	105
FeBr <sub>3</sub> -6H <sub>2</sub> O	27	105
LiClO <sub>3</sub> -3H <sub>2</sub> O	8	253
KF-4H <sub>2</sub> O	18.5–19	231
Mn(NO <sub>3</sub> ) <sub>2</sub> -6H <sub>2</sub> O	25.3	125.9
CaCl <sub>2</sub> -6H <sub>2</sub> O	28–30	190–200
LiNO <sub>3</sub> -3H <sub>2</sub> O	30	256
Na <sub>2</sub> SO <sub>4</sub> -10H <sub>2</sub> O	34	256
Na <sub>2</sub> CO <sub>3</sub> -10H <sub>2</sub> O	33	247
NaCH <sub>3</sub> COO-3H <sub>2</sub> O	55.6–56.5	237–243
CaBr <sub>2</sub> -6H <sub>2</sub> O	34	115.5
Na <sub>2</sub> HPO <sub>4</sub> -12H <sub>2</sub> O	35–45	279.6
Zn(NO <sub>3</sub> ) <sub>2</sub> -6H <sub>2</sub> O	36	146.9
Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> -5H <sub>2</sub> O	48–55	201
Na(CH <sub>3</sub> COO)-3H <sub>2</sub> O	58	226
Na <sub>2</sub> P <sub>2</sub> O <sub>7</sub> -10H <sub>2</sub> O	70	184
Ba(OH) <sub>2</sub> -8H <sub>2</sub> O	78	266
(NH <sub>4</sub> )Al(SO <sub>4</sub> ) <sub>2</sub> -12H <sub>2</sub> O	95	269
MgCl <sub>2</sub> -6H <sub>2</sub> O	117	169
Mg(NO <sub>3</sub> ) <sub>2</sub> -6H <sub>2</sub> O	89.3	150

### 5.3 Eutectic PCMs

The table below (Table 7) lists the best-known eutectic PCMs.

**Table 7.** Thermal properties of eutectic PCMs [35].

Eutectic	Composition (%)	Melting temperature (°C)	Heat of fusion (kJ/kg)
CaCl <sub>2</sub> -6H <sub>2</sub> O + CaBr <sub>2</sub> -6H <sub>2</sub> O	45 + 55	14.7	140
C <sub>14</sub> H <sub>28</sub> O <sub>2</sub> + C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	34 + 66	24	147.7
CaCl <sub>2</sub> + MgCl <sub>2</sub> -6H <sub>2</sub> O	50 + 50	25	95
CH <sub>3</sub> CONH <sub>2</sub> + NH <sub>2</sub> CONH <sub>2</sub>	50 + 50	27	163
Ca(NO <sub>3</sub> ) <sub>2</sub> -4H <sub>2</sub> O + Mg(NO <sub>3</sub> ) <sub>3</sub> -6H <sub>2</sub> O	47 + 53	30	136
CH <sub>3</sub> COONa-3H <sub>2</sub> O + NH <sub>2</sub> CONH <sub>2</sub>	40 + 60	30	200.5
NH <sub>2</sub> CONH <sub>2</sub> + NH <sub>4</sub> NO <sub>3</sub>	53 + 47	46	95
Mg(NO <sub>3</sub> ) <sub>3</sub> -6H <sub>2</sub> O + NH <sub>4</sub> NO <sub>3</sub>	61.5 + 38.5	52	125.5
Mg(NO <sub>3</sub> ) <sub>3</sub> -6H <sub>2</sub> O + MgCl <sub>2</sub> -6H <sub>2</sub> O	58.7 + 41.3	59	132.2
Mg(NO <sub>3</sub> ) <sub>3</sub> -6H <sub>2</sub> O + MgCl <sub>2</sub> -6H <sub>2</sub> O	50 + 50	59.1	144
Mg(NO <sub>3</sub> ) <sub>3</sub> -6H <sub>2</sub> O + Al(NO <sub>3</sub> ) <sub>2</sub> -9H <sub>2</sub> O	53 + 47	61	148
CH <sub>3</sub> CONH <sub>2</sub> + C <sub>17</sub> H <sub>35</sub> COOH	50 + 50	65	218
Mg(NO <sub>3</sub> ) <sub>2</sub> -6H <sub>2</sub> O + MgBr <sub>2</sub> -6H <sub>2</sub> O	59 + 41	66	168
NH <sub>2</sub> CONH <sub>2</sub> + NH <sub>4</sub> Br	66.6 + 33.4	76	151
LiNO <sub>3</sub> + NH <sub>4</sub> NO <sub>3</sub> + NaNO <sub>3</sub>	25 + 65 + 10	80.5	113
LiNO <sub>3</sub> + NH <sub>4</sub> NO <sub>3</sub> + NH <sub>4</sub> Cl	27 + 68 + 5	81.6	108

### 5.4 PCMs used in buildings

Three phase-change temperature ranges have been suggested by Cabeza et al. [7] for the use of PCMs for thermal storage in buildings (up to 21 °C for cooling applications, between 22 and 28 °C for thermal comfort applications and between 29 and 60 °C for hot water applications). Kalnæs et al. [19] included in their study examples of PCMs with phase change temperatures ranging from 15 to 32 °C. In this study, we focus on thermal energy storage as an application to thermal comfort in buildings.

The energy used to ensure the phase transition of the material leads to more stable and comfortable indoor conditions, as well as reducing cooling and heating peaks [8]. In order to keep indoor temperatures within the desired comfort temperature range for as long as possible and without heating

or cooling loads, candidate materials need to have a fairly high heat of fusion and a melting temperature within the thermal comfort temperature range. In order to select the appropriate PCM for application to thermal comfort in buildings, a scan of some potential PCMs studied in the literature is presented in Table 8.

**Table 8.** Thermal properties of PCMs used for thermal comfort in buildings [7].

PCM	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)
Paraffin C <sub>16</sub> -C <sub>18</sub>	Organic	20-22	152	-
Paraffin C <sub>13</sub> -C <sub>24</sub>	Organic	22-24	189	0.21
Paraffin C <sub>18</sub>	Organic	28	244	0.15
Butyl stearate	Organic	19	140	-
1-dodecanol	Organic	26	200	-
n-octadecane	Organic	28	200	-
Vinyl stearate	Organic	27-29	122	-
Dimethyl sabacate	Organic	21	120-135	-
Polyglycol E600	Organic	22	127.2	0.189
Propyl palmitate	Organic	16-19	186	-
Octadecyl 3- mercaptopropylate	Organic	21	143	-
34% C <sub>14</sub> H <sub>28</sub> O <sub>2</sub> + 66% C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	Organic Eutectic	24	147.7	-
Octadecane + docosane	Organic Eutectic	25.5-27	203.8	-
FeBr <sub>3</sub> 6H <sub>2</sub> O	Inorganic	21	105	-
Mn(NO <sub>3</sub> ) 6H <sub>2</sub> O	Inorganic	25.8	125.9	-
CaCl <sub>2</sub> 6H <sub>2</sub> O	Inorganic	29.2	171 [39]	-
50% CaCl <sub>2</sub> + 50% MgCl <sub>2</sub> 6H <sub>2</sub> O	Inorganic Eutectic	25	95	-
48% CaCl <sub>2</sub> + 43% NaCl + 0.4% KCl + 47.3% H <sub>2</sub> O	Inorganic Eutectic	26.8	188	-

Many components have been investigated as potential PCMs, but a limited number have been commercialized [7]. Kalnæs et al. [19] introduced an overview of commercial PCM products for application in buildings and their thermal properties, as well as their industrial manufacturers. Konuklu et al. [18] listed companies that offer commercial PCMs in a wide range of phase change temperature, such as ‘BASF’ and ‘Rubitherm GmbH’ in Germany, ‘Cristopia’ in France, ‘TEAPEnergy’ in Australia, ‘PCM Products’ in the UK, ‘Climator’ in Sweden and ‘Mitsubishi Chemical’ in Japan. However, they pointed out that only BASF and ‘Microteklab’ have developed micro-encapsulated PCMs designed for application to thermal comfort in buildings. Examples of commercial PCMs available on the international market and used in buildings are given in the following table 9 [7, 54].

**Table 9.** Thermal properties of commercial PCMs used for thermal comfort in buildings.

PCM name	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Manufacturer
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RT 20	Paraffin	22	172	0.88	Rubitherm GmBH
Climsel C23	Hydrated salt	23	148	-	Climator
ClimselC24	Hydrated salt	24	108	1.48	Climator
RT 26	Paraffin	26	179	-	Rubitherm GmBH
RT 25	Paraffin	25	180	0.2	Rubitherm GmBH
STL 27	Hydrated salt	27	213	1.09	Mitsubishi chemical
S27	Hydrated salt	27	190	0.79	Cristopia
RT 30	Paraffin	28	206	0.2	Rubitherm GmBH
RT 27	Paraffin	28	179	0.87	Rubitherm GmBH
TH 29	Hydrated salt	29	188	-	TEAP
RT31	Paraffin	31	165	0.2	Rubitherm GmBH



Figure 7. Examples of BASF products: (a) Micronal PCM dispersed in a liquid and in powder form (b) Gypsum wallboard with Micronal PCM.

## 6. Conclusion

The ability to store thermal energy is important for the efficient use of solar energy in buildings. Due to the low thermal mass of materials in lightweight buildings, they tend to have large temperature fluctuations, resulting in high heating and cooling demands. Currently, thermal energy storage has become an important aspect of energy management.

- A review of different types of thermal energy storage is carried out focusing on the latent heat storage through phase change materials (PCMs).
- Phase change materials (PCMs) must have a melting/solidification temperature within the practical range of the application and they must have a high latent heat of fusion and high thermal conductivity.
- An overview of the classification and properties (thermo-physical, kinetic, chemical and economic) of potential PCMs and their application in buildings as passive and active storage systems is presented in this study.
- Examples of latent thermal energy storage materials are listed, specifying their temperature and heat of fusion according to their type and practical application.

## Declaration statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## AI-Based Optimization of Submerged Arc Welding Using AISA Algorithm

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### Abstract

The precision of parameter selection in submerged arc welding (SAW) significantly influences weld quality, strength, and efficiency in industrial manufacturing. Artificial intelligence offers advanced tools for addressing the complex, non-linear optimization challenges in welding processes where traditional trial-and-error methods fall short. This paper introduces the Adolescent Identity Search Algorithm (AISA), an AI-based, human-inspired optimization technique, to optimize SAW parameters. Implemented in MATLAB, the algorithm was applied to minimize bead width (BW)—a critical indicator of weld quality—by refining welding current, voltage, speed, and wire feed. Comparative analysis with the Rao-1 algorithm was conducted under varying population sizes and iteration counts. Results show that AISA consistently achieved a minimum bead width of 17.06 mm with a success rate exceeding 99%, outperforming Rao-1, which recorded a minimum of 17.23 mm under the same conditions. These findings demonstrate AISA's robustness, stability, and adaptability in parameter optimization, confirming its potential as an effective tool for enhancing manufacturing precision.

**Keywords:** Artificial Intelligence; Optimization; Welding process; AISA algorithm; Submerged arc welding.

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## **1. Introduction**

In manufacturing, welding quality plays a pivotal role in determining the durability, strength, and overall reliability of components and structures. With the growing demand for precision and quality in welded products across industries—from automotive to aerospace—optimizing welding parameters has become crucial. Key parameters, such as current, voltage, welding speed, and gas flow rate, directly influence the quality of welds and, consequently, the performance of welded structures [1]. However, identifying the optimal combination of these parameters is challenging due to the complexity and interdependence of welding variables [2]. Consequently, this optimization task resembles a complex decision-making process, where multiple factors must be balanced to achieve a desired outcome.

Artificial Intelligence (AI) has emerged as a valuable tool for solving such optimization challenges. Among AI methodologies, metaheuristic optimization techniques stand out as effective approaches for navigating large solution spaces and identifying optimal parameters in complex systems [3], [4], [5]. These algorithms simulate natural decision-making processes observed in biological systems, allowing them to address complex, non-linear optimization problems by iteratively refining potential solutions.

In the context of welding, metaheuristic optimization plays a dual role: not only does it optimize specific process parameters to improve weld quality, but it also aids in decision-making by systematically evaluating trade-offs between conflicting objectives, such as minimizing weld defects while maximizing strength and efficiency [6]. For instance, adjusting the welding speed to increase productivity might affect the penetration and quality of the weld, requiring a decision-making approach that considers both performance and quality metrics. Metaheuristic algorithms are particularly effective here as they employ exploration and exploitation strategies to balance these objectives, identifying solutions that might not be obvious through traditional trial-and-error methods. Rao algorithms [2], [7] whale optimization algorithm [5], Heat Transfer Search Algorithm [8], grey wolf optimization [9], and different physics-based optimization techniques [6] are recent examples of optimization methods implementation to identify the best welding process input parameters.

These studies have highlighted the efficacy of metaheuristic algorithms in welding by demonstrating their ability to enhance weld strength and reduce defects through optimized input variables. However, the “No-free lunch theory” [10] confirms that no single algorithm can universally outperform others across all optimization issues. This insight opens new opportunities for researchers to develop or explore alternative algorithms for various challenges. Moreover, the exploration of human-based algorithms for parameter identification in welding processes remains limited.

This paper aims to address these gaps by evaluating the application of a recent human-based algorithm for parameter optimization in submerged arc welding (SAW). This approach, known as the Adolescent Identity Search Algorithm (AISA) [11], draws on the idea that adolescent identity development in a peer group can be categorized into three various behaviours: identifying favourable group characteristics, emulating peers with desirable traits, and learning from observed undesirable traits within the group.

## 2. Methods

### 2.1 The selected welding process and objective function

In this work, we explore a recent human-based optimization algorithm, the AISA algorithm [11], to determine the optimal input parameters for the Submerged Arc Welding (SAW) process. During SAW, an arc is formed between a consumable electrode and the work piece, with the arc concealed beneath a layer of granular flux [2]. This unique flux layer not only protects against atmospheric contamination but also boosts heat transfer efficiency and enables weld metal alloying. SAW is extensively applied in industries such as nuclear, aerospace, automotive, and marine due to its reliability, high deposition rates, high productivity, and deep weld penetration. The optimization problem in this case study is based on empirical models for the bead width (BW) outlined in [12] and given by Eq.

(1) as follows:

$$\begin{aligned} \text{minimize } BW = & 475.425 - 0.9814I - 15.0015V + 2.4805S - 0.351F \\ & + 0.001179I^2 + 0.25575V^2 - 0.109781S^2 + 0.000773F^2 \end{aligned} \quad (1)$$

where  $I$  is the welding current (A) and  $V$  represents the voltage (V). The wire feed (cm/min) and the welding speed (cm/min) are noted by  $F$  and  $S$ , respectively. In this case, studying the regression model given in the previous equation is considered the objective function. Thus, the process parameters that must be identified are  $I$ ,  $V$ ,  $F$ , and  $S$ .

Although Eq. (1) optimizes only BW, the AISA framework can be easily adapted for multi-objective optimization. This can be achieved by (i) defining a weighted composite objective function that aggregates several quality metrics such as penetration depth and Heat-Affected Zone (HAZ) width, or (ii) implementing a Pareto-based strategy where AISA identifies a set of non-dominated solutions representing optimal trade-offs among multiple objectives. This extension will be considered in future work to broaden the applicability of the approach.

The empirical model for BW adopted in this study, originally presented by Rao and Rai [12], was selected due to its strong experimental validation and frequent use in welding optimization literature.

This regression equation reliably captures the nonlinear relationships between welding parameters (current, voltage, speed, and wire feed) and bead geometry, making it an appropriate and credible objective function for evaluating and optimizing welding quality in the present work.

## 2.2 The proposed Adolescent Identity Search Algorithm (AISA)

This study implements the Adolescent Identity Search Algorithm (AISA) [11], a recently developed human-based optimization technique, to solve the parameter estimation problem in Submerged Arc Welding (SAW). Bogar and Beyhan [11] formulated AISA based on identity formation processes observed in adolescent peer groups, modeling it as an optimization framework. The algorithm comprises three fundamental identity formation behaviors:

**Feature Selection (Case 1):** This mechanism identifies optimal traits within the peer group through orthogonal mapping via Chebyshev polynomials, ensuring diverse feature selection across the solution space. For the  $j$ th adolescent, the position vector update is expressed as:

$$x_{new}^j = x^j - r_1(x^j - x^*) \quad (2)$$

where  $x^*$  represents the optimal trait vector in the population and  $r_1 \in [0, 1]$  is a stochastic coefficient.

**Role Model Imitation (Case 2):** This behavior facilitates convergence toward high-performing solutions by emulating attributes of exemplary individuals within the population, formulated as:

$$x_{new}^j = x^j - r_2(x^p - x^{rm}) \quad (3)$$

where  $x^p$  denotes the  $p$ th adolescent ( $p \neq rm$ ),  $x^{rm}$  represents the role model vector, and  $r_2 \in [0, 1]$  is a random parameter.

**Undesirable Trait Adoption (Case 3):** This mechanism introduces stochastic perturbations to avoid local optima by incorporating variation through:

$$x_{new}^j = x^j - r_3(x^j - x^q) \quad (4)$$

where  $x^q$  denotes a randomly selected undesirable trait vector and  $r_3 \in [0, 1]$  is a stochastic coefficient.

The position update follows a probabilistic selection mechanism among these three cases:

$$x_{new}^j = \begin{cases} \text{Case 1: } x^j - r_1(x^j - x^*), & \text{if } r_4 \leq \frac{1}{3} \\ \text{Case 2: } x^j - r_2(x^p - x^{rm}), & \text{if } \frac{1}{3} < r_4 \leq \frac{2}{3} \\ \text{Case 3: } x^j - r_3(x^j - x^q), & \text{if } r_4 > \frac{2}{3} \end{cases} \quad (5)$$

where  $r_4 \in [0, 1]$  is a random variable determining case selection. For comprehensive details on AISA methodology, readers are directed to references [11] and [13].

In this study, the stochastic coefficients  $r_1, r_2, r_3$  were uniformly sampled from the interval  $[0,1]$ , a common choice in metaheuristic optimization to maintain unbiased exploration of the search space. While this approach yielded stable performance, no alternative distributions were tested. The AISA algorithm terminates when either the maximum number of iterations (MaxIt) is reached.

Lastly, Figure 1 illustrates the workflow of AISA, consisting of initialization, probabilistic selection among three identity formation mechanisms (feature selection, role model imitation, and undesirable trait adoption), and iterative updates until stopping conditions are met. This structure allows AISA to balance exploration and exploitation effectively.

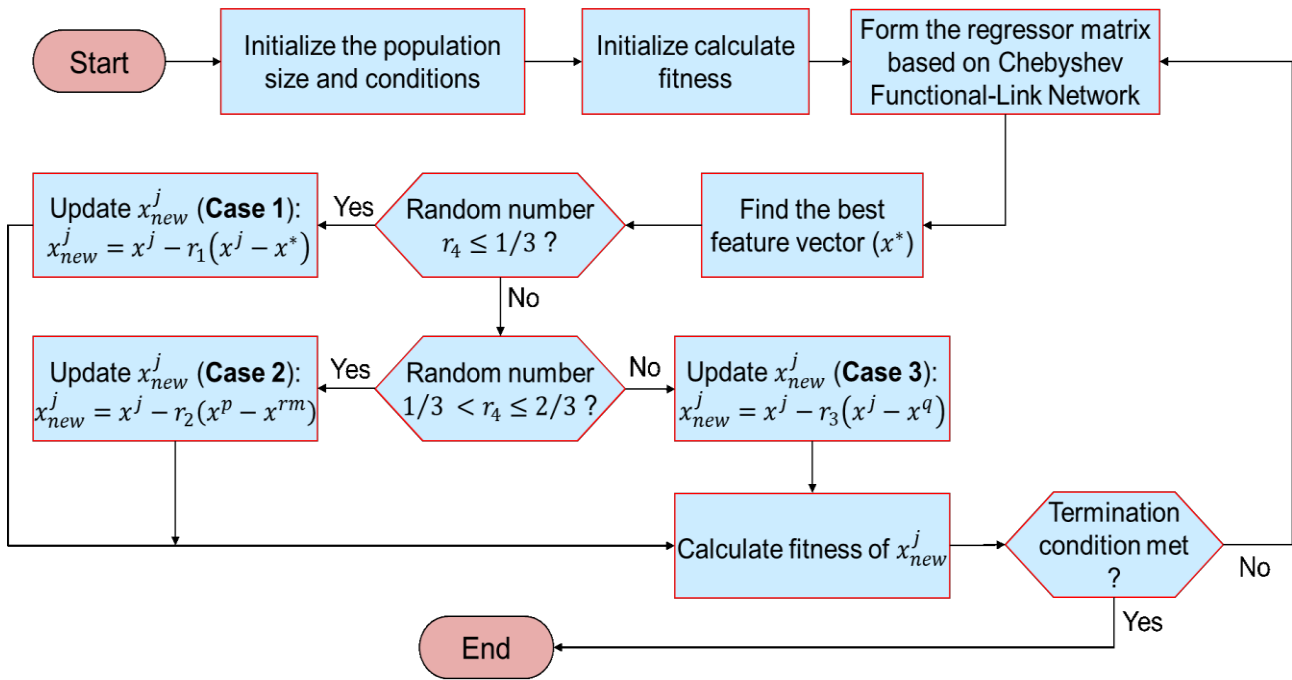


Figure 1. Flowchart of AISA method [14].

### 3. Simulation results

This section describes the implementation of the proposed AISA algorithm in MATLAB to optimize SAW welding process parameters, aiming to minimize bead width as defined in Eq. 1. For comparison, we also implemented the recently studied Rao method, which has been shown to effectively determine welding process parameters [2]. We compare these methods by evaluating the impact of population size (PopSize) and iteration count (MaxIt), exploring two distinct scenarios. The AISA was implemented in MATLAB R2021a on a workstation equipped with an Intel i7 processor and 32 GB RAM.

### 3.1 First case study

In this case study, we assess the effect of varying the iteration count, initially set at 30, then increased to  $\text{MaxIt} = 50$ , while keeping the population size constant at  $\text{Pop-Size} = 30$ . To ensure reliable comparisons, each method is independently run 15 times. “Avg” denotes the average success rate (%) across all runs. The results for minimizing DW, including the best parameters, statistical values, and convergence curves, are presented in Table 1 and Table 2, as well as in Figure 2.

The simulation results in Table 1 show that AISA achieves the lowest DW value (17.08 mm) and outperforms the method used in [2]. Furthermore, the statistical results confirm this outcome with a lower standard deviation (Std) value, indicating greater stability. Figure 2(a) shows the convergence graphs, where it is evident that AISA consistently converges better than the Rao-1 method. With the number of iterations increased to 50, both methods improve in minimizing the DW value. Although both methods achieve better results (Table 2), AISA consistently produces the best DW value and greater stability compared to the Rao-1 technique. The two convergence curves are illustrated in Figure 2(b), where it is clear that Rao-1 becomes trapped in a local optimum before converging to the best value.

Table 1. Comparison of results across 15 runs with fixed population size and 30 iterations.

Algo	$I$ (A)	$V$ (V)	$S$ (cm/min)	$F$ (cm/min)	<i>best (Min)</i>	<i>worst (Max)</i>	<i>Mean</i>	<i>Std</i>	<i>Avg</i> (%)
Rao-1	424.688	30.178	20.000	204.568	17.722	22.300	19.448	1.2930e+00	91.496
AISA	415.045	29.281	19.998	232.254	17.088	17.478	17.224	1.0355e-01	99.211

Table 2. Comparison of results across 15 runs with fixed population size and 50 iterations.

Algo	$I$ (A)	$V$ (V)	$S$ (cm/min)	$F$ (cm/min)	<i>best (Min)</i>	<i>worst (Max)</i>	<i>Mean</i>	<i>Std</i>	<i>Avg</i> (%)
Rao-1	406.720	29.478	20.000	218.364	17.232	20.961	19.337	1.0590e+00	89.371
AISA	414.982	29.317	19.999	226.972	17.065	17.146	17.107	2.2067e-02	99.752

### 3.2 Second case study

In this case, we investigate the effect of varying the population size on the optimization performance. The number of iterations is fixed at  $\text{MaxIt} = 100$ , while the population size ( $\text{PopSize}$ ) is initially set to 30 and then increased to 50. Each algorithm is executed independently over 30 runs to ensure the

consistency of results and to provide a robust comparison of performance under different population sizes. “Avg” denotes the average success rate (%) across all runs.

In the second case study, the results for minimizing DW with varying population sizes (PopSize) are summarized in Table 3 and Table 4, with convergence trends shown in Figure 3. As observed in Table 3, the AISA algorithm achieves the lowest DW value at 17.062 mm, demonstrating superior optimization performance over the Rao-1 method. The statistical analysis further supports AISA's advantage, as it presents a lower standard deviation (Std), indicating enhanced stability and consistency in reaching optimal solutions. Figure 3(a) shows the convergence patterns, where AISA's convergence is more consistent and faster compared to Rao-1, particularly as the population size increases. When PopSize is raised from 30 to 50, both methods show improved DW minimization (Table 4); however, AISA continues to outperform Rao-1 in both accuracy and robustness. In Figure 3(b), the convergence curve of Rao-1 reveals instances of premature convergence, while AISA demonstrates a more effective search, reaching lower DW values without becoming trapped in local optima.

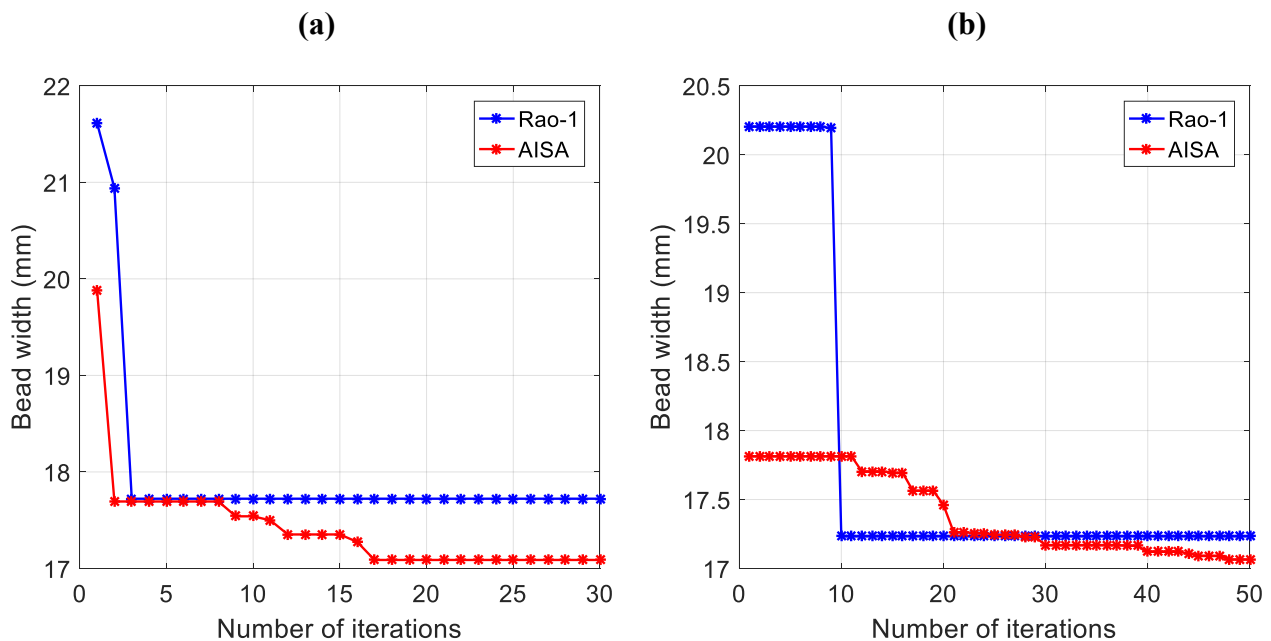


Figure 2. Convergence of BW values across: **a)** 30 iterations and **b)** 50 iterations.

Table 3. Comparison of results across 30 runs with fixed iterations and 30 population size.

Algo	<i>I</i>	<i>V</i>	<i>S</i>	<i>F</i>	<i>best (Min)</i>	<i>worst (Max)</i>	<i>Mean</i>	<i>Std</i>	<i>Avg</i>
	(A)	(V)	(cm/min)	(cm/min)					(%)
Rao-1	410.141	28.856	20.000	243.996	17.385	20.769	19082	8.2211e-01	91.268
AISA	416.204	29.332	19.999	227.060	17.062	17.096	17066	6.0073e-03	99.978



Table 4. Comparison of results across 30 runs with fixed iterations and 50 population size.

Algo	$I$ (A)	$V$ (V)	$S$ (cm/min)	$F$ (cm/min)	$best (Min)$	$worst (Max)$	$Mean$	$Std$	$Avg$ (%)
Rao-1	402.472	29.193	20.000	231.756	17.306	20.370	18.764	8.5351e-01	92.413
AISA	415.930	29.346	19.999	226.750	17.063	17.078	17.066	2.8177e-03	99.982

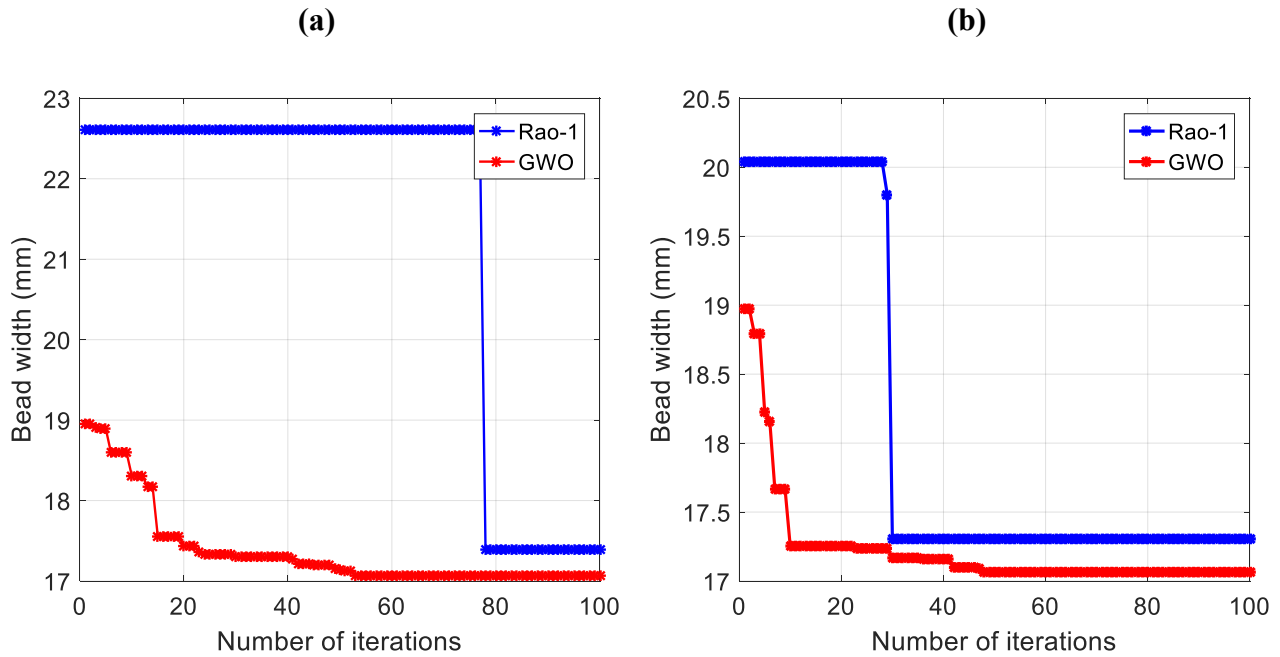


Figure 3. Convergence of BW values across: **a)** 30 population size and **b)** 50 population size.

### 3.3 Discussion

The numerical results demonstrate that AISA consistently outperforms Rao-1 across all scenarios. For instance, in the first case study with 30 iterations, AISA achieved a minimum bead width of 17.088 mm, compared to 17.722 mm for Rao-1, representing an improvement of approximately 3.6%. Under 50 iterations, AISA further reduced the bead width to 17.065 mm, a 4.0% improvement over Rao-1's 17.232 mm. Additionally, the average success rate of AISA exceeded 99%, compared to 91–92% for Rao-1, confirming a performance gain of nearly 8% in solution reliability.

The convergence behavior shown in Figure 2 highlights that Rao-1 becomes trapped in a local optimum, whereas AISA continues progressing toward better solutions. This results contributes significantly to the algorithm's robustness against local entrapment.

AISA outperforms Rao-1 due to its adaptive balance between exploration and exploitation. The integration of three identity-based behaviors—feature selection, role model imitation, and undesirable trait adoption—allows AISA to both exploit promising regions and introduce diversity to escape local optima. In contrast, Rao-1 relies on deterministic updates with limited diversity mechanisms, making it more prone to premature convergence in complex search spaces.

While this work compares AISA only with the Rao-1 algorithm, we acknowledge that other metaheuristics, such as the Whale Optimization Algorithm [5] and Grey Wolf Optimization [9], have also demonstrated strong performance in welding parameter optimization. Future studies will incorporate these algorithms with and other human-inspired algorithms (e.g., Cultural Algorithms, Social Group Optimization) as additional benchmarks to further validate AISA's effectiveness across a broader range of optimization techniques.

### **3. Conclusion**

This study demonstrates the effectiveness of the AISA in optimizing critical parameters within the SAW process. By minimizing bead width, AISA proved to be a robust and adaptable AI-driven solution, effectively navigating the complex relationships among welding parameters. Comparative analysis with the Rao-1 algorithm confirms that AISA delivers superior accuracy in parameter optimization, especially under varying population sizes and iteration settings. This work highlights the growing significance of artificial intelligence in enhancing manufacturing precision and efficiency, laying the groundwork for future research to explore AI-driven optimization across broader industrial applications. Key findings of this study include:

- AISA consistently achieved a minimum bead width of 17.06 mm, outperforming Rao-1 (17.23 mm) under similar conditions.
- The algorithm demonstrated high stability, with an average success rate exceeding 99%, representing an 11–12% improvement over Rao-1.
- The tri-behavioral structure of AISA effectively balanced exploration and exploitation, avoiding local optima and ensuring robust convergence.
- The algorithm showed scalability, performing effectively under various population sizes and iteration counts.
- Future work may include experimental validation, multi-objective, comparison with other recent algorithms, and integration with IoT-based real-time monitoring systems for adaptive welding control.

## Nomenclature and Abbreviations

Symbol / Abbreviation	Description
<b>AI</b>	Artificial Intelligence
<b>AISA</b>	Adolescent Identity Search Algorithm (human-inspired metaheuristic)
<b>Avg</b>	Average Success Rate (%) – a measure of algorithm stability across runs
<b>BW</b>	Bead Width ( <i>mm</i> ) – primary welding quality metric minimized
<b>CA</b>	Cultural Algorithm
<b>DW</b>	Bead Width (alternative notation in tables)
<b>SAW</b>	Submerged Arc Welding
<b>SGO</b>	Social Group Optimization
<b>WOA</b>	Whale Optimization Algorithm
<b>MaxIt</b>	Maximum Iterations – total number of algorithm iterations
<b>PopSize</b>	Population Size – number of candidate solutions per iteration
<b>Std</b>	Standard Deviation – variation in optimization results
<b>GWO</b>	Grey Wolf Optimization
<b>HAZ</b>	Heat-Affected Zone
<b><i>F</i></b>	Wire Feed Rate ( <i>cm/min</i> ) – filler wire feeding rate
<b><i>I</i></b>	Welding Current ( <i>A</i> ) – process parameter affecting heat input
<b><i>n</i></b>	Degree of Chebyshev polynomial used in orthogonal mapping
<b><i>S</i></b>	Welding Speed ( <i>cm/min</i> ) – travel speed of the torch
<b><math>r_1, r_2, r_3</math></b>	Stochastic coefficients used in AISA update equations, uniformly sampled $\in [0,1]$
<b><math>r_4</math></b>	Random selector determining which behavioral case is applied in AISA
<b><math>T_k</math></b>	Chebyshev polynomial of degree $k$ , used in orthogonal mapping
<b><i>V</i></b>	Arc Voltage ( <i>V</i> ) – parameter affecting arc stability and bead shape
<b><math>x_j</math></b>	Position vector of the $j^{th}$ individual in the population
<b><math>x^*</math></b>	Optimal trait vector representing the best solution
<b><math>x_{rm}</math></b>	Role model vector selected for imitation in Case 2
<b><math>x_q</math></b>	Undesirable trait vector chosen from low-performing individuals in Case 3

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## On eJU-Algebras: An Extension of JU-Algebras

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### Abstract

This article introduces a class of algebraic structures, called eJU-algebras, as a natural extension of JU-algebras using structural hypotheses. The extension arises by replacing classical notion of a constant unit element in JU-algebras with a framework based on non-empty subsets, leading to a broader and more flexible algebraic model. We investigate fundamental properties of eJU-algebras and establish their theoretical foundation by deriving them from traditional JU-algebras. This extension not only enhances the structural richness of JU-algebras but also opens new directions for the development of algebraic systems beyond conventional constraints.

**Keywords:** eJU-algebras; Minimals; eJU-subalgebras; eJU-ideals.

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## 1. Introduction

Theory of logical algebras were introduced by mathematician George Boole [1] in 1847 as a formal framework for reasoning and computation. The authors described completeness theorem and many more concepts and theorems on logical algebras. Imai and Iseki [2] in 1966 established some classes of logical algebras; one of them was BCK-algebras. After some time Iseki [3] introduced a different category of logical algebra referred to as BCI-algebras. Iseki has also given their properties as well. Hu and Li [4] in 1983, initiate a class of logical algebras which is BCH-algebras. Komori [5] introduced the idea of BCC-algebras, whereas Dudek [6] in 1992 re-defined the concept of the BCC-algebras, by applying dual form to common definition. Jun et al. [7] in 1998 presented the idea of BH-algebras; this is the generalization of BCK/BCH/BCI-algebra. For further overview about logical algebra one can see [8, 9, 10, 11]. Commutative groups of BCI algebras in specific instances such as Boolean algebras, NM-algebras, residuated lattices, BL-algebras, MTL-algebras, MV-algebras, BE-algebras, Hilbert-algebras and weak-R0 algebras are extensively studied. The researchers focused on the formulation of models of algebras for multiple-valued logics that are not commutative, such algebras are called extended algebraic structures. It inspired us to construct the extended new BCK-algebras called sBCK/sBCI/ eBCK/eBCI-algebras that take into consideration. In this particular case, specifically, a new algebraic structure called sBCK/sBCI/ eBCK/eBCI-algebras are obtained from given BCI/BCK-algebras [12].

JU-algebra is the natural generalization of KU-algebra introduced by Prabpayak and Leerawat [13]. Many authors have conducted extensive research on KU-algebras in a variety of applications including neutrosophic, fuzzy and intuitionistic, rough and soft sense, etc. The notion of JU-algebra was introduced by Ansari, et al. [14]. JU-algebra may rather be thought of as a pseudo KU-algebra. They analyzed the related characteristics of ideals of JU-algebras and p-closure of subsets as well as the p-closure of subset J that is not empty within the JU-algebra X. Romano [15] also discovered various new facts on JU-algebras. Additionally some concepts of JU-algebras, JU-subalgebras, and JU-ideals are also defined in [16]. A few recent studies based on JU algebras structures are presented in [17] and [18].

As generalizations of the concepts of KU/UP-algebras, new concepts of eKU/sKU /eUP/sUP-algebras are proposed. These new extensions of algebras are then investigated for several related features, and it is demonstrated that the axioms of these new extensions are independent [19].

In this work, we originate the notion of an eJU-algebra, extending the framework of JU-algebras. Our focus involves the study of a subset  $A \neq \varnothing$ , within the eJU-algebras X, exploring the associated properties of subsets of eJU-algebras. Furthermore, we seek into the analysis of eJU-subalgebras, eJU-ideals and Minimals.

In this work, we introduce the concept of eJU-algebras as a meaningful extension of the classical JU-algebra framework. The core of our investigation centers on a non-empty subset  $A \neq \emptyset$ , within an eJU-algebra  $X$  through which we explore a range of structural and algebraic properties intrinsic to such subsets. Building on this foundation, we further examine the internal structure of eJU-algebras by analyzing key components, including eJU-subalgebras, eJU-ideals, and minimal elements. This study not only broadens the theoretical scope of JU-algebras but also provides a deeper understanding of their generalized forms and associated algebraic behavior.

## 2. Preliminaries

This section includes fundamental definitions of our related topics that help us to understand our main results and to prove the relevant results.

**Definition 2.1.** A JU-algebra is defined as an algebra  $(X, \cdot, 1)$  with a binary operation  $\cdot$  satisfying the following:

$$(JU_1) (\gamma \cdot z) \cdot [(z \cdot \kappa) \cdot (\gamma \cdot \kappa)] = 1, \quad \forall \kappa, \gamma, z \in X,$$

$$(JU_2) 1 \cdot \kappa = \kappa, \text{ for } \kappa \in X,$$

$$(JU_3) \kappa \cdot \gamma = \gamma \cdot \kappa = 1 \Rightarrow \kappa = \gamma, \quad \forall \kappa, \gamma \in X.$$

**Definition 2.2.** A KU-algebra  $(X, \cdot, 1)$  with  $\cdot$  as single binary operation which satisfies the conditions  $\forall \kappa, \gamma, z \in X$ .

$$(KU1) (\kappa \cdot \gamma) \cdot [(\gamma \cdot z) \cdot (\kappa \cdot z)] = 1,$$

$$(KU2) \kappa \cdot 1 = 1,$$

$$(KU3) 1 \cdot \kappa = \kappa,$$

$$(KU4) \kappa \cdot \gamma = 1 = \gamma \cdot \kappa \text{ implies } \kappa = \gamma.$$

It is evident from the above definitions that JU-algebras are a specialized class of logical algebraic structures that provides a generalization of foundational framework of KU algebras. We will provide an extension of JU algebras. Extension of algebras means to extend the concept of algebras by giving different hypothesis and generalization to algebras by taking non-empty subsets instead of constants 1.

## 3. Main Results

We will precisely articulate the concept of eJU-algebras illuminating their algebraic properties and providing relevant examples.

**Definition 3.1.** An algebra  $(X, \cdot, A)$  is called an eJU-algebra, here  $X$  is non-empty set,  $\cdot$  is single binary operation on  $X$ , and its non-empty subset satisfying the following properties:

- (eJU<sub>1</sub>)  $(\gamma.z).[(z.\kappa).(\gamma.\kappa)] \in A, \forall \kappa, \gamma, z \in X$ ,
- (eJU<sub>2</sub>)  $A.\kappa = \{\kappa\}, \forall \kappa \in X$ , i.e.  $a.x = x, \forall a \in A$ ,
- (eJU<sub>3</sub>)  $\kappa.\gamma \in A, \gamma.\kappa \in A$  implies  $\kappa = \gamma, \forall \kappa, \gamma \in X \setminus A$ .

**Definition 3.2.** Consider an eJU-algebra  $(X, \cdot, A)$  given in above definition. We define a relation " $\leq$ " in  $X$  given as  $\gamma \leq \kappa$  iff  $\kappa.\gamma \in A$ , for  $\kappa \in X \setminus A$ .

**Remark 3.1.** Note that, whenever  $\kappa \leq a$  for any  $a \in A$ , it implies  $a.\kappa = \kappa \in A$  (by Definition 3.2 and eJU<sub>2</sub>).

Throughout this article  $X$  will represent as eJU-algebra and  $A$  will represent as the subset of  $X$  with the binary operation  $\cdot$  and special element 1 until specified.

**Remark 3.2.** An eJU-algebra  $X$  and its non-empty subset  $A$  implies:

Let  $\kappa \in A$ . Implies  $A.\kappa = \{\kappa\}, \forall \kappa \in A$  and  $A.\kappa \subseteq A$ .

Also,  $\bigcup_{\kappa \in A} A.\kappa = A$  and hence  $A.A = A$ .

Now we will introduce some new lemmas related to our definitions and provide corresponding proofs.

**Lemma 3.1.** A set  $(X, \leq)$  is a POSET if  $X$  is an eJU-algebra i.e,

- (eJ<sub>4</sub>)  $\kappa \leq \kappa$ ,
- (eJ<sub>5</sub>)  $\kappa \leq \gamma, \gamma \leq \kappa$  implies  $\kappa = \gamma$ ,
- (eJ<sub>6</sub>)  $\kappa \leq z, z \leq \gamma$  implies  $\kappa \leq \gamma$ .

*Proof.* Taking  $\gamma \in A$  and  $z \in A$  in eJU<sub>1</sub>, we can see that,

$(A.A).[(A.\kappa).(A.\kappa)] \subseteq A \Rightarrow A.(\kappa.\kappa) \subseteq A \Rightarrow \kappa.\kappa \in A$ , by using eJU<sub>2</sub>.

It gets,  $\kappa \leq \kappa$  and the condition eJ<sub>4</sub> is proved.

As its given:  $\kappa \leq \gamma$  and  $\gamma \leq \kappa$  which implies  $\gamma.\kappa \in A$  and  $\kappa.\gamma \in A$  respectively.

Now using eJU<sub>3</sub>:  $\kappa \leq \gamma$  and  $\gamma \leq \kappa \Rightarrow \kappa = \gamma$  and hence eJ<sub>5</sub> is proved.



As we know:  $\kappa \leq z$  implies  $z.\kappa \in A$  and  $z \leq \gamma$  implies  $\gamma.z \in A$ , showing that  $\gamma.\kappa \in A$ .

From  $(eJU_1)$ ;  $(z.\kappa).(\gamma.\kappa) \leq \gamma.z$  because  $z.\kappa \in A$ , using  $eJU_2$ , implies  $(\gamma.z).(\gamma.\kappa) \in A$ .

Similarly,  $\gamma.\kappa \in A$  because  $\gamma.z \in A$ .

This implies  $\kappa \leq \gamma$ , yields  $eJ_6$  is proved. □

**Lemma 3.2.** An  $eJU$ -algebra  $X$  satisfies following inequalities  $\forall \kappa, \gamma, z \in X$ :

$(eJ_7) \kappa \leq \gamma \Rightarrow \gamma.z \leq \kappa.z$ ,

$(eJ_8) \kappa \leq \gamma \Rightarrow z.\kappa \leq z.\gamma$ ,

$(eJ_9) (z.\kappa).(\gamma.\kappa) \leq \gamma.z$ ,

$(eJ_{10}) (\gamma.\kappa).\kappa \leq \gamma$ .

*Proof.* Putting  $\kappa = z$  and  $z = \kappa$  in  $eJU_1$   $(\gamma.\kappa).[(\kappa.z).(\gamma.z)] \in A$ .

Since  $\kappa \leq \gamma$  implies  $\gamma.\kappa \in A$ .

By using  $eJU_2$ :  $(\gamma.\kappa).[(\kappa.z).(\gamma.z)] = (\kappa.z).(\gamma.z) \in A \Rightarrow \gamma.z \leq \kappa.z$  means  $eJ_7$  is proved.

As we know that;  $\kappa \leq \gamma \Rightarrow \gamma.\kappa \in A$ .

Putting  $\gamma = z$  and  $z = \gamma$  in  $eJU_1$ .  $(z.\gamma).[(\gamma.\kappa).(z.\kappa)] \in A$ . Since  $\gamma.\kappa \in A$ , So using  $eJU_2$ :

$(\gamma.\kappa).(z.\kappa) = (z.\kappa) \Rightarrow (z.\gamma).(z.\kappa) \in A \Rightarrow z.\kappa \leq z.\gamma$ ,  $eJ_8$  is proved.

From  $eJU_1$ , it implies that  $[(z.\kappa).(\gamma.\kappa)] \leq (\gamma.z)$ ,  $eJ_9$  is proved.

Putting  $z = \gamma$  and  $\gamma \in A$  in  $eJU_1$ :  $(\gamma.\gamma)[(\gamma.\kappa).(\gamma.\kappa)] \in A$ . Using  $eJU_2$ :  $\gamma.\gamma = \gamma$  and  $\gamma.\kappa = \kappa$  implies that:  $\gamma.[(\gamma.\kappa).\kappa] \in A \Rightarrow (\gamma.\kappa).\kappa \leq \gamma \Rightarrow eJ_{10}$  is proved. □

**Lemma 3.3.** An  $eJU$ -algebra  $X$  satisfying, for any  $\kappa, \gamma, z \in X$ .

$(eJ_{11}) \kappa.\kappa \in A$ ,

$(eJ_{12}) [(z.\kappa).\kappa] \leq z$ ,

$(eJ_{13}) z.(\gamma.\kappa) = \gamma.(z.\kappa)$ ,

$(eJ_{14}) X$  is  $KU$ -algebra, if  $(\kappa.\gamma).\gamma = 1$ ,

$(eJ_{15}) \kappa.\alpha_1 = \kappa.\alpha_2$  for all  $\alpha_1, \alpha_2 \in A$ ,

$(eJ_{16}) (\gamma.\kappa).A = (\gamma.A).(\kappa.A)$ .

*Proof.* The proof of  $eJ_{11}$  is similar to the proof of  $eJ_4$ .

For  $eJ_{12}$ , take  $\gamma = a \in A$  in  $eJU_1$ , we get,  $(a.z).[(z.\kappa).(a.\kappa)] \in A$ .

By using  $eJU_2$ ,  $z.[(z.\kappa).\kappa] \in A$ . Implies,

$$[(z.\kappa).\kappa] \leq z. \tag{1}$$

As ( $eJ_7$ ) is:  $\kappa \leq \gamma$  implies  $\gamma.z \leq \kappa.z$ .

Let  $z = \gamma.\kappa$  and using  $eJ_7$  and (1):

$$(z.(\gamma.\kappa)) \leq ((z.\kappa).\kappa).(\gamma.\kappa). \quad (2)$$

Replacing  $z$  with  $(z.\kappa)$  in  $eJU_1$ :  $(\gamma.(z.\kappa)).[((z.\kappa).\kappa).(\gamma.\kappa)] \in A$ .

$$[((z.\kappa).\kappa).(\gamma.\kappa)] \leq (\gamma.(z.\kappa)). \quad (3)$$

As ( $eJ_6$ ) is:  $\kappa \leq z, z \leq \gamma$  imply  $\kappa \leq \gamma$ .

From (2) , (3) and by using  $eJ_6$ :

$$z.(\gamma.\kappa) \leq \gamma.(z.\kappa). \quad (4)$$

Replacing  $\gamma$  and  $z$  with  $z$  and  $\gamma$  respectively,

$$\gamma.(z.\kappa) \leq z.(\gamma.\kappa). \quad (5)$$

As ( $eJ_5$ ) is:  $\kappa \leq \gamma, \gamma \leq \kappa$  imply  $\kappa = \gamma$ .

From (4) , (5) and by using  $eJ_5$ :  $z.(\gamma.\kappa) = \gamma.(z.\kappa) \Rightarrow eJ_{13}$  is proved.

Since every JU is an eJU with  $A = \{1\}$ .

To prove  $eJ_{13}$  we only have to show:  $\kappa.1 = 1, \forall \kappa \in X$ .

Let  $z = \kappa, \gamma = 1$  and  $\kappa = \gamma$  in  $eJU_1$ , it gives  $(1.\kappa).[(\kappa.\gamma).(1.\gamma)] = 1$ .

$$\kappa.[(\kappa.\gamma).\gamma] = 1. \quad (6)$$

We have given that  $(\kappa.\gamma).\gamma = 1$ , putting in 6:  $\kappa.1 = 1$ ,  $eJ_{14}$  is proved.

For any two elements  $\alpha_1, \alpha_2 \in A$ . The elements  $\alpha_1.\alpha_2$  and  $\alpha_2.\alpha_1 \in A$ . By ( $eJU_1$ ) and ( $eJU_2$ );  $(\kappa.\alpha_1).(\kappa.\alpha_2) = (\kappa.\alpha_1).[(\alpha_1.\alpha_2).(\kappa.\alpha_2)] \in A$ .

Similarly,  $(\kappa.\alpha_2).(\kappa.\alpha_1) = (\kappa.\alpha_2).[(\alpha_2.\alpha_1).(\kappa.\alpha_1)] \in A$ .

Now by  $eJ_5$ ;  $\kappa.\alpha_1 = \kappa.\alpha_2 \Rightarrow eJ_{15}$  is proved.

Taking any element  $a \in A$ .

$(\gamma.a).(\kappa.a) = (\gamma.a).[\kappa.((\gamma.\kappa).(\gamma.\kappa))]$  (by  $eJ_{11}$  and  $eJ_{15}$ )

$= (\gamma.a).[(\gamma.\kappa).(\kappa.(\gamma.\kappa))]$  (by  $eJ_{13}$ )

$= (\gamma.\kappa).[(\gamma.a).(\kappa.(\gamma.\kappa))]$

$= (\gamma.\kappa).[(\gamma.a).(\gamma.(\kappa.\kappa))]$

$= (\gamma.\kappa).[(\gamma.a).(\gamma.a)]$

$= (\gamma.\kappa).a$  (L.H.S),  $eJ_{16}$  is proved. □

**Theorem 3.1.** *If  $(X, \cdot, 1)$  is a JU-algebra, then  $(X, \cdot, \{1\})$  is an eJU-algebra but converse is not true.*

**Remark 3.3.** *Therefore eJU strictly generalizes JU; Example 3.2 shows the containment is proper.*

**Example 3.1.** *Consider  $X = \{1, 2, 3\}$  is a set where  $\cdot$  is described in the following table:*

*We take  $\gamma = 1, \kappa = 2, z = 3$ .*

$(JU_1) (\gamma.z).[(z.\kappa).(\gamma.\kappa)] = 1.$

*By putting values, we have  $= (1.3).[(3.2).(1.2)] = 3.(1.2) = 3.2 = 1.$*

*Hence  $(JU_1)$  is satisfied.*

$\cdot$	1	2	3
1	1	2	3
2	1	1	2
3	1	1	1

*Checking for  $(JU_2)$ :*

$(JU_2): 1.\kappa = \kappa$

*For set  $X$  we can see that:  $1.1 = 1; 1.2 = 2; 1.3 = 3.$*

*Hence  $(JU_2)$  is satisfied.*

*Lets see  $(JU_3)$ :*

$(JU_3): \kappa.\gamma = \gamma.\kappa = 1$  *implies  $\kappa = \gamma$ .*

*For  $\kappa = 1 = \gamma$ , we have:  $1.1 = 1.$*

*For  $\kappa = 2 = \gamma$ , we have:  $2.2 = 1.$*

*For  $\kappa = 3 = \gamma$ , we have:  $3.3 = 1.$*

*Hence  $(JU_3)$  is satisfied.*

*After checking  $X$  for all possible subsets, we have come to know that  $X$  is a JU-algebra. Hence every JU-algebra is an eJU-algebra if we take  $A = \{1\}.$*

Now we will show that not every eJU-algebra is a JU-algebra.

**Example 3.2.** *Consider  $X = \{1, 2, 3\}$  is a set where  $\cdot$  is described in the following table:*

*Let  $A = \{1, 2\}$*

$\cdot$	1	2	3
1	1	2	3
2	1	2	3
3	1	2	1

*We take  $\gamma = 2, \kappa = 2, z = 3.$*

Since  $(eJU_1) (\gamma.z).[ (z.\kappa).(\gamma.\kappa)] \in A$ .

By putting values, we have:  $= (2.3).[ (3.2).(2.2)] = 3.(2.2) = 3.2 = 2 \in A$

Hence  $(eJU_1)$  is satisfied.

Checking for  $(eJU_2)$ ;

$(eJU_2)$ :  $A.\kappa = \{\kappa\}, \forall \kappa \in X$ ,

By putting values, we have

$1.2 = 2; 2.2 = 2$  which equals to  $\kappa$ .

Hence  $(eJU_2)$  is satisfied.

Checking for  $(eJU_3)$ ;

$(eJU_3)$ :  $\kappa.\gamma \in A, \gamma.\kappa \in A$  implies  $\kappa = \gamma$ ,

For  $\kappa = 2$  and  $\gamma = 2$ , we have  $2.2 = 2 \in A$ .

Hence  $(eJU_3)$  is satisfied.

After checking  $X$  for all the possible subsets, we have come to know that  $X$  is an  $eJU$ -algebra.

Now we will check if  $X$  is a  $JU$ -algebra or not?

We take  $\gamma = 2, \kappa = 2, z = 3$ .

$(JU_1) (\gamma.z).[ (z.\kappa).(\gamma.\kappa)] = 1$ .

By putting values, we have:  $= (2.3).[ (3.2).(2.2)] = 3.[2.2] = 3.2 = 2$  which does not equals to 1.

Hence proved that it is not a  $JU$ -algebra.

## 5. $eJU$ -Ideals and minimals

Here we will discuss the concept of  $eJU$ -subalgebras,  $eJU$ -ideals and minimals with their related algebraic properties.

**Definition 4.1.** An  $eJU$ -subalgebra of  $X$  is defined as  $J \neq \emptyset$  subset of set  $X$  satisfying  $\gamma.\kappa \in J$ , for all  $\kappa, \gamma \in J$ .

**Definition 4.2.** A  $p$ -semisimple  $eJU$ -algebra is an  $eJU$ -algebra  $X$  satisfying  $(\kappa.A).A = \{\kappa\}$ , for all  $\kappa \in X$ . A **minimal element** is an element  $j$  of  $X$  satisfying  $\kappa \leq j$  implies  $\kappa = j$ ,  $\forall \kappa \in X$ .

The branch of  $j$  for a minimal element  $j \in X$ , denoted as  $K(j)$  and described as  $K(j) := \{\kappa \in A \mid \kappa \geq j\}$ .

The set  $B_A = \{\kappa \in X \mid \kappa.A = A\}$  is called the  $eJU$ -part of  $X$ .

**Definition 4.3.** Suppose  $X$  is an  $eJU$ -algebra with a subset  $J \neq \emptyset$  in it, is  $eJU$ -ideal if;

i)  $A \subseteq J$ ,

ii)  $\kappa.\gamma, \kappa \in J$  implies  $\gamma \in J$ ,  $\forall \kappa, \gamma \in X$ .

**Example 4.1.** From  $eJU_1$ , we can see that  $(X, \cdot, 1)$  is an  $eJU$ -algebra.

Now let's see the  $eJU$ -ideals of  $X$ .

Let  $R = \{1, 2\}$  be an ideal. Then  $\kappa, \kappa.\gamma$  imply  $\gamma \in J, \forall \kappa, \gamma \in X$ .

*Proof.*  $J = \{1, 2, 3\}$

$1.2 = 2 \in J, 2.1 = 1 \in J, 1.1 = 1 \in J, 2.2 = 2 \in J$ .

Hence the given condition holds. □

Now let  $S = \{1, 3\}$ :

(i)  $S \subseteq J$ ,

*Proof.* Obvious. □

(ii)  $\kappa, \kappa.\gamma$  imply  $\gamma \in J, \forall \kappa, \gamma \in X$ .

*Proof.*  $J = \{1, 2, 3\}$

$1.3 = 3 \in J, 3.1 = 1 \in J, 1.1 = 1 \in J, 3.3 = 1 \in J$ .

Hence (ii) is satisfied. □

We can see that  $R = \{1, 2\}$  and  $S = \{1, 3\}$  are  $eJU$ -ideals of  $X$ .

**Definition 4.4.** A  $p$ -ideal of the set  $X$  is a subset  $J$  of an  $eJU$  algebra  $X$  satisfying:  $A \subseteq J$  and  $\gamma, (z.\gamma).(z.\kappa) \in J$  implies  $\kappa \in J \forall \kappa, \gamma, z \in X$  and  $A \subseteq X$ .

Now we will discuss some additional lemmas associated with our definitions providing appropriate proofs to enhance the depth of our argument.

**Lemma 4.1.** Consider  $X$  is an  $eJU$ -algebra. Suppose  $\kappa, \gamma \in X$ . Then

i)  $((\gamma.\kappa).\kappa)^n.\kappa = \gamma^n.\kappa$  for  $n \in \mathbb{N}$ .

ii)  $(\kappa^n.A).A = (\kappa.A)^n.A$  for  $n \in \mathbb{N}$ .

**Proof.** i) Using induction method to prove these statements.

For  $n = 0$ , it's true.

Suppose it's true for  $n = k$ .

i.e  $((\gamma.\kappa).\kappa)^k.\kappa = \gamma^k.\kappa$  for any  $k \in \mathbb{N}$ .

Now

$$\begin{aligned} & ((\gamma.\kappa).\kappa)^{k+1}.\kappa \\ &= (\gamma.\kappa).\kappa.((\gamma.\kappa).\kappa)^k.\kappa \\ &= (\gamma.\kappa).\kappa.\gamma^k.\kappa \\ &= \gamma^k.((\gamma.\kappa).\kappa.\kappa), \text{ by using } eJ_{12} \\ &= \gamma^k.(\gamma.\kappa), \text{ by using } eJ_{11} \end{aligned}$$

$$= \gamma^{k+1} \cdot \kappa.$$

So, this equality also applies to  $n = k + 1$ .  $((\gamma \cdot \kappa) \cdot \kappa)^n \cdot \kappa = \gamma^n \cdot \kappa$  for  $n \in \mathbb{N}$ .

ii) Without any loss of generality, Suppose that  $n \geq 1$ . Now using the left distribution law on

$$(\kappa^n \cdot A) \cdot A = \kappa \cdot (\kappa^{n-1} \cdot A) \cdot A.$$

We get,

$$\begin{aligned} (\kappa^n \cdot A) \cdot A &= (\kappa \cdot A)(\kappa^{n-1} \cdot A) \cdot A \\ &= (\kappa \cdot A)^2 (\kappa^{n-2} \cdot A) \cdot A = (\kappa \cdot A)^3 (\kappa^{n-3} \cdot A) \cdot A = \dots = (\kappa \cdot A)^n \cdot A. \end{aligned}$$

□

**Theorem 4.1.** *The following properties are equivalent, consider  $X$  is an eJU-algebra and  $j \in X$ .*

i)  $j$  is minimal;

ii)  $(j \cdot A) \cdot A = \{j\}; A \subseteq X$

iii) there is  $\kappa \in X$  st  $\{j\} = \kappa \cdot A; A \subseteq X$ .

**Proof.** First prove (ii) by using (i),

By putting  $\gamma \in A, z = j, \kappa \in A$  in  $eJU_1$ ,

We get;  $(A \cdot j) \cdot [(j \cdot A) \cdot (A \cdot A)] \subseteq A$

$j \cdot [(j \cdot A) \cdot A] \subseteq A$ , by using  $eJU_2$ .

Since  $j$  is minimal if  $\kappa \leq j$  implies  $\kappa = j$

Here  $\{\kappa\} = (j \cdot A) \cdot A$ .

$\forall a \in A, (j \cdot a) \cdot a \leq j$  implies  $(j \cdot a) \cdot a = j$ .

Now proving (i) by using (iii),

Given that:  $\{j\} = \kappa \cdot A$  for an  $\kappa \in X$ .

For  $\gamma \in X$ , if  $j \cdot \gamma \in A$ , then  $(\kappa \cdot a) \cdot \gamma \in A$ .

For all  $a \in A$ , we have;

$$\begin{aligned} \gamma \cdot j &= \gamma \cdot (\kappa \cdot a) \\ &= \gamma \cdot (((\kappa \cdot a) \cdot a) \cdot a), \text{ using } eJ_{10} \\ &= ((\kappa \cdot a) \cdot a) \cdot (\gamma \cdot a), \text{ using } eJ_{12} \\ &= ((\kappa \cdot a) \cdot \gamma) \cdot a, \\ &= a \cdot a = a, \text{ since } (\kappa \cdot a) \cdot \gamma \in A. \end{aligned}$$

Thus  $\gamma \cdot j \in A$ .

Additionally,  $j.\gamma \in A$ . Using  $eJU_3$ , we get  $\gamma = j$ . Hence  $j$  is a minimal element of  $X$ . Now proving (iii) using (ii)., By hypothesis,  $\{j\} = (j.A).A$ . Assume that  $j.A = \{\kappa\}$  for some  $\kappa \in X, A \subseteq X \Rightarrow \{j\} = \kappa.A$  for some  $\kappa \in X$ , here  $\{\kappa\} = j.A$ . Hence  $\{j\} = \kappa.A$ . □

## 5. Conclusion

In this work, we defined the extension of JU algebras where we opted for a non-empty subset in place of special element 1. We established a relation  $\leq$  within the set  $X$  and also specified that for any element  $\kappa$  in the set  $A$ , we have  $A.\kappa = \{\kappa\}$ . We presented a lemma concerning partially ordered sets (POSET) in eJU algebras, outlining certain properties, and demonstrate the validity of these properties with the help of axioms of eJU algebras. We state certain inequalities and specify the condition under which  $X$  qualifies as a KU algebra. We also study the conditions where the JU algebra is an eJU algebra but the converse does not exist. We introduced p-semisimple eJU algebras, eJU-ideals, eJU-subalgebras, minimals and p-ideals in eJU algebras defining their algebraic properties. This extension represents a new approach to the previously established concept of JU-algebras.

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## Interaction of Chimney Plumes with an Isolated Obstacle: Experimental and Computational Study

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### Abstract

This study investigates the dispersion of pollutants emitted from a chimney in the vicinity of a three-dimensional rectangular building. In the experimental part, a wind tunnel setup was used, where tracer discharges (air seeded with glycerin particles) were continuously released from a point source located within a regular array of building-like obstacles. Measurements of mean velocity and turbulence parameters were obtained. Particle Image Velocimetry (PIV) was employed to capture both instantaneous and mean dynamic characteristics. In the numerical part, the proposed model simulates the flow dynamics and heat transfer using the three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations with an RSM turbulence closure model. The comparison between experimental and numerical results shows a high level of agreement. A comprehensive analysis was conducted to assess the influence of wind velocity on pollutant dispersion from the chimney around the building and its surroundings.

**Keywords:** Experimental Study; Numerical Simulation; Obstacle; Recirculation Zone.

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## 1. Introduction

With urban and industrial growth, air pollution has become a major concern for organizations working to improve environmental conditions. Protecting air quality in cities requires understanding how pollutants spread and disperse, whether they are gases, particles, liquids, or even noise. In the case of gaseous emissions, factors such as building density, street geometry, and layout play a key role in how pollutants move. Regulations aim to keep emissions low enough to minimize their impact on the environment. At the local scale, the presence of buildings strongly influences airflow. Obstacles such as towers or street canyons create recirculation zones that trap pollutants and lead to high, uneven concentrations. Our focus is on this scale, studying how different building shapes cylindrical, rectangular, or parallelepiped affect the surrounding airflow and turbulence. The flow field is complex, especially when rough urban surfaces interact with environmental winds. Earlier research often simplified the problem, either by ignoring pollutant sources or by studying dispersion over flat terrain without considering buildings. To capture these dynamics more realistically, we use a 2D block-structured hexahedral mesh with FLUENT. Different turbulence models are applied (standard  $k-\epsilon$ ,  $k-\omega$ , and Reynolds Stress Transport) to simulate the flow. Previous studies have also highlighted the importance of building shape and wind direction. For example, Liu et al. [1] used LES to model pollutant transport in street canyons, showing its effectiveness for predicting dispersion in crowded areas. Lateb et al. [2] studied roof-stack emissions near towers, analyzing the effect of stack height and exhaust velocity. Gausseau et al. [3] examined how wind direction changes dispersion from building-mounted stacks, while Sivanandan et al. [4] investigated how temperature gradients and stack orientation influence plume rise and spread. Turbulence was modeled using the realizable  $k-\epsilon$  approach in FLUENT. In inline stack configurations, the upwind plume shields the one behind it, allowing for greater plume rise under the same temperature gradient. Compared to angled or staggered setups, the inline case also shows stronger plume oscillations. Several experimental and numerical studies help shed light on these dynamics. Mahjoub et al. [5,6] used Particle Image Velocimetry (PIV) to study coherent structures in the wake of a circular jet from a stack in crossflow, focusing on regions near the chimney tip. In another study, Mahjoub et al. [7] examined flow around 3D rectangular obstacles in a wind tunnel, testing different angles of attack. Contini et al. [8] showed that the Reynolds number of the stack flow can strongly influence plume trajectories in small-scale experiments. Other researchers looked at building effects. Saathoff et al. [9] studied how rooftop structures change dispersion from rooftop stacks, while Castro et al. [10] compared experiments with LES and DNS, finding LES gives excellent agreement. Fuka et al. [11] investigated scalar dispersion in building arrays, showing how even slight shifts in wind direction can alter pollutant spread. Amamou et al. [12]

explored chimney emissions near a cylindrical obstacle in a wind tunnel, combining PIV experiments with RSM simulations. Their results confirmed that wind speed and obstacle presence strongly affect the velocity, temperature, and concentration fields. We carried out a wind tunnel experiment to study how airflow interacts with an obstacle, using Particle Image Velocimetry (PIV). Different wind speeds were tested to measure flow behavior, especially turbulence near the obstacle. The experimental results were then compared with numerical simulations based on the Reynolds Stress Model (RSM). Once validated, the model was used to examine how obstacle position affects the flow.

## 2. Experimental set-up

The experiments were performed in a 3 m-long wind tunnel with a  $0.2 \text{ m} \times 0.5 \text{ m}$  test section. The jet was produced by a smooth iron pipe, 0.1 m long and 10 mm in diameter, connected to the main air supply and discharging air at constant temperature. An isolated rectangular obstacle and the chimney were both positioned along the central vertical plane of the tunnel (Figure 1). Flow measurements combined Particle Image Velocimetry (PIV) to capture instantaneous and mean velocity fields with hot-wire anemometry to validate the cross-flow velocity. To minimize boundary effects, the setup was placed about 2.9 m upstream of the tunnel exit. The cross-flow was generated by motors at the tunnel entrance, with velocities limited to 12 m/s from the lower inlet section. To visualize mixing, glycerin particles were added to the chimney jet. PIV measurements were carried out using a TSI PowerView system, and the averaged fields were obtained from 500 successive acquisitions.

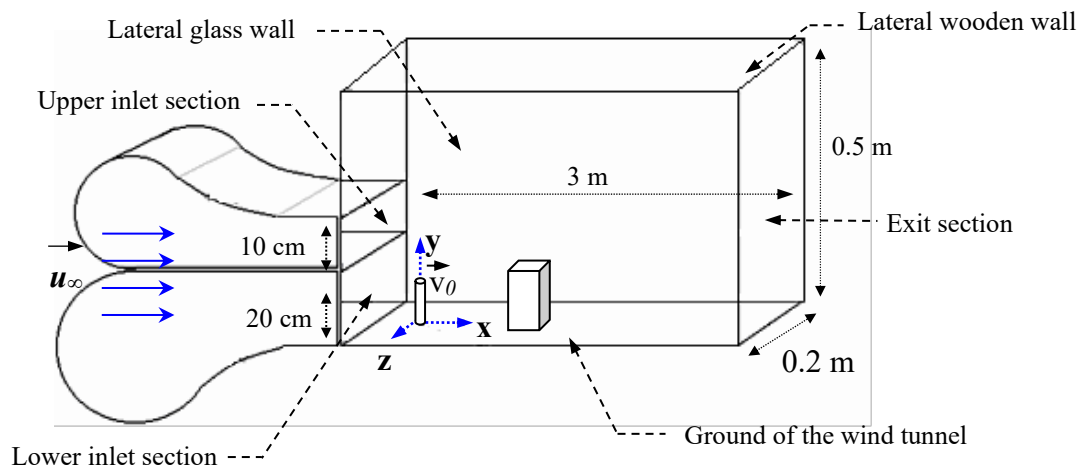


Figure 1. The emplacement of the chimney, obstacle and the Cartesian coordinate system in the wind tunnel

## 3. Computational set-up

The average flow field around the stack and the rectangular obstacle at ground level was simulated under steady, three-dimensional, turbulent conditions. The numerical approach follows the

methodology of Mahjoub et al. [5], first validating the model and then introducing additional conditions to better capture real flow behavior. The governing equations include conservation of mass, momentum, energy, and species transport, expressed in Cartesian coordinates and solved using Favre's decomposition. To close the system, the Reynolds Stress Model (RSM) was adopted, as it accounts for the effects of turbulence through second-order closure. The main modeled terms include molecular diffusion, turbulence production, turbulent diffusion, buoyancy effects, pressure strain, and dissipation.

Equations for turbulent kinetic energy ( $k$ ) and its dissipation rate ( $\varepsilon$ ) were also solved. The boundary conditions applied to the system are summarized in Table 1.

Table 1. Boundary condition.

Boundaries	Velocity (m/s)	Temperature (K)	Mass Fraction	Kinetic energy $\text{m}^2/\text{s}^2$	Rate of dissipation $\text{m}^2 \text{s}^{-3}$
Chimney	$\tilde{u} = u_0, \tilde{v} = 0, \tilde{w} = 0$	$\tilde{T} = T_0$	$\tilde{f} = f_0$	$k_0 = 10^{-3}u_0^2$	$\varepsilon = k_0^{\frac{3}{2}}/0.5d$ [13]
Crossflow	$\tilde{u} = u_\infty, \tilde{v} = 0, \tilde{w} = 0$	$\tilde{T} = T_\infty$	$\tilde{f} = 0$	$k_\infty = 5 \cdot 10^{-3}u_\infty^2$	$\varepsilon = k_0^{\frac{3}{2}}/0.2H_T$ [13]
Obstacles and ground	$\tilde{u} = 0, \tilde{v} = 0, \tilde{w} = 0$	$\partial\tilde{T}/\partial n = 0$	$\partial\tilde{f}/\partial n = 0$	$k = 0$	$\partial\varepsilon/\partial y = 0$
Other boundaries of the domain	$\frac{\partial\tilde{u}}{\partial n} = 0, \frac{\partial\tilde{v}}{\partial n} = 0, \frac{\partial\tilde{w}}{\partial n} = 0$	$\partial\tilde{T}/\partial n = 0$	$\partial\tilde{f}/\partial n = 0$	$\partial k/\partial n = 0$	$\partial\varepsilon/\partial n = 0$

Running the numerical simulation posed several challenges. The flow structure required very fine meshing across much of the domain. To capture the details, especially around the chimney, the obstacle, and the ground, we used a non-uniform grid with denser cells in these regions (standard wall functions applied). Overall, the mesh remained very fine in a large part of the domain (Table 2).

Table 2. Grid steps in the different locations of the domain.

Direction		$\Delta$	$\alpha_x$	$\Delta y$	$\Delta z$
Longitudinal	Upstream of the chimney	0.008	0.98		
	Near the chimney and the obstacle	0.001	1		
	Downstream of the obstacle	0.006	0.98		
Transverse	Near the ground			0.001	
	As we move away, the step of calculation increases gradually			0.003	
	Step of calculation increases gradually			0.007	
Lateral					0.004

The grid was refined between the elevated jet and the obstacle (Figure 2) to better capture flow details. We tested three grids: a coarse one ( $216 \times 130 \times 35$ ), a finer one ( $250 \times 145 \times 40$ ), and a very fine one ( $250 \times 155 \times 50$ ) with more cells in the vertical and lateral directions. The final computations were carried out with the finest grid ( $250 \times 155 \times 50$ ), since grid-independence tests showed that the difference from the medium grid was less than 5%. This confirms that the chosen mesh provides grid-independent results.

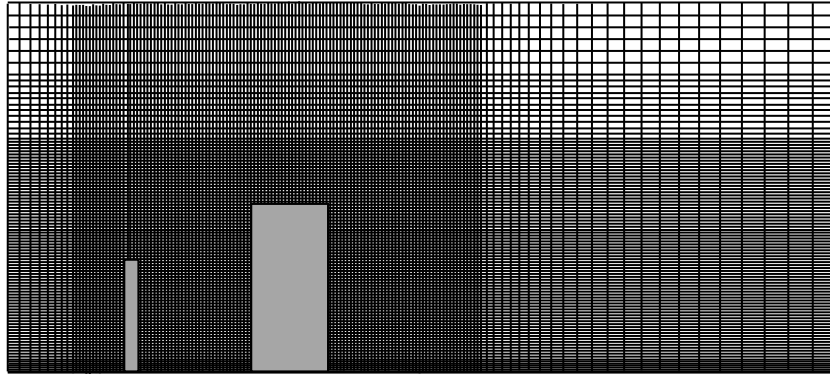


Figure 2. Computational grid on the median plane

#### 4. Results and discussion

Laboratory experiments are a valuable tool for studying pollution dispersion. They provide scaled-down insights that can be applied to real situations, complementing other approaches such as field observations, analytical models, and numerical simulations. Each method has its strengths and limitations, but together they help clarify the mechanisms involved. In Figure 3, we examined how the distance between the chimney and the obstacle affects plume behavior. Two cases were tested: one where the distance equals three times the chimney height, and another where it equals twice the chimney height. The obstacle height was fixed at 9 cm, with both wind and ejection velocities set to 8 m/s. Results show that the plume impact is stronger when the obstacle is placed farther away (three times the chimney height). This is expected, as the plume spreads conically with distance from the chimney. The velocity ratio here is 1.

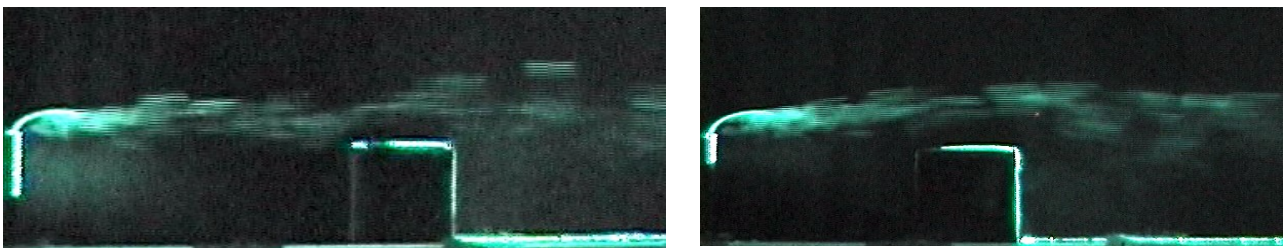


Figure 3. Plume evolution around an obstacle for a velocity ratio equal to 1 and for two gaps from the source (20 cm, 30 cm)  $v_0 = 8$  m/s,  $u_\infty = 8$  m/s

In Figure 4, the obstacle height was varied ( $h_b = 6$  cm and  $h_b = 9$  cm) while keeping its distance from the 10 cm chimney fixed at 20 cm. When  $h_b = 9$  cm, the plume rises, bends, and flows over the obstacle. For  $h_b = 6$  cm, the plume clears the obstacle without direct contact.

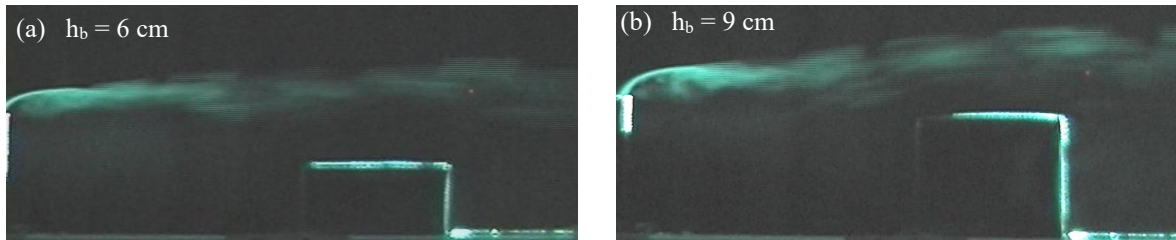


Figure 4. Effect of obstacle height,  $v_0 = 8$  m/s,  $u_\infty = 8$  m/s

Figure 5 shows the plume in the horizontal plane through the chimney exit (xz-plane). The results indicate that the flow is not purely two-dimensional, as vortices and lateral bypasses appear near the chimney, revealing non-zero velocity along the z-direction. When the wind tunnel flow exceeds the plume velocity (Fig. 5a), the plume behaves passively, simply following the transverse wake created behind the chimney similar to the wake of a cylinder. This wake-like structure persists even when the crossflow velocity is lower (Fig. 5b).

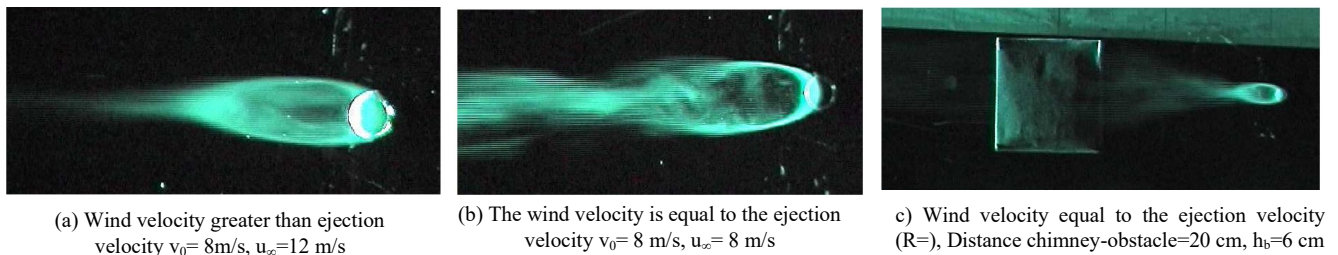


Figure 5. Visualization of the plume in a horizontal plane

At the chimney exit, turbulent structures known as Kelvin–Helmholtz instabilities appear (Figure 6, for  $R = \infty, 5.4, 1.4$ , and  $0.7$ ).

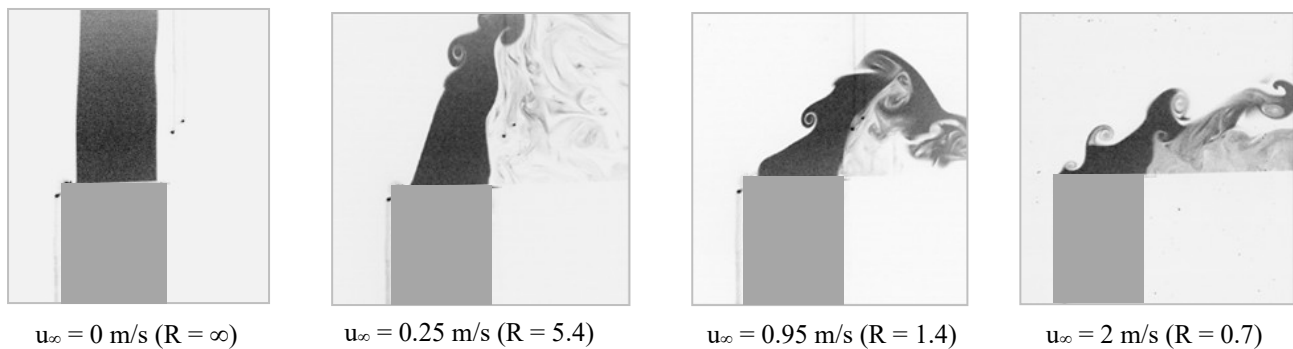


Figure 6. Experimental visualization of the influence of the external flow near the chimney exhaust,  $v_0 = 1.35$  m/s

These arise when two fluid layers moving at different speeds interact, forming a vortex sheet at their boundary. The rotation of these vortices depends on the velocity ratio between the jet and the wind ( $v_0/u_\infty$ ). To study this effect, we considered four velocity ratios. When  $R = \infty$  (no wind), the jet expands freely outward. With external flow added ( $R = 5.4, 1.4$ , and  $0.7$ ), the shear layer changes direction: clockwise when the jet dominates, and counterclockwise when the wind prevails.

The experimental setup was reproduced numerically to ensure consistency. We modeled a 3D isothermal jet flow in a steady turbulent regime ( $T_\infty = 293.15$  K,  $v_0 = 8$  m/s,  $Re_d = 5128$ ). Figure 7 compares experimental and numerical results obtained with the second-order turbulence model, focusing on the longitudinal and vertical mean velocity components. At  $x = 0.05$  m (between the chimney and the obstacle) and  $x = 0.125$  m (on the obstacle roof), the longitudinal velocity shows clear disturbances caused by the building, with results matching the experiments well. For the vertical velocity, profiles at the same locations confirm this agreement. At  $x = 0.05$  m, the vertical velocity is higher than at  $x = 0.125$  m, indicating that the obstacle slows the flow. The section above the roof shows two peaks, reflecting a recirculation zone and negative velocities just above the surface. Overall, the RSM turbulence model reproduces the main features of pollutant dispersion around buildings under different wind conditions with good accuracy.

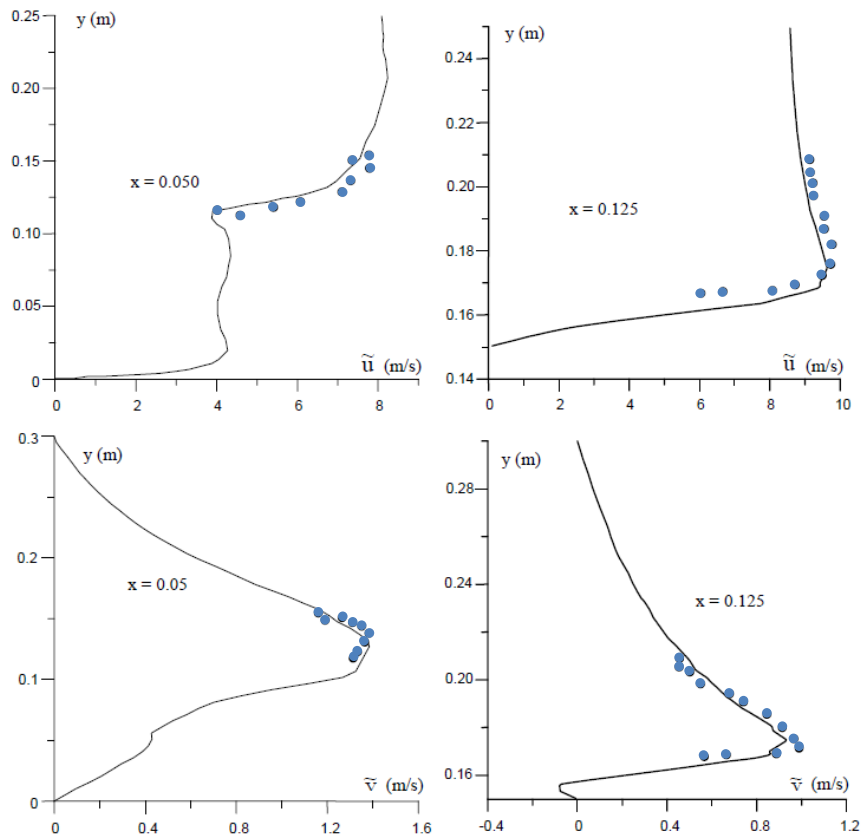


Figure 7. Mean longitudinal  $\tilde{u}$  and normal  $\tilde{v}$  velocity profiles at  $v_0 = 8$  m/s and  $u_\infty = 8$  m/s



Figure 8 presents the longitudinal and vertical velocity profiles along the normal coordinate  $y$  at different positions ( $x= 0.20, 0.30, 0.35$ , and  $0.40\text{m}$ ) in the recirculation zone. Downstream of the obstacle, the negative velocity values confirm the presence of recirculation. The longitudinal velocity shows two peaks: the upper peak corresponds to the pollutant jet trajectory, while the lower peak results from fluid passing through the wake near the ground. Both peaks decrease with distance downstream. Recirculation is clear at  $x=0.20\text{m}$  and  $x=0.30\text{m}$ , but nearly absent at  $x=0.40\text{m}$ .

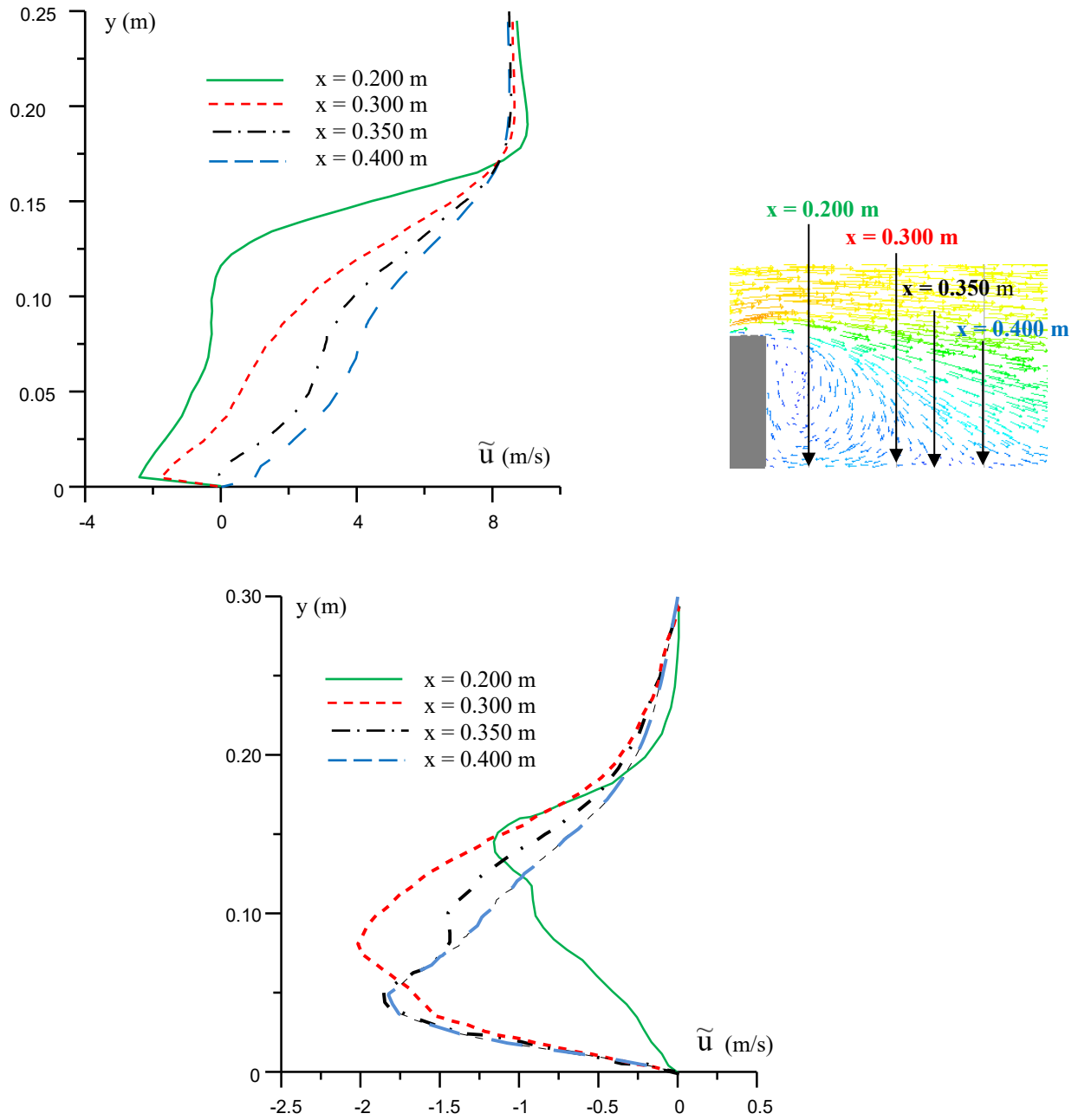


Figure 8. Velocity profiles behind the obstacle (in the recirculation zone)  $v_0= 8$  m/s ,  $u_\infty= 8$  m/s



## **5. CONCLUSION**

Our paper presents both experimental and numerical investigations to better understand the interaction between a continuous plume emitted from a chimney and a nearby building under varying wind velocities. The experiments were conducted using Particle Image Velocimetry (PIV), while the numerical simulations employed the Reynolds Stress Model (RSM) for turbulence. All collected data have been thoroughly validated. The agreement between the wind tunnel measurements and the numerical results, using identical inlet boundary conditions, was quite good. Key flow features, particularly the large vortex structures, were predicted very accurately. Plume dispersion was also analyzed using digital image techniques, and the turbulent dispersion model describing pollutant spread is presented.

The most significant findings of our study can be summarized as follows:

- The presence of a building behind the stack strongly affects the flow structure.
- Differences in height between the stack and the building modify the plume pattern.
- Higher wind speeds cause the plume to spread further before reaching ground level.
- At low wind speeds, the plume tends to rise more vertically due to the greater momentum difference between the released pollutant and the incoming wind.

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## Comparison of Environment Protection and Public Health Practices in Islamic Culture to the Modern Regulations

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### Abstract

The whole world suffers nowadays from the environmental pollution and arising new diseases. Islamic culture places great emphasis. For protecting the environment and preserving human public health. Islam forbids wasting of resources and destroying the environment as it makes the environment conservation is a religious duty of every Muslim. Various Islamic habits were practiced for centuries ago concerning about the cleanliness and avoiding diseases spread, which have recently been approved by health organizations and scientific theories. In this paper, all these practices were collected, analyzed, and compared to the recent approved health habits worldwide. The results confirmed that Muslims have the priority before many modern nations for safeguarding the environment and public health. Islam guides significantly people to safeguard the environment and preserve the resources. It is proved that most of the modern guidelines organizing human rights and duties align with Islamic teachings practiced centuries ago.

**Keywords:** Environmental protection; water conservation; public health; diseases spread; Islamic habits.

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## **1. Introduction**

Due to the human activities, the pollution increased, and environmental imbalance has triggered serious warnings such as the climate change and new diseases spread. It becomes essential to human to look for a solution and stop destroying the environment. Recently many regulations are adopted to manage the natural resources and protect the environment. Most of these current regulations related to preserve the environment and public health were adopted fourteen centuries ago since Islam religion began. The holy book of Islam, i.e., the Noble Quran, showed clearly that Allah, the only god, almighty, created all things in the earth and the whole universe with precise measurements. These great measures assure the survival of living things and sustainability of natural resources. For examples, the planets and stars move in certain tracks in the space without any conflict as mentioned in Chapter 36: Verse 40 “It is not for the sun to catch up with the moon, nor for the night to outstrip the day, each is floating in its own orbit” [1]. In another example, Quran also describes that the sky was built as a strong structure without any space, cracks or faults and it decorated by stars and planets as mentioned in several verses such as Chapter 50: Verse 6. Modern astronomy scientists used to adopt the terminology, space, referring to the universe around the earth, but they discovered recently that there is no space and it is a precise building called cosmic web [2]. Thus, as referred by the Noble Quran, the universe is very accurate and balanced creation. In addition, the Noble Quran shows that resources and components in the earth incorporated in very accurate cycles such as water cycle as described precisely by several verses fourteen centuries ago, which showed the relation between rain and rivers and streams. This hydraulic cycle and how charging the rivers by the rain were not known until discovered decades ago by modern researchers [3].

Consequently, Islam advises humankind to keep this stability of the environment as it was created because humankind was created as trustees and stewards on the earth [4]. Islam defined the environment as a comprehensive meaning that consist of sky and earth including soils, mountains, water bodies, plants, and all creatures with humankind and their morals and behaviors [5]. All these creatures were created and interacted in a balance to service the humankind. Therefore, the humankind is responsible for preserving all these components of the environment [4].

In this paper, there is an attempt to compare Islamic rules adopted centuries ago to the modern regulations espoused by the organizations and countries to protect the environment and keep its natural sustainability. Islam regulations were captured from the holy book of Islam, i.e., Noble Quran, and from the teachings of the messenger of Islam, Prophet Muhammad, peace be upon him (PBUH). The study focusses on Islamic guidance for the human responsibility to conserve the resources and public health. This responsibility will be elaborated in the next sections.

## **2. Research methods**

A qualitative research method is adopted in this study. The qualitative research help in understanding reasons, opinions, and motivations. It also delivers a deep sight into the problem and ideas for potential solutions. The study collected data about Islamic views of environmental protection and public health from primary and secondary sources. Primary sources are such as Noble Quran, historical books, and scientific research articles, and secondary sources included websites and newspapers. Authors have tried to rely on the English translation for many references such as the Noble Quran, which they are originally in Arabic language to make it easy for all readers to follow and read these references. The collected data then were analyzed and compared to the modern guidelines about these subjects. A summary was concluded about the feasibility of Islamic views and their impacts on the people and environment.

## **3. Results and Discussion**

### **3.1. Islam and environment protection**

Islam promotes the protection of the surrounding environment because it is the source of life. Therefore, according to Islamic rules, humankind is asked to protect these resources and do not harm any element in the nature including water bodies, plants, animals, birds, places, air, and others. The Noble Quran, at Chapter 28: Verse 77, forbids destroying the environment and orders the humankind to use it in the good way. “And do good as Allah, God, has been good to you. Moreover, do not seek to cause corruption in the earth. Allah, God, does not love the corrupters” [1]. In a clear picture, Islam gives warnings about spread the corruption by alteration the environment balance as mentioned in Quran, at Chapter 30: Verse 41, that “Corruption has appeared in both land and sea because of what people’s own hands have brought. So that they may taste something of what they have done. So that hopefully they will turn back” [1]. Thus, from Islamic perspective, the unbalance in the environment including all environmental crises such as the climate change was brought because human activities and abuse of resources [6]. United Nations (UN) reported that the main causes for climate change is the modern human activities such generating electricity and heat by burning fossil fuels; manufacturing too many goods, cutting down forests to create farms or pastures; using transportation running on fossil fuels; powering buildings by burning oil and natural gas; and consuming too many products. All these activities led to increase generating greenhouse gas emissions, which act as a blanket covering the Earth and trapping the sun’s heat. Therefore, this leads to a global warming and climate change [7]. All creatures have the right to use the natural resources and benefit from them as mentioned in several verses in Quran, for example at Chapter 80: Verses 24-32 [1]. The humankind, as the only rational creature on the earth, is responsible about saving and managing these resources to be suitable for

utilizing sustainably. Islam advises the human to not waste resources as mentioned in Chapter 7: Verse 31, “Eat and drink, but do not waste, for He, Allah, does not like the wasteful”. From the teachings of the messenger of Islam, Prophet Muhammad, peace be upon him (PBUH), he advised that the benefit of the thing is in turn for the need attached to it. The Prophet (PBUH) also advised one of his companions called Saad ibn Abi Waqas, when he was performing a ritual cleaning of body parts in preparation for the prayer to not waste too much water even if he is at a flowing river. [8]–[10]. Thus, the utilization performance in Islam view is conditional on the need. Thus, this saves the natural resources and reduce the garbage, which assures protecting the environment. The waste reduction surely helps in saving resources and clearing the environment [4]. Many recent studies demonstrated this alarming problem of wasting the natural resources. One recent study concluded that since the starting of industrial revolution in the end of 19th century, industrialized countries wasted huge amount of the natural resources in two ways. First, they relied on non-renewable resources. Then they destroy or misuse about 78% of the extracted groundwater, 49% of the produced food, 31% of the generated energy, 85% of extracted minerals and 26% of non-metallic materials. Therefore, due to this overconsumption and overexploitation, resources were exhausted, and ecosystems were contaminated leading to adverse impacts on the environment and societies [11].

### **3.2. Water Importance in Islam Views**

Everything was created from water: In the Noble Quran, Allah Almighty showed that He (Almighty) created all living things from the water as mentioned at Chapter 21: Verses 30. In another verse Allah Almighty describes that “Allah has created every animal or creature from water. Of them are some that creep on their bellies, some that walk on two legs, and some that walk on four and Allah creates what He wills” (24:45) [1]. These meanings have been supported recently by the scientific theories such as that the life began in the oceans’ water what they called water world theory of life's origins [12]. Furthermore, the recent research proved that every living organism requires water to stay alive. Besides, it is water that helps in performing all the activities as well as functions in the body, which it is filled with around 70% of water and this is what makes it perform perfectly. In human, the brain requires 80% of water, lungs 90%, blood 83%, bones 30%, muscles 75%, and skin 64% respectively. Therefore, the body completely relies on water to make all the vital organs function properly.

Water cycle: The water cycle is a series of evaporation, condensation and precipitation processes that controls the freshwater map on the earth. This important cycle driven by sun energy, was not discovered by modern researchers until few hundred years ago. There are many verses in the Noble Quran explaining the journey of freshwater in the earth that now has been proven by recent scientific studies. For example, what is mentioned at Chapter 78: Verses 13 and 14. The first verse indicates to

the sun as a shining lamp of extremely intense heat. Then in the next verse, 14, talks about sending down water from clouds, which describes the second and third parts of water cycle and linked the role of the sun heating as the first part mentioned in the verse 13. In addition, at Chapter 15: Verse 22, this verse defines the wind as the second controller beside the sun of the water cycle as it is known recently that wind plays a role in increasing the rate of water evaporation in the air. Chapter 24: Verse 43, describes that the high thick clouds are responsible for the formation of rain and ice. Quran in many verses talks about sending rain and running it in rivers and springers and storing underground. This hydraulic cycle and how charging the rivers by the rain were not known until discovered hundred years ago by modern researchers [3].

The barrier between fresh and salt waters: As apart of water cycle, the rivers and streams having freshwater drain finally at a sea or ocean and return water to the sea without polluting freshwater with salt and bitter. In the Noble Quran, at several positions such as Chapter 25: Verse 53 and Chapter 55: Verses 19-20, it is mentioned that there is a barrier keeping the fresh water clean from mixing with the salt. This barrier is discovered recently by marine scientists. They discovered that in general whereas two different water bodies come together, there is a barrier formed between them due to the difference in temperature, density, and salinity. Then when the water body enters the other, the distinctive characteristic of both becomes homogenized with the other. In this case the barrier works as a transitional zone for the two waters [13], [14]. Recent human activities start to interrupt this barrier and cause freshwater pollution. Many studies recently were investigated the reasons and impacts of causing seawater intrusion into freshwater [15].

Water pollution and purification: For water pollution, polluting water intentionally is forbidden in Islam based on the general advice of Islam Prophet (PBUH) who said that no harm shall be inflicted or reciprocated in Islam. He (PBUH) also forbidden relieving yourselves or urinating in a watering place. He (PBUH) established borders for water springs and wells to prevent them from agriculture and building to protect groundwater from possible contaminations. For water purification, the Islam Prophet (PBUH) was asked about water and how some animals might drink from it. He (PBUH) advised that when the water volume is more than 50 waterskins, then nothing makes it impure. if it does not change its smell, and its taste, it is safe to use. According to [16] this above amount is equal around 270 liters and Muslim scholars recommended that adding a clean amount of this volume to any impure water will turn it all to a pure water, which suitable for religious cleanliness habits. This refers to the impact of water dilution factor and self-purification when the contaminated water was mixed with the clean water. This is approved by recent scientific research and water quality guidelines (Keller *et al.*, 2014; Colman *et al* 2016; Wahyudianto *et al.*, 2019). For example, regarding what mentioned about animal polluting water, if it is assumed that animal saliva will be add to the water by 0.5 to 1 ml

due to its drink, then dilution factor will be 270,000 to 540,000 according to the above suggested water amount, which shows how the impact of the pollutant will be very minimal.

Water treatment in Muslim Civilization: In the Islamic golden age traditionally dated from the 8th century to the 13th century, many scientific, economic, and cultural flourishing were arisen. Water treatment is one of the important features of this era. Several practices were adopted for water treatment. For turbidity removal, an experiment of water purification was described in Islamic medical books in accurate details. Jabir Ibn Hayyan known as Geber, the chemist in the 8th century, recommended the siphons axis usage as a method of purification of water. Ibn Rubn Al-Tatari, died in the ninth century A.D, informed that based on studying the ancient Egyptian sciences, water turbidity can be removed by throwing crushed kernel cores of peach and apricot into water to become clear and by using curdling aids as well [20]. Al-Jazari mentioned several ways to purify turbid water. One of them was by putting water in porous pottery jars to allow infiltration of water from the inside to the outside, so the clean water is filtered towards the outside. Ibn Sina, in the tenth century A.D, proposed for removing turbidity using two pots, an upper pot filled with muddied water and the lower is an empty pot and in between a priming of a wool. Then water will drop by gravity as pure water drips into the empty pot [21].

For water sterilization, recently it is known that boiling water for a period of five to ten minutes gives a safe water without germs. Al-Tamimi, in the tenth century A.D, concluded that for full water sterilization, water should be boiled for a sufficient time until a quarter of it evaporates. Then water is filtered in a newly made ceramic pot with large pores to get rid of all impurities [22]. In addition, Al-Razi, mentioned that boiling water for a long time then cool it very quickly will help removing all contaminates.

For seawater desalination, Ibn Qaim Al-Jawzih, in the thirteenth century A.D, suggested water filtration through soil layers to get fresh water from seawater. His method by making many series large holes beside the seashore, so that seawater is filtered to the first, and then filtered to a next hole and so on until the water becomes pure and sweet [23].

Muslim's invention in water technology: Water technology is also an important sign of the Islamic golden era. Many technologies were proposed, implemented, and used as a base for the modern civilization and technologies. Many scientists in that time invented several devices. Al-Jazari, for example, designed many devices in the field of the water engineering. He invented the water clock, which is used to measure time by the regulated flow of liquid into or out from a vessel. He also invented a water-raising machine known as Noria. It is a historically very significant machine for lifting water. It consists of a large wheel made of timber and provided with paddle. The most amazing of Al-Jazari's inventions was the water-driven twin-cylinder pump. It had a double-acting principle, the conversion



of rotary into reciprocating motion, and the use of true suction pipes [24], [25]. Banu Musa, Persian scholars, were in the period of 803 to 873. They published a book including real practical inventions and engineering tricks focusing on using trick vessels such as alternating fountains. They also adopted the crank or the eccentrically mounted handle of the rotary in several of the hydraulic devices [26]. In addition, the ship-mill is one of the remarkable innovations adopted widely in the Islamic world to control the power of the faster currents at midstream. It also solved the problem of low water levels challenging fixed mills during dry periods. The ship-mills were used in Murcia and Zaragoza in Spain. The tidal power also was exploited in the tenth century in Basra, Iraq, before their adoption in Europe by hundred years [27]. The most advanced hydraulic systems at the time were used for both surface water and groundwater resources by Muslim communities. Most Muslim hydraulic works and water-lifting machines continued the basis for Spanish agriculture and were moved to Europe and modern world systems.

Muslim's approaches for water supply and sanitation: Water is necessary for Muslims like other people for normal human activities such as drinking, food preparation and washing. However, it also is needed for ablution i.e., cleaning for praying and religious activities. In addition, in Islam, delivering water to human, animal, or plantation, is considered as a continuous charity as mentioned in Quran: Chapter 6: Verse 99. Prophet Muhammad (PBUH) advised that supplying water is the best charity. Thus, supplying water is an essential task for the Muslim authorities. Very early in Muslim communities started using distribution systems for drinking water by simple ways such as excavating central wells for each a community as a source of water. They also arranged to supply a clean water by transporting it by animals for homes. The qanat system, i.e., a subterranean canal, was originated in Iran. It was an efficient method transferring surface and spring waters for irrigation and water supply. The qanat technology spread westward to North Africa, Spain, and Sicily in Italy. Then the Spanish transferred this Islamic technology including both institutional framework for irrigation and the distribution of water to the southwest of American continent. Many such qanats were found in Mexico, Peru, and Chile [28]. In addition, many Muslim dams were found in Spain built during the tenth century AD to control the water supply and increase the water harvesting [29], [30]. Many major cities of the medieval Islamic world such as Baghdad in Iraq, Cordoba in old Islamic Spain, Fez in Morocco, and Fustat in Egypt had water supply systems. These systems were operated by hydraulic technology that provided the drinking water for routine washing purposes, mainly in mosques and public baths. These cities also had advanced wastewater disposal systems with interconnected networks of sewers [31].

Water management in Islam: Water has a great importance in Islam as it gives and sustains life in the earth and cleans human bodies for praying and worshiping practices. Some scholars argued that water has been mentioned more than 63 times in the Quran [32]. The first step of water management is its

conservation. Quran supports water demand management by referring to that the water supply is fixed, as in Chapter 40, Verse 18 "And we send down water from the sky in fixed measure. Islam advised people to consider equity and sustainability in using natural resources. The Quran orders humans not to waste resources including water as in Chapter 7: Verse 31, "O Children of Adam, eat and drink, but do not waste, Allah, God, don not like the wasters". The Islamic Prophet (PBUH) used to perform ablution by small amount of water equal two-thirds liter and used to take a bath with around 3 liters. He (PBUH) also forbade wasting water in cleaning for praying even a plenty available such as a flowing river. This behavior exhibits a rational method to water sustainability in such arid area [33]. Thus, water conservation is a major concept in Islam view as it is considered a living style that is not used only as a solution to the shortage, but it should be applied through the Muslim's daily habits.

The second step of water management is, reusing the wastewater. As be referred above about the pollution and water treatment, the light polluted water can be treated and reuse it by very early Muslims. However, the new terminology of wastewater, which has a high level of pollution, and its reuse was not acceptable by Muslim scholars in the beginning especially for using this water for cleanliness due to its dirty. However, after become practicing the treatment method of the wastewater common and it provides the safety and cleanliness for this wastewater. Since 1978, Muslim scientists and engineers recommended that treated wastewater can theoretically be used even for cleaning for praying and drinking as well [34].

### **3.3. Environment Sustainability in Islam**

The sustainability expression was adopted since 1970s to term the equilibrium of the economy with the natural ecosystems. Thus, environmental, economic, and social aspects are considered the three key factors of sustainable development. However, recent models viewed that the natural environment is the controller for the two other aspects or in other words, both economy and society are limited by environmental restricts [35]. The United Nations issued a report in 1987 defining the sustainable development as a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The western liberal capitalism is based on the market economy and profit maximization. Sequentially, the wealthy counties got many benefits and led to failed people and nature as many of people live under the poverty line and many ecosystems were destroyed [36].

Sustainability in Islam may differ from the understanding of industrialists. In Islam, development becomes sustainable if it provides of equilibrium, moderation, and considerations of the social justice. Islam invites for the equilibrium among people by asking reach people to pay some of their money for poor people. Islam teaches moderation in all aspects of human behavior especially in consuming the

natural resources. Islam stresses on the fairness among all humankind. Islam considers all resources are gifts from Allah, almighty, to the whole of the human. Thus, the economic development is embedded in the ethical norms of Islam, which confirms mankind's responsibility in the utilization, allocation, and preservation of natural resources [35].

Sustainability is identified mainly in the perspective of a capitalist economy and the hardline secularism philosophes, which prevents the existence of the human religious. Within Islam, the concept of a strict separation between religious and state affairs, as understood in Western secularism, is not traditionally present. Islamic law (Sharia) provides a framework that encompasses all aspects of life, including governance. Although only a handful of Muslim countries now base their political, judicial, and economic systems completely on Islamic laws such as Saudi Arabia, the influence of Islam is still strong enough to prevent founding a purely secular state in the Islamic countries. Thus, even in relatively secular Muslim countries, appeals to Islamic sustainability based on religious values are common in these countries (Faruqi et al, 2001).

### **3.4. Public Health**

Islam stresses the importance of cleanliness and personal hygiene. Islam urges people to clean their bodies, areas, and their surrounding environment. Many instructions had been recommended by the Islam to protect the general health of people and prevent disease spread.

Cleanliness: Islam asks people to make ablution five times for the daily prayers. It also recommends taking showers every Friday and at the two Muslim festival days and after a sexual relationship for the married people. This care about the cleanliness led to build many public bathhouses very early through the Islamic countries. Islamic hygiene also requires washing with water after using the toilet, for purity and to minimize germs. The Islamic Prophet (PBUH) advised to do five things and called them as an original disposition or natural constitution, called Fitra in Arabic, for people namely, circumcision, removing the pubes, trimming the mustache, clipping the nails, and plucking the armpit hairs [8]–[10]. He (PBUH) also advised people to wash the hands before and after eating and to clean the mouth and teeth by brushing them by a small branch of a type of tree called *Salvadora persica*. This type of plants was approved recently as very useful for clearing mouth and improving its odor and mentioned by the World Health Organization (WHO) for oral hygiene use [37], [38]. The recent proper hygiene and sanitary practices confirm the benefits of cleaning mouth and washing hands before and after eating to wash away any harmful germs/bacteria and reduce the risk of illness. All these Islamic hygienical habits in cleaning the human body and keeping it healthy helped reducing the disease spread among Islamic regions in the earlier eras.

Eating less food for better health: Islam invites normally for the values of moderation and control without extravagance in everything. The Prophet (PBUH) said: “A human being fills no worse vessel than his stomach. It is sufficient for a human being to eat a few mouthfuls to keep his spine straight. But if he must (fill it), then one third of food, one third for drink and one third for air [8]–[10]. The meaning refers to eating light and moderate meals is the best approaches to attain a good health. Because over-consuming food may lead to a negative impact on both mind and body. Dividing the needs of the human body into three thirds for food, drink, and the respiration indicating that Islam is established on the values of moderation without wastefulness. Medical studies showed that drinking water with meals may help regulate your appetite, prevent overeating, and promote weight loss [39].

The Islam Prophet (PBUH) also advised to fast Mondays and Thursdays regularly or three days at least from each month. Beside fasting for religious reasons, the fasting can offer excellent health benefits. The recent research supports the benefits of this regime for general health. Much scientific evidence now supports the benefits of fasting as it cleanses our body of toxins and forces cells into processes that are not usually stimulated when a steady stream of fuel from food is always present. Research has focused on a two-day diet where calories are reduced in half and carbohydrates are limited for two consecutive days in a week [39]. This may be like fasting Monday and Thursday as advised by the Islam Prophet (PBUH).

Recommending eating useful foods and forbidden harmful ones: All foods are allowable in Islam except the pig meat and wine. Many modern studies discussed the risk of eating pig or pork meat and drinking the wine (Meyerholz *et al.*, 2008; Khuroo, *et al.*, 2016; Ahmed and Ghanem, 2020). It is confirmed that the Islam Prophet (PBUH) liked eating some foods such as milk, honey, watermelon, and palm dates. He (PBUH) recommended that if someone eats seven ripe dates in the morning, he will not suffer a harm of the poison in that day [8]–[10]. He (PBUH) liked eating palm dates with watermelon. Recent research confirmed many benefits for these foods and their combination as well. The dates were proved that they include highly nutritious and concentration of antioxidants, and aid in healthy bowel movements. Date and watermelon are proved for their hair and skin benefits. They are anti-aging benefits, brightens and lightens complexion, reduces wrinkles and treatment of skin diseases, anti-inflammatory properties, body hydration, digestive aid, and cancer prevention [43].

Islamic instructions for preventing the disease spread: Islam gives a great care for the infection control and protecting people from the disease spread. The Islam Prophet (PBUH) gave many instructions for his companies regarding conserving the public health. For examples, the Prophet (PBUH) forbids that people relieving yourselves or urinating in a watering place, especially forbidding urinating into resting or permanent water. He (PBUH) also advised to not urinate in the place whereas taking a bathe, to no

doubt that the urine has dirty his body or not. It is proved recently that draining wastewater directly into water bodies without a proper treatment cause the disease spread. Water-borne diseases such as cholera and typhoid made pandemic disaster several times in several Europe cities in 18<sup>th</sup> and 19<sup>th</sup> centuries due to improper wastewater disposal. For example, in Paris, cholera epidemic of 1832 alarmed the awareness of people for the essential need for a proper drainage system of wastewater. Tens of millions of people were killed in pandemics such as the Plague of Justinian in 541 and the Black Death in 1347 to 1351 due to improper wastewater disposal [44]. In addition, the Islam Prophet (PBUH) prohibited the drinking of water directly from the water container and drink by using a cup or vessel to not pollute the water source. He (PBUH) also advised that when you drink water do not breath in the vessel and he (PBUH) used to drink while sitting not standing and take two or three breaths outside the vessel while drinking. All these instructions can help to reduce disease spread among people. Recent studies showed that drinking water while standing, may keep feeling remain thirsty even after drinking water. Thus, it has been suggested that it is preferable always to drink water while sitting and in smaller sips. Furthermore, not advisable to drink water while standing because this may cause digestive disorders or ulcers and heartburn. The reason is the swallowed liquid ends up splashing in the esophagus which disturbs the sphincter. As a result, the acid would give the feeling with the burning sensation. Some studies showed that drinking water while standing can lead to the increase of fluids in the joints, which can initiate inflammation problems and joint damage. It has been also found that the kidney filter works better while sitting. Drinking in standing positions leads to pass water without any filtration to the lower stomach and causes the water impurities to settle in the bladder [45].

Furthermore, regarding the infection transfer from animals, advises were given by the Islam Prophet (PBUH) in this concern. For example, if a dog drinks from a vessel, he (PBUH) advised to wash it seven times to make sure it becomes clean. Recently reported by [46] that dogs transmit several viral and bacterial diseases to humans. Zoonotic diseases can be transmitted to human by infected saliva, aerosols, contaminated urine, or direct contact with the dog. Viral infections such as rabies and norovirus and bacterial infections including *Pasteurella*, *Salmonella*, *Brucella*, *Yersinia enterocolitica*, *Campylobacter* and many others are the most common viral and bacterial zoonotic infections transmitted by dogs to humans. Many studies referred to the major role of animals in transmitting hazards diseases and pandemic to human [47].

For controlling the disease spread or pandemic, the Islam Prophet (PBUH) said, "If you hear of plague in a land, do not enter it; and if it breaks out in a land, in which you are, do not leave it" [8]–[10]. This means that people must never enter nor escape the disease affected area and must take available

procedures to safeguard themselves and others from the disease risks [48]. This is the main guideline adopted recently with the virus spread such what happened with the most recent virus called Corona or Covid 19, which led to close all borders between countries to avoid its spread [40]. This quarantine is essential nowadays, particularly, due to the recent speed travel ways among countries. Diseases can spread very quickly across the whole world in few hours or days, creating a great risk to the public health and economics. It is reported that quarantine and personal hygiene were the core of prevention [49].

### Community Rights

Islam introduces norms for all life aspects including conduct, society, politic, and economy. It calls also to safeguard all forms of the life diversity. It concerns about all living things on the earth including human, animals, and plants. The Arabic root of word Islam is “Salam”, which means peace and harmony to all surrounding environments.

Rights of people: Islam advised followers to behave in a good way to all mankind and stressed on relatives and neighbors even non-Muslim. Islam Prophet (PBUH) advised that to get a complete faith in Islam, you must like for your brothers of Muslim what you like for yourself. This rule generates a very strong community. He (PBUH) advised that if anyone have extra staff or food should give it to whom do not have it. He (PBUH) also said that the believer is not he who eats his fill while his neighbor is hungry [8]–[10]. Islam asked wealthy Muslim to give a small part of their money to the poor people especially their relatives to help them on their needs in the life. Islam Prophet (PBUH) asked to visit the relatives and ask about them regularly and He (PBUH) advised to gentle dealing with women and He (PBUH) himself was helping the wife in household duties. Islam advised to save refugee if even it is a non-Muslim as mentioned in Chapter 9, Verse 6 [1]. All these advises are to enhance the social connection among people in the community. These advises adopted recently through many of worldwide agreements such as refugee agreement in 1951 and women rights by UN Women, the United Nations Entity for Gender Equality, and the Empowerment of Women. Universal Declaration of Human Rights, in 1948 by UN has gradually expanded human rights law to involve specific standards for women, children, disabled people, minorities and any other vulnerable groups.

Rights of roads and public area: In an explanation of the Islamic rights, Islam established social rules for sitting or walking in roads. Prophet (PBUH) advised that removing harmful things from the road is a good deed and an act of charity. He (PBUH) banned three acts that harm people in their public area namely: urinating in shaded places that utilized by people, in a walkway, or in a water place. He (PBUH) advised also that when people set in roads or public areas to talk, they must give the roads their rights. These rights include lowering the gaze from looking for others passing roads especially women, refraining from harming others, responding for greeting from people, and commanding what

is good, and forbidding what is evil [8]–[10]. These guidelines keep the security and harmony among people in the community. This exhibits the Islam care about introducing common respect and safeguarding in the community against rights of others. UN human rights covered many rights including the freedom of living of people in public area without annoying them by anybody, however, it does clearly state these rights.

Rights of animals: Islam gives a great care to animals as many instructions call for safeguarding and feeding them. Prophet (PBUH) advised that not killing a sparrow or anything bigger than without a need to eat, not simply to chop off its head and then throw it away. Prophet (PBUH) advised also that there is a reward from the god (Allah almighty) for serving any living beings, i.e., feeding, and caring. He (PBUH) gave examples of a man entered the paradise for giving water for a thirsty dog and a women entered the hell because of a cat, which she had tied it, neither giving it food nor leaving it free to eat from the vermin of the earth. These instructions encourage people to save animals even roaming animals such as dogs and cats and not killing animals just for matter of playing. These rights have been agreed recently in 1978 by Universal declaration of animal rights at the UNESCO headquarters in Paris.

Rights of plants: Islam invite people to save and plant trees. It is reported that Prophet (PBUH) stated that if a Muslim plant a tree or sows seeds, and then a bird, or a person or an animal eats from it, it is regarded as a charitable gift for him. He (PBUH) also encouraged people that if even the Day of Judgment, i.e. Resurrection, has been upright, while you have a shoot of a plant in your hands and it is possible to plant it, you should plant it [8]–[10]. This stresses on the important of planting. He (PBUH) forbidden also cutting trees without a right or reason. These instructions guide people to save the whole environment as plants are the producer of the food for all living things.

### **3.4. Islam view about human responsibility**

As described above Islam asked people to not pollute the environment such water and land. Islam shows the rights of people and all other creatures. Islam also prohibits taking the money of others or any type of financial corruption and cheating as mentioned in many instructions of the Islam Prophet (PBUH) [8], [9]. As aforementioned that Islam introduces the humankind as the steward and vicegerent on the earth and added to them the responsibilities of managing all resources and protecting all other living things. Islam educates Muslims to follow God's orders in everything that they perform including the rights of the others; therefore, Islam intended to reach further than the individuality by guiding all Muslims to think about the whole society in their activities as a part of their religion. There are several modern hypotheses describing the human responsibility about the environment protection. For instant, Legitimacy theory indicates that organizations or companies should communicate their environmental

responsibility to legitimize their continual existence to stakeholder otherwise they will be rejected. Stakeholder theory on the other side suggested that companies should be operated in ways that are sustainable. The organizations can enhance the interests of its stockholders without damaging the interests of the rest of the society. Another group of theories called instrumental theories undertake that the single social responsibility of the company is wealth creation (Garriga and Mele, 2004). The difference between the Islamic view and that of these assumptions is that Islam view of responsibility stresses public interests over individual interests. Therefore, companies and individuals should protect and maintain the environment even if doing so will affect their specific interests. Because this responsibility is combined with the strong motivation to please the God, Allah almighty (Salem et.al, 2012). Figure 1 shows a flowchart summing up the Islamic recommendations regarding human responsibility toward environment and public health.

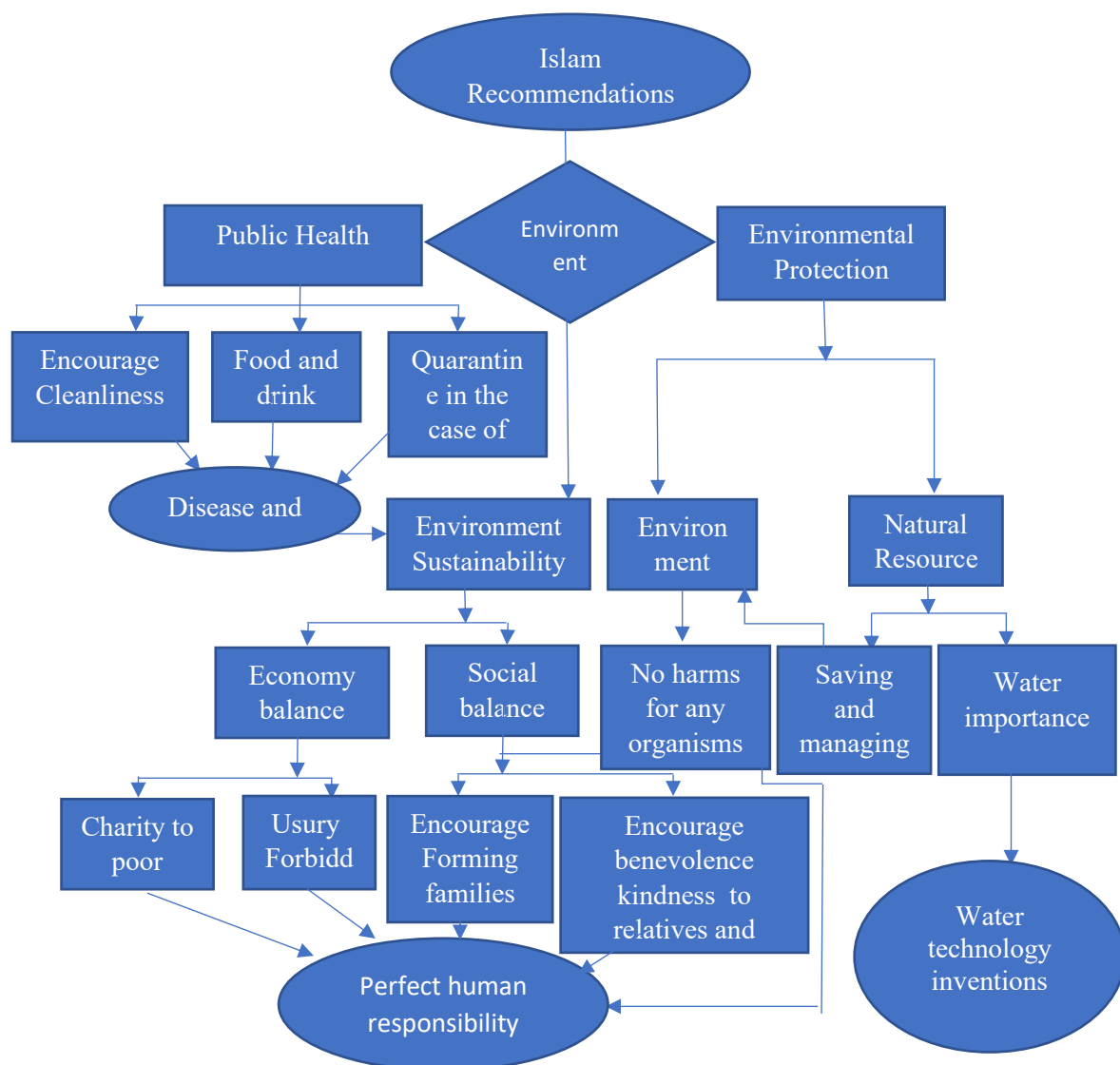


Figure 1: Flowchart summarize the Islamic recommendation toward environment and public health



#### **4. Conclusion**

Islam does not only show what is a good and bad sense from a religious aspect but also it introduces guidelines for each precise details of the life. Islamic way of life asks people to live in peace and harmony for both social and ecological sides and protect the environment. Through all above discussions in various aspects, it is proved that most modern guidelines organizing the human rights and duties were introduced by Islam rules fourteen centuries ago. In addition, many water technologies in water supply and sanitation were introduced by Muslim scientists since 8<sup>th</sup> century and used as a fundamental to many of the modern technologies. Several points can be spotted from the research analysis as follows:

- A practicing Muslim, who obeys Islamic teachings, should behave friendly to the environment elements, and save and manage the available resources.
- Islamic hygienic habits have several elaborate rules including ablution for the daily prayers, as well as taking regular showers. All these instructions help in cleaning the human body and keep it healthy and reduces the disease spread among Islamic regions in the earlier eras.
- Islam established a good relation among the community members by advising to distribute any extra supplies with people to others, by which it saves environment and reduce the waste generation.
- Islam asks for conserve the resources by following the sustainable consumption as much as possible.
- Islam advises to keep the environment clean and safe and to plant trees and to care about the animals.
- Most Muslim hydraulic works and water-lifting machines continued the basis for Spanish agriculture and were moved to Europe and modern world systems.
- Islam view of the responsibility stresses public interests over individual interests.
- UN human rights covered many rights including the freedom of living of people in public area without annoying others, however, it does clearly state the road rights as in Islam.
- Islamic teachings historically addressed many principles now found in international human rights frameworks.
- Islamic teachings provide a comprehensive, faith-based ethical framework for sustainability that pre-dates and aligns with modern principles

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## Balancing Personalization and Transparency in User-Centered AI Systems Through Explainable Deep Learning Interfaces

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### Abstract

As AI systems become more advanced and personalized for user experiences in multiple contexts, such as e-learning, finance, and healthcare, the need and necessity for transparency become even greater. While deep learning models can provide the highest quality and recommendations, their black-box nature can inhibit user understanding, trust, and control. In this work, we explore the balance between personalization and transparency in user-centered AI systems by including explainable AI (XAI) techniques in deep learning algorithm-based recommender systems. Our study provides a system with a hybrid architecture that models user behavior embeddings, LSTM/CNN layers, and attention-based mechanisms. Explanations were provided for users through SHAP values, attention-based visual cues, and natural language text that helped users interpret their recommendations in real time. The interface with visual overlays and user interactive panels were designed for the user as a function of cognitive load and types of explanation. The proposed system was tested through two phases of user studies, both with quantitative performance metrics and qualitative data. The results indicated better recommendation accuracy, trust, perceived fairness, and user satisfaction when users received explanations. This work indicates how we can build ethical and usable AI systems. We show that by employing explainable interfaces we can not only enhance the effectiveness of personalized technology, but also increase human-level acceptability.

**Keywords:** UX, XAI; Personalization; User-Centered AI; Deep Learning; Transparency.

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## **1. Introduction**

The mass proliferation of artificial intelligence (AI) into consumer facing applications has radically transformed the relationship users have with digital systems. Personalization is virtually ubiquitous in today's applications, from personalized learning environments and streaming services to healthcare and financial services; AI systems increasingly personalize both the content and decision-making to suit individual user preferences and behaviours [1]. These capabilities have significantly enhanced user engagement and satisfaction, and are increasingly powered by deep learning models. Despite their overall benefits, however, there is an important limiting factor - these systems often provide limited transparency, leaving users unclear as to how decisions are arrived at, or why specific recommendations are offered [2]. This opacity undermines user trust, can reduce perceived control, and obstructs the development of an accurate mental model the user may need for confident interaction. This research investigates the core challenge of achieving a balancing act of personalization and transparency in user-centered AI systems. Deep learning models can provide highly accurate, contextual, and reliable recommendations, even if those recommendations are not always reasonable to the user, but they often function in a black box manner that is opaque to the user, rendering the system unexplainable, and difficult for the user to interpret or question [3]. In contrast, interpretable models will generally lend themselves to more transparency, but they will trade-off performance and can often provide some transparency, but at a cost to the performance. This design problem is important to consider when developing AI applications, especially in domains in which user trust, user autonomy, and ethics are critical.

To anchor this research in recognized user experience (UX) and human-computer interaction (HCI) theory, the research introduced several established foundations. Don Norman's Seven Stages of Action, prompts us that the human-computer interaction is the distance between the system's output and user intent [4]. For users to feel in control and make decisions, they need to get a sense of the AI system's behavior including perceiving, interpreting and evaluating. It is not a surprise that when explanations are not present or are unintelligible, this alignment is lost. Lee and See Trust in Automation framework, introduces that "trust in machine learning process is dynamic and need to be calibrated to display effective trust and reduce excess trust" [5]. The extent to which a user is blind to automation depends on the transparency of the system, which aids the user in developing the right amount of trust where they are neither blindly reliant on nor unjustifiably sceptical of the automated process. Additionally, principles from the Cognitive Load Theory to avoid cognitive overload from complexity and over-Information [6]. To be sufficiently informative and helpful enough to meet the information needs of

users, explanations must allocate concise cognitive load that is just enough to be helpful, but not so much as to be unmanageable.

To address these individual concept challenges, this research introduced a hybrid deep learning framework capable of reporting accurate personalized recommendations but simultaneously including aspects of XAI for user understanding and promoting trust. The proposed system utilizes embedding and sequence-based models to recognize user behavioral patterns and user preferences. By including SHAP (SHapley Additive exPlanations) [7] values to show feature contributions, and attention-based approaches to surface important behavioral indicators for recommendations, the design addresses the need for transparency. The objective is to provide a way to explain recommendations from the recommendation system with visual (e.g., charts/heatmaps) and textual (e.g., natural language summaries) explanations for users with varying levels of technical knowledge.

The framework is evaluated by using a comprehensive user study that measures both objective performance measures (e.g., the accuracy of recommendations) and subjective measures (e.g., trust, satisfaction, and perceived transparency) including how users engage with explainable recommendation interfaces and how explanations influence their perceptions of the system. By studying these actions and situations within a real-world application space, the research will help examine the nuanced relationship of personalization and interpretability.

Altogether, the work contributes to designing ethical, user-aligned AI systems by showcasing that explainable deep learning-based interfaces improve not just the performance of the system but also the trust, satisfaction, and engagement of users. This contributes to the goal of informing further development of transparent human-centered AI systems which promote informed decision-making and responsible automation.

## **2. Background**

The growth of interactive AI systems in several sectors including e-learning, digital marketing, healthcare, and entertainment has vastly improved user experience via personalized content recommendation, contextual relevance and task performance [8]. These systems use user information to better recommend, predict and decide within a normal user's preferences for a more relevant and engaging experience.

Deep learning has fueled personalization as it can best represent complex user-item interaction, temporal behaviour and high-dimensional feature space [9]. The growth of interactive AI systems in several sectors including e-learning, digital marketing, healthcare, and entertainment has vastly improved user experience via personalized content recommendation, contextual relevance and task performance [8]. These systems use user information to better recommend, predict and decide within



a normal user's preferences for a more relevant and engaging experience. Deep learning has fueled personalization as it can best represent complex user-item interaction, temporal behaviour and high-dimensional feature space [9]. Nonetheless, even when successful, personalization systems powered by deep learning have a common challenge: complexity has rendered them opaque. Users generally are not able to understand the logic leading to an AI-enabled decision, especially in high-stakes or sensitive domains. Impaired trust and confidence is not the only concern; it may also limit users' ability to make rational, informed decisions or challenge what the system may output [10]. To deal with this issue, the new field of explainable AI (XAI) [11], has started to present methods to make AI decisions interpretable and accessible for end users.

Explainability is a design issue, in human-computer interaction (HCI) terms, not just a technical issue. It is a design issue in which user psychology and cognition are critically important [12]. Benefits of a user-centered design approach, and appropriate UX and HCI normative theories, systems must provide the user with outputs that they can see and evaluate with respect to their goals and expectations [13]. If a user cannot understand why a system made a recommendation, then they cannot build a correct mental model, which is affecting how usable the system is. Similarly, the trust in AI systems which can be modeled with frameworks, such as Lee and See's Trust in Automation, - requires that the AI system provide justification which manages requirements for trust levels (e.g., calibration of trust) [14]. Cognitive load theory advises caution against providing overly elaborate details or technical explanations that exceed a user's cognitive processing capacity, suggesting a need for lightweight, contextualized, and actionable explanations. As such, the implementation of explainability with AI systems (e.g., personalization) must be a transdisciplinary problem involving machine learning, user-centered design, and cognitive science.

### **3. Related Work**

The intersection of personalization and transparency in user-centered AI systems is still an active area of research, especially in developing explainable deep-learning interfaces that inform explanation, generate trust and understanding. Some recent literature has emphasized the important design task of incorporating personalization into user-centered AI-based development while still being able to produce clear and interpretable explanations. A study by [15], highlights the importance of user-centered explainability in the context of energy demand forecasting in smart homes, emphasizing that personalized explanations for the end-user enhance usability and trust in the system. Authors [16], proposed a human-centric approach to personalization in AI for education, suggesting a multimodal modular architecture and an interpretable modular system that enables the model to choose explanations according to user's context, thus making a trade-off between personalization and

transparency. This approach demonstrates that adaptive explanations can be generated for many different groups of users despite the complexity of each group, thus enhancing understanding and engagement. In the healthcare, the need for transparent AI models is relevant because many users prefer an interoperable rationale AI model. A recent review on explainable AI in healthcare notes that if an AI model is transparent for example, it allows the user to build trust and better decision-making especially if it can explain how it makes decisions [17]. Complementing this, AI's role in hospitals and clinics demonstrates how explainability facilitates an improvement in traditional systems, such as finding meaning within high-dimensional data, that leads to clinical decision-making [18]. Educational settings also provide motivation for explainable AI. The review on AI in education notes how explainability can help adaptive learning systems improve decision support. Educators and students can improve their understanding of recommendations, feedback, and learning pathways stemming from the use of AI systems [19]. Other complexities in this literature address AI systems' adaptability, with a multi-layered framework for research advocating safe and personalized explainability, with recommendations for future systems to modify the explanations given based upon individual user preferences and knowledge, making systems customizable for the end user through trustworthiness and usability [20]. Much of the literature concerning an explanation's approximation of black-box models lays claim to unintentional consequences on developing explainability toward traditional AI system users. Nevertheless, other recent reviews have noted the intent of explainability methods to generate explainable outcomes that are readable, usable, and provide users understanding and trust. These user-interface design methods cross domains, often in regard to trust and understanding, as associated with acceptance processes and improved understanding of AI reasoned thinking within domains including healthcare and education [21, 22]. There is clear divergence in the design approach towards intuitive, user-centered interfaces, intended to design transparent AI applications that align with human-centered design principles toward usability and trustworthiness as a primary consideration in designing explainability [23]. Additionally, the development of explainability and comprehensibility is proven to be essential in developing user trust in deep learning systems. There are a variety of discoveries that explain the production of a decision, based on statistical pattern recognition methods, that can help make the output of AI more comprehensible to foster acceptance [24]. The concept of human-centered AI (HCAI) directly endorses systems that provide clear insight into their reasoning process so that users can understand and assess AI's decisions [25]. Lastly, design research on the usability and trustworthiness of AI-based interfaces is on the rise, with studies suggesting that explainability increases user confidence and acceptance of the system. Studies from multiple disciplines suggest that designing AI interfaces with explainability not only creates transparency, but also aligns with user expectations for having a benevolent and trustworthy

personalized AI [26]. Specifically, the body of literature examined shows that creating a user-centered AI system requires balancing personalization and transparency in the adequacy of designing user centered AI systems requires creating adaptable but interpretable explanations, which balance different user needs while ensuring the user understands AI's reasoning process. Ultimately, the balance will be necessary for trust, usability, and humans and AI system collaboration across various application areas.

#### 4. System Architecture and XAI-Driven Interface Design

The proposed system consists of human-centered, explainable deep learning architecture that captures accuracy of user-centered personalized recommendations with transparent, interpretable justification to users. The architecture consists of three parts as given in Fig (1): (1) hybrid deep learning model for user behavior learning, (2) an explainability layer for generating real-time human-understandable explanations, and (3) a user interface that presents explanation to the user in visual and textual form.

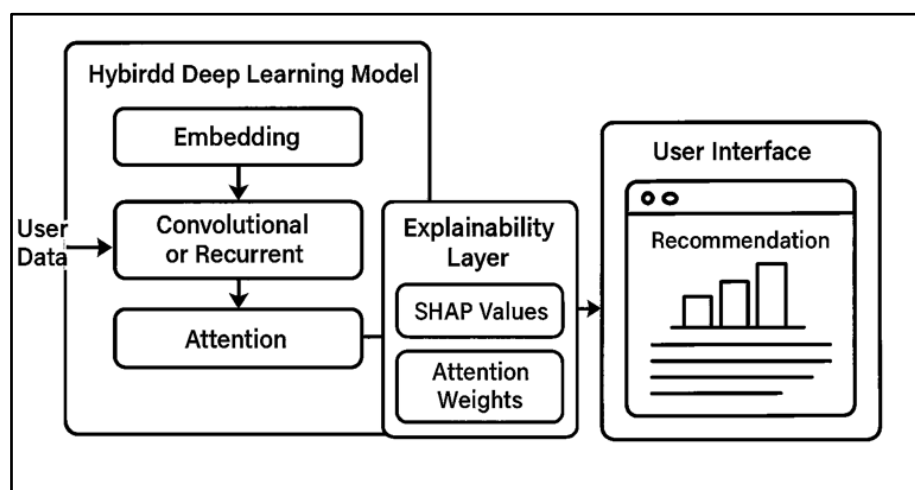


Fig 1: Proposed Approach

The architecture uses user interaction data as input including the user ID, item ID, user engagement history, and item content metadata. These inputs are embedded into dense vectors, and then passed through CNN and LSTM layers to learn spatial and temporal patterns in user behavior. An attention mechanism then aggregates the representations by assigning weights to the most important user interactions, which produces the final recommendation output according to either ranked items or predicted preferences. The explainability layer will run in tandem and will provide SHAP-based feature attributions and attention maps that highlight important pieces of evidence, when possible. The recommendation and explainability outputs will then be combined, converting each into visual and

textual explanations, through the explanation engine, in a way that allows the user to visualize both the prediction and the reasoning behind the prediction through the interface.

#### 4.1 Hybrid Deep Learning Model

The system employs a hybrid deep learning model—including representations of both static user features and dynamic behavior patterns so it can move toward high personalization performance. The model architecture contains embedding layers, convolutional, recurrent layers, and an attention layer. The embedding layers convert categorical input to dense vector representations for instances that have user IDs, item IDs, and/or user-enhanced content metadata elements. The goal is to learn the latent associations between user, and item. From these embeddings each of which are of a specified embedding length, the layers are either sent into Long Short-Term Memory (LSTM) units or 1D Convolutional Neural Networks (CNN) units based on the nature of input. LSTM model it is important for capturing temporal sequences history of temporal/user engagement such as the order of accessed learning resources or user engagement (time-stamped history). The CNN model is best suited to recognize local patterns in the user's interaction (fixed length sequences) or the nature of features in the content descriptors. In either setup the network is trained to learn associations between a set of behavioral patterns and their likely user preference behaviors. An attention mechanism is included in the last stage of the network to improve interpretability as well as performance. The attention module will assign a relevance score for each element in the input (e.g., previous user interaction) relative to the final output prediction. This affords the model an opportunity to emphasize the most contextually relevant elements and provides a natural incorporation point for explanations, as attention weights can simply be visualized or used to rank inputs by contribution Algorithm 1 provides the technical details of the proposed approach.

The combination of CNN, LSTM, SHAP, and attention mechanisms improves accuracy and interpretability. CNN layers extract local spatial features from user–item interactions, and LSTM layers model temporal dependencies in the user behavior. The attention mechanism gives relevance weights to user interactions in order to highlight the most important user–item interactions, providing an interpretive bridge between CNN and LSTM outputs. Then, we use SHAP for post-hoc feature attribution, providing clear transparency along multiple levels of the recommendation process.

#### 4.2 Explainability Layer

Although the hybrid deep learning model is strong in terms of prediction strength, it has interpretability through the explainability layer. The explainability layer gives some information to the user about the

recommendation that is made by combining model-specific and model-agnostic methods in near real time. The first part of the explanation is the use of SHAP (SHapley Additive exPlanations) values, which is a model-agnostic way to estimate the contribution of input features to the final prediction. SHAP has global and local interpretability: it can tell you which features are generally important across users and it is also able to explain the recommendations for a particular user by showing the importance of the input feature. The second part of the explanation is the use of the model's attention mechanism. During training, the model will learn what the attention weights mean and this allows the model to make recommendations. The attention weights show what parts of the interaction history for a user mattered for the recommendation, as a measure of importance. Careful extraction of this information will provide additional supporting visual cues in the user interface. For example, the prompts can be presented by highlighting elements, intensities of bars or colors, along timelines, and so forth. The next stage is the textual explanation generator that parses SHAP and attention layer technical outputs into natural language statements. These statements are produced by pre-existed templates, which are filled out dynamically, depending on the actual inputs and the model outputs. For example: "This module is recommended because you recently interacted with topics similar to data privacy and cyber security". The aim is to produce concise, human-readable explanations that follow user's mental models and cognitive capabilities.

By combining SHAP with attention mechanisms, we create a multi-level framework for explainability. The attention layer adds an inherent level of interpretability by presenting salient interactions. SHAP features, on the other hand, provide model-agnostic feature attributions, in terms of significance, after a prediction has been made. Both techniques work in conjunction to create more transparency, by providing attention-based descriptions of influence with SHAP-based feature attributions, in a visual and text-based output, to increase understanding for the user.

Figure 2 presents the proposed Algorithm 1 that describes the hybrid recommendation process. Features for users and items are embedded and passed through CNN and LSTM layers to extract and learn spatial and temporal features. Attention assigns weights to important interactions and outputs recommendations at the recommendation stage. In the explainability stage, we calculate SHAP values for feature attribution, and examine important interactions using the attention weights to prompt potential behavior evidence. The explanation engine combines the attribution and important nature of interactions to provide textual and visual explanations to users.

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**Algorithm 1** Proposed Algorithm

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1: Notation:
2:  $\text{Embed}(\cdot)$ : Embedding layer
3:  $\theta$ : Model parameters
4:  $\sigma(\cdot)$ : Sigmoid activation
5: procedure HYBRIDMODEL( $u, X, i$ )
6:    $e_u \leftarrow \text{Embed}_{\text{user}}(u)$  ▷ User embedding
7:    $E_{\text{seq}} \leftarrow \text{Embed}_{\text{seq}}(X)$  ▷ Sequence embedding
8:   if using LSTM then
9:      $h_t \leftarrow \text{LSTM}(E_{\text{seq}}; \theta_{\text{LSTM}})$ 
10:  else
11:     $h_t \leftarrow \text{CNN}(E_{\text{seq}}; \theta_{\text{CNN}})$ 
12:  end if
13:   $\alpha_t \leftarrow \text{softmax}(W_a[h_t; e_u])$  ▷ Attention weights
14:   $c \leftarrow \sum_{t=1}^T \alpha_t h_t$  ▷ Context vector
15:   $s(u, i) \leftarrow \sigma(W_s[c; e_u; e_i] + b_s)$  ▷ Scoring
16:   $R \leftarrow \text{topk}_i s(u, i)$  ▷ Top- $k$  recommendations
17:  return  $R, \alpha_t$ 
18: end procedure
19: procedure EXPLAINABILITY( $R, u, X$ )
20:   $\phi_j \leftarrow \text{SHAP}(s, u, i, X)$  ▷ Feature contributions
21:   $E_{\text{text}} \leftarrow \text{Template}(\phi_j, \alpha_t, X)$  ▷ Natural language
22:   $E_{\text{visual}} \leftarrow \text{Render}(\alpha_t, \phi_j)$  ▷ Heatmaps/bars
23:  return  $E_{\text{text}}, E_{\text{visual}}$ 
24: end procedure
25: procedure INTERFACE( $u, q$ )
26:   $X \leftarrow \text{GetInteractions}(u)$ 
27:   $R, \alpha_t \leftarrow \text{HybridModel}(u, X)$ 
28:   $E \leftarrow \text{Explainability}(R, u, X)$ 
29:   $\text{Display}(R, E_{\text{visual}}, E_{\text{text}})$ 
30: end procedure

```

---

Fig.2. The proposed Algorithm 1

### 4.3 User Interface Prototype

The explainable recommendation system is made available to users in a responsive and intuitive, web-based interface that was designed with well-established human-computer interaction (HCI) principles that prioritize usability, cognitive load, and limited interference with users' regular activities. The front-end incorporates many user-facing components that support interpretability and user control. These include visual overlays (e.g., progress bars, heatmaps, or badges) that elaborate on specific user behaviours or item attributes impacting the recommendations. Such visual indicators enable users to quickly understand how or why a suggestion is being offered without needing a technical background. Additionally, the inclusion of interactivity that triggers tooltips upon a hover indicates something more than a visual representation. The tooltips offer a simple recommendation explanation that is concise and based upon SHAP. Users that would prefer a more elaborate explanation among the user-facing components can access dedicated explanation panels. The explanation panels allow for longer and formatted textual descriptions that articulate the most influential factors that impacted the decision and choices, representing transparency and user confidence. Modern web frameworks such as React.js or

Vue.js are used to develop the frontend component in order to provide modularity, ability to create responsive interfaces, and ease of integration with backend services. The backend architectural includes two connected components, the model inference engine and explanation engine. The model inference engine will load and run the trained hybrid deep learning model to produce real-time, personalized recommendations. The explanation engine will compute SHAP values and an attention map (when relevant to the recommendation) to provide the rationale for the recommendation. These outputs will be formatted dynamically for the visual and textual components of the frontend interface.

In order to maintain the responsiveness of the system, pre-cached explanations are kept in memory for frequently requested queries (in this case, the most common interactions), while all other interactions involve on-demand computation. In other words, a hybrid caching approach will provide flexibility to make trade-offs between performance and responsiveness. The backend capability is designed in a Python-based microservices architecture (Flask, FastAPI) and will be created with common and popular ML libraries (TensorFlow, PyTorch) when serving models, SHAP, and attention. Altogether the frontend and backend capabilities result in a solid architecture that provides both high-quality personalizations and meaningful transparency that is aligned with users.

## **5. User Study Design**

To assess the effectiveness, transparency, and alignment with user views concerning the proposed explainable recommendation system, a two-phase user study was conducted with a combination of qualitative and quantitative components. The study was conducted with the university context of an e-learning platform for learners as they receive recommendations for learning resources, including course modules, video lectures, and additional readings. Using an educational context for the study was important since educational environments require a high level of user trust, perceived equity, and autonomy, creating an environment that could help to evaluate how explainable interfaces impact users' perception of AI positive recommendations.

For the quantitative phase, the participants who were recruited represented a pool of approximately 100 university students living between 18 to 30 years of age, who were currently or recently actively using online learning platforms. The goal of this was to assess the system's performance in real-world use cases, and whether there was an observable effect on user trust, satisfaction, and perceived quality of the system, when using explainable components. It was most important that the participants interacted with a real world interface. The participants were randomly assigned to either of two conditions in an A/B testing context. The control group engaged with a non-explained recommendation

interface, while the experimental group engaged with the explained interface, which included SHAP values, attention based highlights, and text based justifications.

A number of metrics were employed to assess outcomes for both groups. Recommendation effectiveness was evaluated using standard performance metrics: precision, recall, and Normalized Discounted Cumulative Gain (NDCG). User experience was gathered using validated measures, including the Trust in Automation Scale which considers dimensions of trust in systems (i.e., reliability, predictability, and trust in the system), System Usability Scale (SUS), which measures overall usability, and additional custom items to assess subjects' views on transparency, fairness, and understandability.

In addition to the quantitative outcomes, a qualitative evaluation of user cognition and emotions were recorded for a smaller cohort of 15-20 students from a variety of disciplines (including computer science, engineering, and arts) to allow for diverse user feedback regarding the recommendation system which ranged from highly technical users to less knowledgeable users of AI systems. Each participant performed a series of recommendation tasks using the explainable interface while thinking aloud, which was recorded and transcribed for thematic analysis. Upon task completion, participants were engaged semi-structured interviews, to investigate particular aspects of interest relating to system transparency. These aspects included clarity and utility of the explanations, the cognitive effort associated with interpreting and acting upon the feedback from the system, and relevant emotions, including trust, frustration and satisfaction depending on each of a participant's experience. Questions also included whether the explanations created a sense of being in control of their recommendations and whether they would prefer a similar system as part of their daily academic workflows. This combined methodological approach ensured a study which assessed both system effectiveness and user perception, allowing the researchers to develop an overall understanding of how explainability affects user experience, trust and decision-making in a personalized learning experience devoted towards XAI interfaces.

## **6. Results**

The outcomes from the two-phase user study provide strong evidence that using explainable AI techniques within the deep learning recommendation process significantly improves system performance and user experience. The Quantitative results showed that the hybrid deep learning model we proposed (utilizing embedding, LSTM/CNN, and attention capabilities) outperformed the baseline non-explainable recommendation system using standard accuracy metrics. The hybrid models were



found to have higher precision, recall, and Normalized Discounted Cumulative Gain (NDCG) performance levels, indicating it more accurately and contextually understood user preferences. Additionally, there was also a statistically significant increase in user trust and satisfaction for people who interacted with the explainable system. The Trust in Automation Scale and the System Usability Scale (SUS) had higher mean scores in the explainable condition while indicating greater confidence and usability in their rating. A summary of the quantitative evaluation results is presented in the Table 1.

Table 1: Quantitative Results Comparison Between Baseline and Explainable Systems

Metric	Baseline System	Explainable System	p-value
Precision	0.81	0.89	< 0.01
Recall	0.78	0.86	< 0.01
NDCG	0.74	0.82	< 0.01
Trust Score	3.10	4.30	< 0.01
SUS Score	68.00	84.00	< 0.01

These results support that the explainable version of the system not only provides better recommendation performance but also significantly enhances the user experience aspects of trust, usability, and perceived transparency. The qualitative results (Table 2) also provided an in-depth exploration of users' strategies relevant to cognitive and emotional engagement. Users reported a clearer representation and correspondence between their mental models of the system behaviors. People reported that the explanations contributed to a better awareness of perceived reasons about the recommendations made by the system. This alignment appeared to support a sense of control and autonomy over users' interactions with the system. Statistical comparisons were performed using independent-sample t-tests with Bonferroni correction ( $\alpha = 0.01$ ). Effect sizes (Cohen's  $d$ ) indicated large effects across all metrics, confirming the practical significance of the improvements.

Text based explanations were particularly advantageous for users from non-technical backgrounds. These users found the natural language based justifications to be very accessible and informative. The reasons in natural language allowed users to build context around the recommendations without requiring prior cognitive knowledge or grounding in AI or algorithms. In contrast, users with higher technical proficiency valued the visual explanation elements (e.g., the SHAP-based bar charts and attention highlights) for providing quick, clear, and intuitive insights into what mechanisms contributed to recommendations. In general, users categorized the system as more trustful, transparent, and usable, and preferred interfaces with explainable information. All results support the hypothesis.

Adding explainability to deep learning based recommender systems can increase both the performance of those systems and the ethical use of AI in real-world user-centric applications.

Table 2: Summary of Qualitative Findings from User Study

Theme	Baseline System	Explainable System	User Observation
Mental Model Alignment	Limited	Improved	Users reported better alignment with system behavior
Perceived Control & Autonomy	Low	High	Explanations supported a sense of control
Accessibility of Text Explanations	Mixed Feedback	Very Helpful	Non-technical users found natural language justifications useful
Use of Visual Explanations	Underutilized	Highly Appreciated	Technical users preferred SHAP charts and attention overlays
Overall User Preference	Moderate	Strongly Preferred	Majority preferred the interface with explainable information

## 7. Discussion

The current results provide meaningful insight into the impact of providing XAI in improving the usability, trustworthiness, and overall effectiveness of deep learning-based recommendation systems. By providing a SHAP-based feature attribution, attention-based visualizations, and textual explanations, it is evident that the supplementary interpretability tools positively impacted usability and endorsed the use of the recommendations, while also improving the overall systems' performance.

One contribution this work, is that providing explanations to recommendations improved the users' cognitive clarity and emotional trust. Individuals in the explainable condition showed substantially improved levels of mental model alignment throughout the task, indicating a better comprehension of the workings of the system and rationale behind the recommendations. It was further evident that interpretability was improved usability and trust in the accompanying system - two aspects critical for system adoption and continued usage of AI technologies. Users indicated a higher likelihood to trust and use the recommendation from the system, expressed a greater sense of control, and classified the interface as fairer regarding decision making autonomy.

These results are unsurprising, given existing foundations of research in UX and HCI theory. The contributions to our understanding of UX map to Don Norman's Seven Stages of Action, which

suggests that users must be able to perceive, interpret, and evaluate system feedback before they can establish accurate mental models that allow them to successfully achieve their goals. In our study, both types of explanations (visual and textual) provided both perceptual and interpretive bridges between the underlying logic of the system (that a wrong action occurred), and the user expectations. This is a good fit with Norman's Seven Stages of Action.

Our study is also consistent with Lee and See's model of trust in automation. The authors emphasize the importance of calibrated trust - neither over-trust (an unwarranted reliance on the automation), nor under-trust (multiple reasons for suspending trust). By allowing users to read (explanations), understand, and relate (to their own experience) the situation (the explanations must matter to them), we enabled trust to grow out of the user's interaction with the system, rather than out of blind trust in the technology.

The insights also demonstrate important design implications for the future design-explainable AI systems. One of the major takeaways is the need for personalizing the complexity and modality of explanations based on user type. While non-technical users benefitted most from short explanations in natural language, technical users have the tendency to focus mainly on visual cues or required more detailed information in order to gain deeper insight into the reasoning the system's algorithm made. This implies that explanation that is appropriate for one user type is not likely appropriate for the next type. Instead, it would be more effective for a future XAI system to implement adaptive explanation frameworks that would apply explanation content, format, and depth to an individual user's preferred methods of explanation, overall cognitive styles, and domain experience.

Although the study has given very positive results there are some limitations. First, the evaluation was conducted only with university students, and thus, the participants were relatively uniform sampling of a digitally savvy population. While this is appropriate for the educational application domain, it does constrain the generalizability of the findings to other populations, such as older adults, professionals, or even users with lower digital literacy. Future work should draw upon a more diverse group of participants to increase external validity. Second, the application domain was limited to e-learning and while this domain is generally amenable to transparency and control by the user, it may not reflect user behavior in other domains such as e-commerce, healthcare, or social media where the stakes around recommendation and user expectations may be quite different.

From this it is clear that there are many opportunities for future work. One key opportunity is developing adaptive explanation systems that learn from user interactions and adjust the type and

complexity of explanation in real time. Such systems could utilize reinforcement learning or user modeling approaches to culminate the most effective form of explanation based on user needs. Another opportunity is implementing longitudinal studies to find out how sustained explanations affect levels of trust, understand and satisfaction over time. While this study has indicated strong evidence of short-term effects, we cannot ascertain the effect of long term use and adoption of recommender systems that provide explanations. This study has shown that incorporating XAI dimensions in user-centred recommendation systems, enhances technical performance and also embodies core UX and HCI principles, that also contribute to ethical AI. XAI interfaces enhance transparency, provide cognitive support and achieve levels of emotional trust which represent pathways toward usable, ethical, human-aligned AI systems.

## **8. Conclusion**

With the design and evaluation approach, this study provides an integrated framework to tackle the important challenge posed by AI recommender systems: the balance between personalized and transparent recommendations. The study showed that a hybrid deep learning recommender system with built-in explainability (using SHAP-based attributions, attention maps, and natural language explanations) could produce high predictive performance, while providing understandable and trustworthy feedback to users. Using aspects of UX and HCI design principles such as Norman's Action Model and Lee and See's Trust Calibration Framework, the deep-learning recommender produced improvements in cognitive clarity, emotional trust, and reliably confident decision-making, across the diverse university user group in the e-learning context. The quantitative results showed very meaningful improvements in recommendation performance and user satisfaction overall. The qualitative results highlighted the diversity of cognitive needs across the technical and non-technical user group. Visual explanations provided a timely understanding of the recommendations for the experiential users, while textual explanations aided less technical users in building the mental model of the system. This research lays the groundwork for the development of personalized feedback systems that go beyond recommendation quality, and recognize application of user-centered designs recommending flexible and personalized explainability systems, not only in AI applications but where technology, learning, user experience, and user preference convene. The research notes that there are limitations to this research, particularly with respect to the sample population (university students), and contextual limitations (e-learning). Future research would then need to examine the effectiveness of similar explainable systems with different populations, and in increased contexts of examination in much higher stakes applied ethics, such as healthcare and finance. Furthermore, in the area of adaptive

explanation systems, generation of explanations, and longitudinal studies of trust and adoption over time remain ripe for future work. This research enables further development of human aligned AI thinking that explainability is not only a computational additive feature, but rather a central design feature for personalization to be considered ethical, usable, and effective for users becoming empowered with interpretable insight, promoting agency, accountability, and trust, to support and engage in responsible use of AI in pervasive and unchecked ways in everyday life.

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## Thermal Properties and Phase Formation in Zn-Modified Pb–Sn Alloys

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### Abstract

This study investigates the influence of a 2% zinc (Zn) addition on the thermal properties and crystallization kinetics of a Pb-5Sn solder alloy to understand its impact on processing characteristics. Non-isothermal differential scanning calorimetry (DSC) was employed to analyze the melting and crystallization behavior of both the base Pb-5Sn and the modified Pb-5Sn-2Zn alloys at heating and cooling rates of 5, 10, 15, and 25 °C·min<sup>-1</sup>. The Kissinger method was applied to the crystallization peak data to determine the activation energy ( $E_a$ ) for the process. The results revealed a significant decrease in the activation energy for crystallization upon the addition of zinc, from 103.54 kJ/mol for the base Pb-5Sn alloy to 57.93 kJ/mol for the Pb-5Sn-2Zn alloy. Furthermore, the crystallization peak temperatures for the Zn-modified alloy were consistently lower across all cooling rates, indicating an increased propensity for crystallization. This substantial reduction in the energy barrier suggests that zinc atoms act as effective heterogeneous nucleation sites, thereby facilitating the transition from the liquid to the solid phase. These findings demonstrate that minor Zn alloying can significantly alter the phase transformation kinetics, providing a practical route for tailoring the solidification behavior and optimizing the thermal processing for Pb-Sn alloys.

### Keywords

DSC; Kissinger; Activation energy; Crystallization; Thermal behavior.

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## 1. Introduction

Lead–tin (Pb–Sn) solder alloys have long been established as essential materials in soldering and electronic packaging due to their favorable characteristics, including low cost, a eutectic melting temperature near 183 °C for the eutectic composition, and excellent wettability on a wide range of metallic substrates [1,2]. Depending on their composition, these alloys exhibit either a sharp eutectic melting point or an extended "pasty" range, offering versatility that has made them indispensable in various high-reliability joining applications, particularly within the aerospace, automotive, and defense industries. In recent years, the drive for materials with tailored thermal and mechanical performance has prompted research into modifying these traditional alloys [3]. An established strategy for enhancing the performance of binary alloys involves the micro-addition of a third alloying element. This approach can refine the microstructure, improve mechanical properties such as tensile strength and creep resistance, and alter the solidification kinetics. Among various potential elements, zinc (Zn) has garnered significant attention. Zinc is an inexpensive element known for its ability to modify the microstructure and mechanical behavior of solders [4, 5]. The Pb–Sn–Zn ternary alloy system represents a distinct subset where the incorporation of zinc is expected to alter both the thermodynamic and kinetic parameters governing phase transformations during solidification. The influence of zinc in solder alloys is multifaceted. Recent research indicates that minor element additions, like zinc, can significantly impact the thermodynamic properties, phase formation processes, and kinetic behavior of solders, providing a path for precise control over alloy performance during manufacturing [6-9]. In lead-free solder systems, such as Sn–Ag–Cu (SAC) alloys, minor zinc additions have been shown to improve wetting characteristics and suppress the formation of brittle intermetallic compounds [10]. In lead-based systems, zinc addition can refine the grain structure and influence the morphology of the eutectic phases, which directly influences the material's durability and strength. These microstructural changes are intrinsically linked to the alloy's thermal behavior [11]. Zinc's incorporation modifies melting and solidification characteristics, potentially shifting transformation temperatures and influencing the energy barrier required for nucleation and growth during crystallization. Despite the importance of this ternary system, systematic investigations into the non-isothermal thermal behavior and crystallization kinetics of Zn-modified Pb–Sn alloys remain relatively limited [12-15]. Advanced thermal analysis techniques, particularly Differential Scanning Calorimetry (DSC), provide a precise means of characterizing these alloys. DSC allows for the identification of critical phase transformation temperatures such as onset, peak, and completion of melting and crystallization—while also enabling the determination of key kinetic parameters, like the activation energy ( $E_a$ ), using established models such as the Kissinger method. Such information is essential for comprehensively describing an alloy's behavior under the dynamic thermal conditions typical of manufacturing processes [16,17].



The present study provides a detailed thermodynamic and kinetic analysis of a binary Pb-5Sn alloy and a ternary Pb-5Sn-2Zn alloy, with a particular focus on quantifying the influence of zinc addition. By examining phase transformation temperatures and calculating the activation energy for crystallization under varying cooling rates, this work seeks to deliver practical insights for tailoring alloy compositions and optimizing processing for modern soldering and manufacturing applications.

## **2. Experimental Work**

### **2.1. Materials and Alloy Preparation**

Two alloys with the nominal compositions Pb-5wt%Sn (referred to as Pb-5Sn) and Pb-5wt%Sn-2wt%Zn (referred to as Pb-5Sn-2Zn) were prepared for this study. High-purity primary metals (99.999%) of lead, tin, and zinc were used. Precisely weighed amounts of the constituent metals were placed in a graphite crucible within a furnace. The melt was maintained at a temperature of 700 °C for 20 minutes with mechanical stirring to ensure complete chemical homogeneity. The melt was then cast into steel molds filled with paraffin oil to prevent air exposure during casting and was left to cool to room temperature. Subsequently, the as-cast alloys were treated at 438 K for 50 hours.

### **2.2. Differential Scanning Calorimetry (DSC)**

Differential Scanning Calorimetry (DSC) analysis was performed using a Labsys Evo thermal analyzer under a continuous flow of high-purity argon to prevent oxidation during heating. The samples, weighing approximately 40 mg, were placed in alumina crucibles. The melting and crystallization temperatures were recorded from the endothermic and exothermic peaks during the heating and cooling cycles, respectively. Each thermal cycle was repeated three times to ensure experimental reproducibility, and the deviation of the measured peak temperatures was within  $\pm 0.8$  °C. The applied heating and cooling rates were 5, 10, 15, and 25 °C min<sup>-1</sup>, ensuring consistency across all measurements. This approach allowed for an accurate evaluation of thermal transitions and minimized uncertainty in determining the onset and peak temperatures. The activation energy ( $E_a$ ) associated with the crystallization process was estimated based on the Kissinger method.

## **3. Results and Discussion**

### **3.1. Analysis of the Differential Scanning Calorimetry (DSC) Curves**

The DSC thermograms for both the Pb-5Sn and Pb-5Sn-2Zn alloys are presented in Figures 1 and 2, respectively. Figures 1(a) and 2(a) clearly show the presence of two main phase transformations for each alloy. The first transformation is an endothermic peak, directed downwards, which corresponds to the melting process during the heating cycle. The second transformation is an exothermic peak, directed upwards, which is attributed to the crystallization process during the cooling cycle. This behavior is the typical thermal signature of crystalline materials undergoing melting and solidification.

### 3.2. Influence of Thermal Rate on Melting and Crystallization Kinetics

Figures 1(b) and 2(b) focus on the melting peaks. A systematic shift in the melting peak temperature towards higher values is observed with an increasing heating rate ( $\beta$ ). For example, in Figure 1(b), the melting peak at a rate of 25 °C/min occurs at a higher temperature than that at 5 °C/min. This phenomenon is a known kinetic effect attributed to the thermal lag between the heating source (the furnace) and the sample. At higher rates, the system requires more time to reach thermal equilibrium, leading to the peak being recorded at an apparently higher temperature. Conversely, an opposite kinetic effect is observed during the cooling cycle. The upper portions of the curves in Figures 1(a) and 2(a) show a strong dependence of the crystallization process on the cooling rate. The crystallization peak temperature shifts significantly towards lower temperatures as the cooling rate increases. This effect is the essence of kinetic studies. The crystallization process requires a thermodynamic driving force in the form of undercooling to initiate. The higher the cooling rate, the shorter the time available for the formation and growth of crystalline nuclei, and thus the system requires a greater degree of undercooling (i.e., a lower temperature) to stimulate the solidification process, which explains this large shift.

### 3.3. Effect of Zinc Addition

By comparing Figure 1(b) with Figure 2(b), it can be observed that the addition of 2% zinc leads to a slight decrease in the melting temperature. The melting peak for the Pb-5Sn-2Zn alloy occurs at slightly lower temperatures than that of the Pb-5Sn alloy at the same heating rates. This indicates that zinc alters the phase equilibrium diagram of the Pb-Sn system, shifting the composition towards a region with a lower melting temperature. When comparing the crystallization peaks (in Figures 1(a) and 2(a)), it is found that the addition of zinc significantly alters the solidification kinetics. By comparing Figure 1(b) with Figure 2(b), it can be observed that the addition of 2% zinc leads to a slight decrease in the melting temperature. The melting peak for the Pb-5Sn-2Zn alloy occurs at slightly lower temperatures than that of the Pb-5Sn alloy at the same heating rates. This indicates that zinc alters the phase equilibrium diagram of the Pb-Sn system, shifting the composition towards a region with a lower melting temperature. When comparing the crystallization peaks (in Figures 1(a) and 2(a)), it is found that the addition of zinc significantly alters the solidification kinetics.

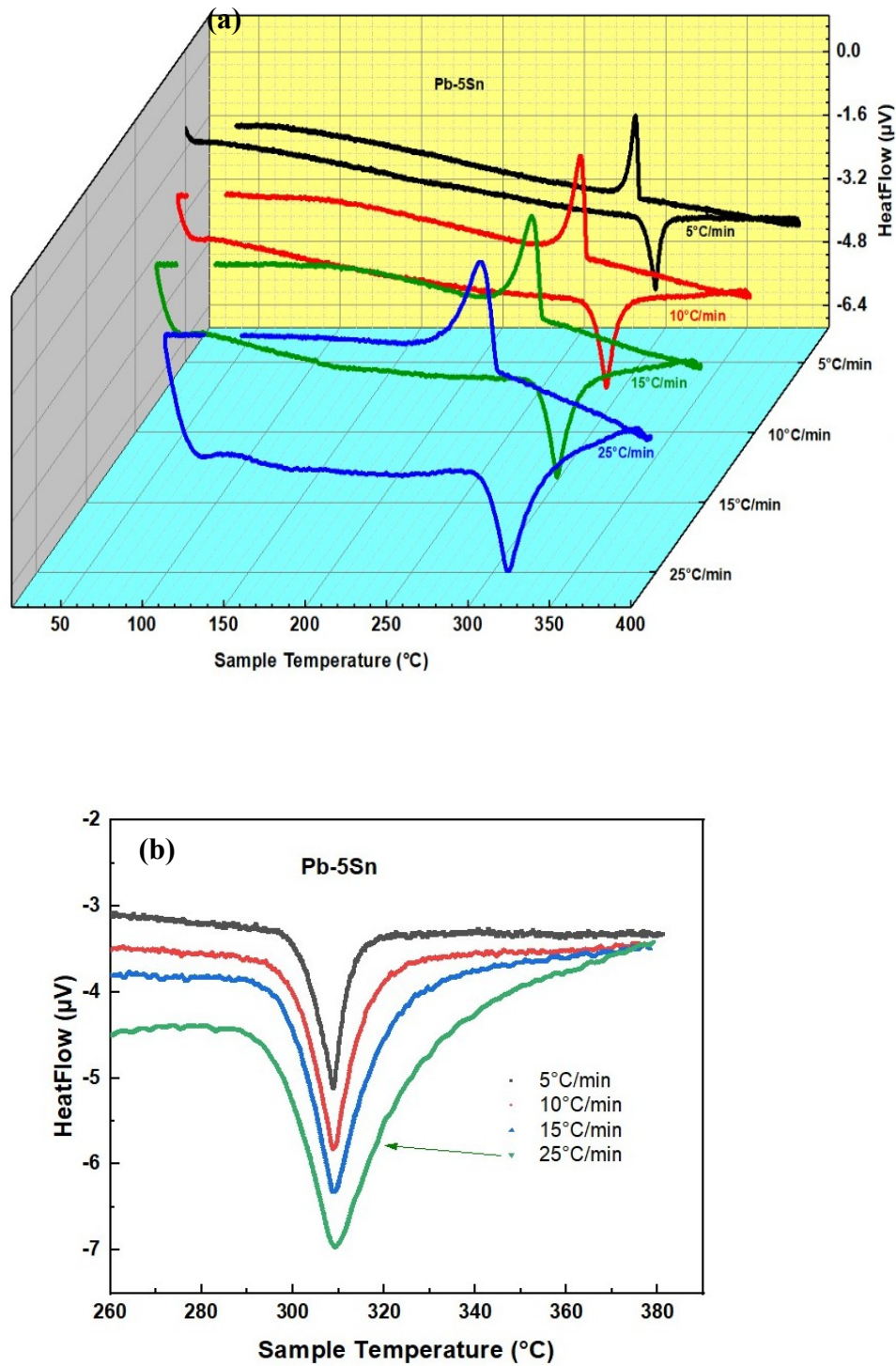


Figure 1. DSC curves for the Pb-5Sn alloy: (a) plot showing full heating and cooling cycles at rates of 5, 10, 15, and 25 °C/min; (b) Detailed view of the endothermic melting peaks at different heating rates.

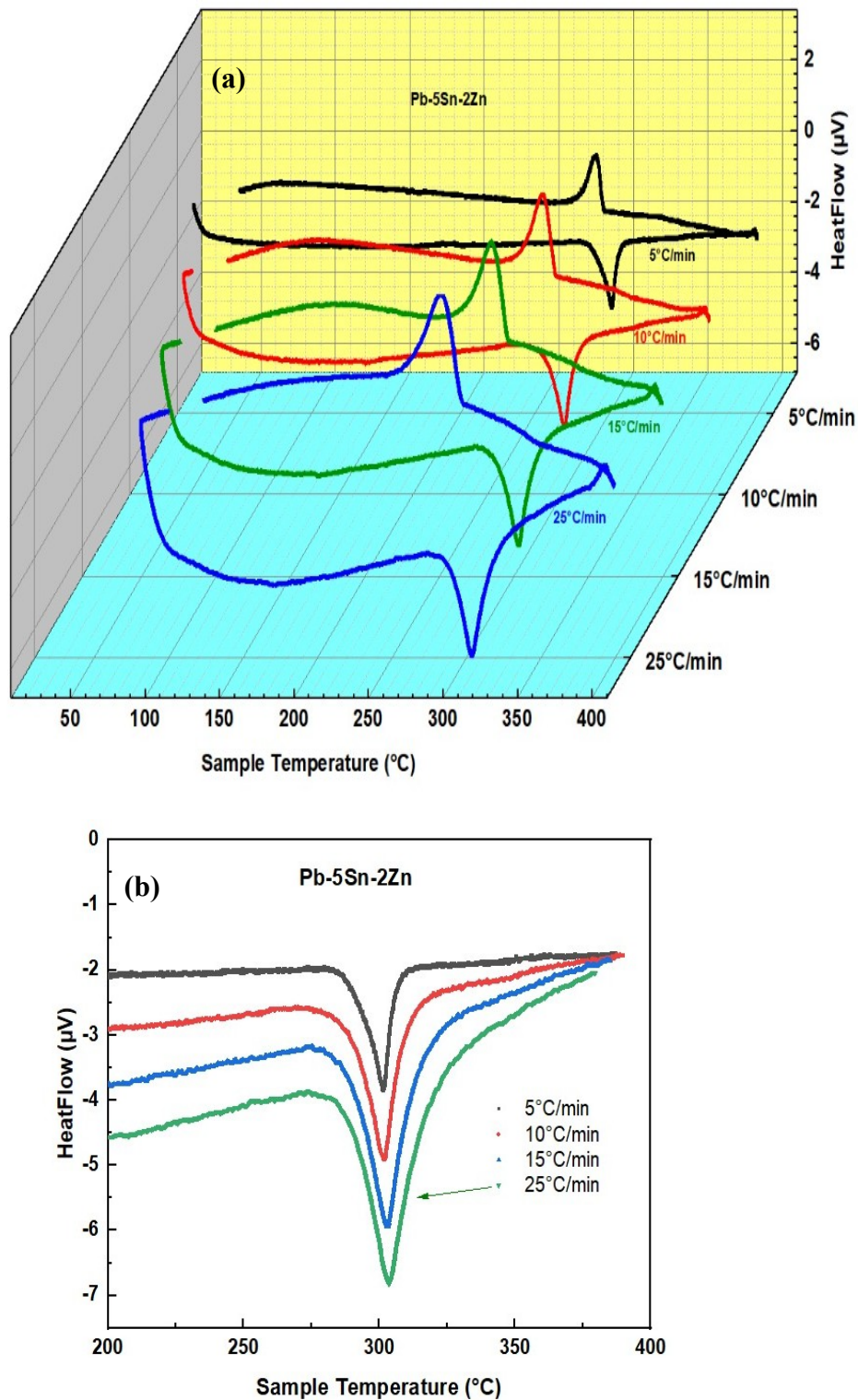


Figure 2. DSC curves for the Pb-5Sn-2Zn alloy: (a) plot showing full heating and cooling cycles at rates of 5, 10, 15, and 25 °C/min; (b) Detailed view of the endothermic melting peaks at different heating rates.

A direct visual comparison of the curves (Figure 3a) shows that the addition of zinc fundamentally alters the thermal response, shifting the melting and crystallization events towards lower temperatures. This conclusion is quantitatively confirmed in Figure 3(b), which illustrates that the melting temperature of the Pb-5Sn-2Zn alloy is consistently about 5-6 °C lower than the base alloy across all heating rates. This decrease in the melting temperature is a thermodynamic effect, reflecting a modification in the phase equilibrium diagram of the Pb-Sn-Zn system, whereas the slight increase in melting temperature with an increasing heating rate in both alloys is an expected result of thermal lag. Regarding the crystallization behavior, a more pronounced kinetic effect is observed, where the crystallization temperature sharply decreases with an increasing cooling rate for both alloys, confirming that the solidification process requires a driving force in the form of undercooling to initiate. The addition of zinc also significantly lowers the crystallization temperatures. This behavior is consistent with findings reported in the literature [18, 19].

### 3.2. Kissinger Analysis of the Activation Energy for the Crystallization Process

Data was extracted from experimental measurements and organized in the Table 1, which shows the crystallization temperatures at different cooling rates ( $\beta$ ). A comprehensive analysis of the experimental data related to the crystallization of two alloys, Pb-5Sn and Pb-5Sn-2Zn, is presented. The objective is to calculate the activation energy ( $E_a$ ) for the crystallization process of each alloy using the Kissinger method and to analyze the effect of zinc (Zn) addition on this property. The Kissinger method is based on the following linear relationship [20].

$$\ln\left(\frac{\beta}{T_p^2}\right) = -\frac{E_a}{(R \times T_p)} + C ,$$

Where  $T_p$  represents the absolute crystallization temperature (in Kelvin). The necessary variables for applying linear regression were calculated for each alloy.



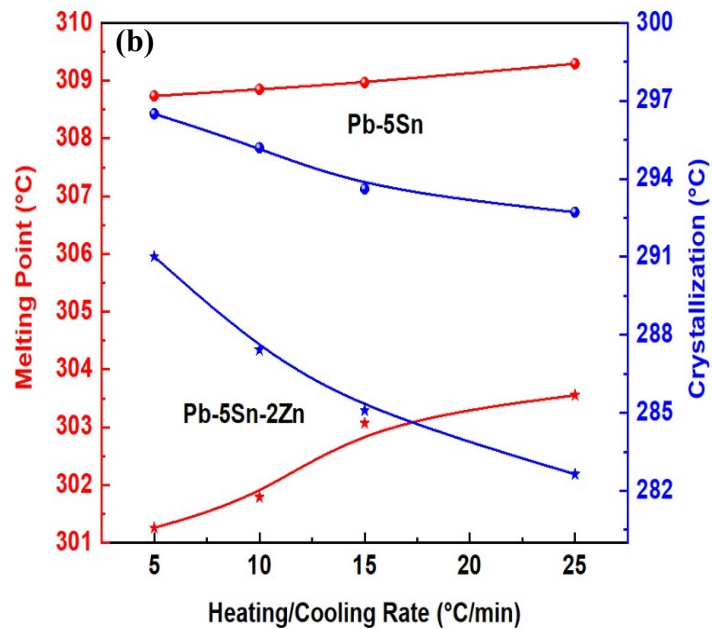
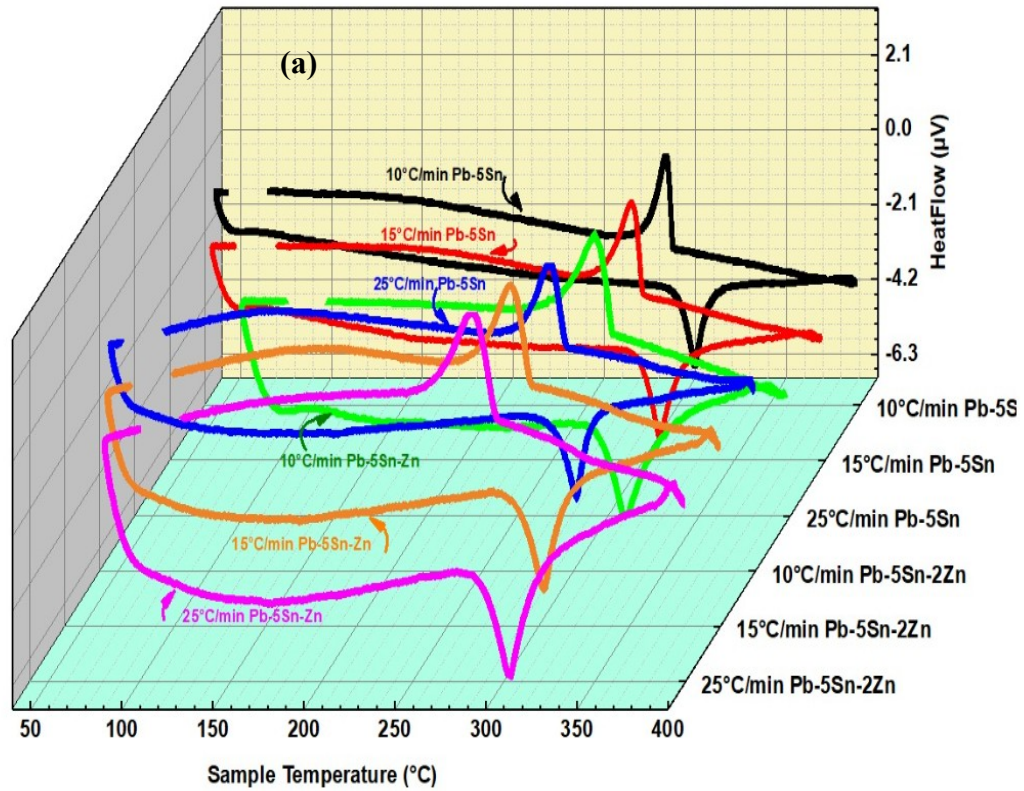


Figure 3. Comparative thermal analysis of Pb-5Sn and Pb-5Sn-2Zn alloys: (a) DSC plot showing the full thermal cycles for both alloys at different rates, directly comparing their endothermic and exothermic responses; (b) Variation of melting point (left axis) and crystallization temperature (right axis) as a function of the heating/cooling rate.

Table 1: Kissinger Method Calculation Data for Determining Activation Energy.

Alloy	$\beta$ ( $^{\circ}\text{C}/\text{min}$ )	$T_p$ (K)	$1/T_p$ ( $\text{K}^{-1}$ )	$\ln(\beta/T_p^2)$
Pb-5Sn	5	569.655	0.0017555	-10.992
	10	568.346	0.0017595	-10.380
	15	566.767	0.0017644	-10.002
	25	565.869	0.0017672	-9.516
Pb-5Sn-2Zn	5	564.157	0.0017726	-11.082
	10	560.567	0.0017839	-10.370
	15	558.237	0.0017914	-9.998
	25	555.786	0.0017993	-9.519

The relationship between  $\ln(\beta/T_p^2)$  and  $1/T_p$  was plotted for each alloy as shown in figure 4. The slope of the resulting straight line ( $m$ ) is related to the activation energy ( $E_a$ ) by the equation  $E_a = -m \times R$ , where  $R$  is the universal gas constant ( $8.314 \text{ J/mol}\cdot\text{K}$ ). The results yielded an activation energy ( $E_a$ ) of  $103.54 \text{ kJ/mol}$  for the Pb-5Sn alloy and an activation energy ( $E_a$ ) of  $57.93 \text{ kJ/mol}$  for the Pb-5Sn-2Zn alloy. The linear regression results showed excellent data fit, with  $R^2$  values of  $0.989$  for the Pb-5Sn alloy and  $0.999$  for the Pb-5Sn-2Zn alloy.

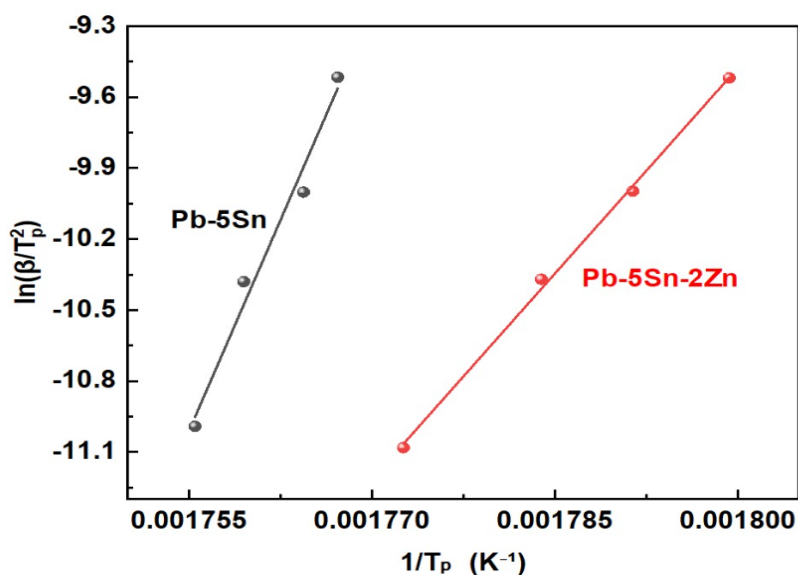


Figure 4. Kissinger plots  $\ln(\beta/T_p^2)$  vs  $1/T_p$  used to estimate the crystallization activation energy for Pb-5Sn and Pb-

The results clearly show that the activation energy for the crystallization process in the Pb-5Sn alloy (103.54 kJ/mol) is significantly higher than that of the Pb-5Sn-2Zn alloy (57.93 kJ/mol). This considerable decrease in activation energy indicates that the addition of 2% zinc (Zn) to the lead-tin alloy significantly facilitates the crystallization process. This can be explained by the possibility that zinc atoms act as effective nucleation sites, which lowers the energy barrier required for the initiation of crystal formation during the alloy's cooling. This means the zinc-containing alloy requires less energy to transition from the liquid (or amorphous) state to the stable crystalline state, making the crystallization process faster and easier. Upon reviewing scientific literature, it is found that the activation energy values for lead-tin alloys vary depending on the precise composition and experimental conditions. For example, these values can be affected by the presence of other elements or by the heating and cooling rates used [21, 22]. In general, adding a third element to a binary alloy can significantly alter the kinetics of the crystallization process. Studies on other alloys, such as magnesium-zinc alloys, have shown that the addition of elements like platinum or silver changes the activation energy and enhances thermal stability [23-24]. Similarly, in other systems, it has been observed that the addition of extra elements can either facilitate or hinder the crystallization process.

#### **4. Conclusion**

In this study, the influence of adding 2 wt.% zinc (Zn) on the thermal properties and crystallization kinetics of a Pb-5Sn solder alloy was successfully investigated using Differential Scanning Calorimetry (DSC) at various cooling and heating rates. The following key conclusions have been drawn:

1. The addition of zinc demonstrated a twofold effect on the alloy's thermal properties; it led to a significant decrease in both the melting temperature (by approx. 5–6 °C) and the crystallization temperature across all tested rates. This indicates that zinc not only alters the thermodynamic equilibrium of the system but also significantly influences the kinetics of the solidification process.
2. The analysis of crystallization kinetics using the Kissinger method proved that zinc addition drastically lowers the apparent activation energy for crystallization ( $E_a$ ). The value decreased from 103.54 kJ/mol for the base Pb-5Sn alloy to 57.93 kJ/mol for the modified Pb-5Sn-2Zn alloy, a reduction of approximately 44%.
3. This substantial reduction in the energy barrier is attributed to the role of zinc atoms acting as effective heterogeneous nucleation sites within the melt. These sites facilitate the onset of solidification by providing favorable low-energy surfaces for the formation of crystalline nuclei, thereby significantly lowering the energy required to activate the crystallization process.



4. The results confirm that minor zinc additions effectively modify the solidification of Pb-Sn alloys by facilitating nucleation, which is key to refining the microstructure and enhancing mechanical properties. These insights can be used to optimize thermal processing in industrial applications, such as reflow soldering. Future work should investigate different zinc concentrations and perform mechanical analysis to fully correlate kinetic changes with structural performance.

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## A Comparative Analysis of Methodologies for Oscillation Theory in Parabolic Partial Differential Equations

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### Abstract

This paper presents a comprehensive review, from 1986 to 2001, of the literature concerning the oscillatory behavior of solutions to parabolic partial differential equations with deviating arguments. We focus on the development of criteria for oscillation, highlighting the effects of discrete and continuous distributed delays, nonlinearities, forcing terms, and various boundary conditions. The review synthesizes methodologies commonly employed in the field, such as the reduction to ordinary differential inequalities and the use of integral averaging techniques. Finally, we emphasize current trends and suggest potential directions for future research.

**Keywords:** Oscillation; Parabolic equation; Deviating arguments.

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## 1. Introduction

The study of oscillatory behavior in differential equations has a rich history dating back to the pioneering work of Sturm in the 19th century on the zeros of solutions to ordinary differential equations. Classical oscillation theory for ordinary differential equations has been extensively developed over the past century, with comprehensive results established for various classes of equations including linear, nonlinear, delay, and functional differential equations. The fundamental questions addressed by oscillation theory whether all solutions exhibit persistent sign changes and under what conditions such behavior occurs have profound implications for understanding the long-term dynamics of systems modeled by differential equations.

The oscillatory behavior of solutions to differential equations has been a subject of significant attention and has motivated extensive literature over the years [2, 8, 12, 16]. Because partial differential equations are key to modeling phenomena in science and engineering, there is a growing interest in studying their oscillatory behavior. We refer the reader to [7, 11, 13, 15, 26, 27, 29, 30, 36, 37] for parabolic equations and to [4, 14, 17–20, 23, 24, 28, 32, 34, 38] for hyperbolic equations.

In recent decades, there has been a significant extension of oscillation theory from integer to arbitrary order differential equations [1, 3, 5, 6, 9, 10, 21, 22, 25, 35], particularly for parabolic-type equations with deviating arguments. This extension represents a natural but challenging progression, as it requires addressing the additional complexities introduced by spatial variables, boundary conditions, and the interplay between temporal and spatial behaviors. The transition from ODEs to PDEs in oscillation theory has necessitated the development of new methodological approaches that can handle the infinite-dimensional nature of the problem while preserving the core philosophical framework of classical oscillation theory.

The extension to partial differential equations has been particularly fruitful for parabolic equations, where the maximum principle and spectral properties provide powerful tools for analysis. Researchers have successfully adapted techniques from ODE oscillation theory while developing novel approaches specific to the PDE context. The eigenfunction method, which reduces the spatial problem to a temporal one through integration against appropriate test functions, has emerged as a particularly effective strategy that bridges the finite and infinite-dimensional theories.

The study of oscillatory behavior in parabolic differential equations is of paramount importance in applied mathematics and theoretical analysis as oscillations are intrinsically linked to the stability of equilibrium solutions. A non-oscillatory solution converging to an equilibrium typically indicates asymptotic stability. In contrast, persistent oscillations can signify instabil-

ity, the existence of limit cycles, or Hopf bifurcations, where a stable equilibrium loses stability and gives rise to a periodic orbit. Determining oscillation criteria is often a more general and powerful method than directly solving the nonlinear equation.

Understanding oscillatory behavior is a fundamental aspect of predicting the long-term dynamics, stability, and real-world manifestations of complex systems modeled by PDEs.

A solution  $u(x, t)$  of a boundary value problem for an FPDE is said to be oscillatory in the domain  $\Omega \times \mathbb{R}_+$  if for every positive number  $T > 0$ , there exists a point  $(x_0, t_0) \in \Omega \times [T, \infty)$  such that  $u(x_0, t_0) = 0$ .

Conversely, a solution is called nonoscillatory if there exists a  $T > 0$  such that  $u(x, t) \neq 0$  for all  $(x, t) \in \Omega \times [T, \infty)$ . That is, the solution has a fixed sign (either positive or negative) for all sufficiently large time  $t$  and all points  $x$  in the spatial domain  $\Omega$ .

This review focuses specifically on six seminal works that represent key milestones in the development of oscillation theory for parabolic partial differential equations with deviating arguments. The selected articles were chosen according to the following criteria:

1. Methodological Significance, as each paper significantly develops important technical approaches that have become standard in the field.
2. Chronological Progression. The selection spans the development of the field from its foundations to more recent advances, showing the evolution of ideas and techniques.
3. Comprehensive Coverage as the chosen works address the main types of equations studied in this area—nonlinear equations, forced oscillations, distributed delays, neutral equations, and mixed functional arguments.
4. Boundary Condition Variety. The collection includes results for all major boundary conditions: Dirichlet, Neumann, and Robin problems.
5. Theoretical Influence. Each paper has been highly influential, generating subsequent research and establishing directions for further development.

The papers by Yoshida (1986, 1987) form the foundation of the modern approach, establishing the eigenfunction reduction technique for equations with discrete delays. Fu and Zhang (1995) extend this framework to distributed delays using Stieltjes integrals, while Cui and Li (1998) provide the important advancement of necessary and sufficient conditions. The work by Wang and Ge (2000) addresses increasingly complex equation structures, including mixed delays. Finally, Tanaka and Yoshida (1997) represent a sophisticated treatment of multiple deviating arguments with forcing terms.

This review systematically analyzes these key contributions, examining their methodological approaches, main results, and interconnections. By understanding the development captured in these works, we can appreciate both the current state of oscillation theory for parabolic PDEs and identify promising directions for future research. The following sections provide detailed analysis of each work, comparative assessment of methodologies, and discussion of open problems that remain challenging for the field.

## 2. Oscillation under different Boundary Conditions

In his work [36], Yoshida establishes oscillation criteria for solutions to certain classes of nonlinear parabolic partial differential equations (PDEs) that include deviating arguments of the form:

$$(E_-) \quad u_t = a(t)\Delta u - q(x, t)f(u(x, \sigma(t))), \quad (x, t) \in \Omega \times \mathbb{R}_+,$$

$$(E_+) \quad u_t = a(t)\Delta u + q(x, t)f(u(x, \tau(t))), \quad (x, t) \in \Omega \times \mathbb{R}_+,$$

where:

- $\Delta$  is the Laplacian,
- $\Omega \subset \mathbb{R}^n$  is a bounded domain with piecewise smooth boundary,
- $a(t), q(x, t), f(s), \sigma(t), \tau(t)$  satisfy certain regularity and sign conditions (Assumptions A-I – A-VI).

by reducing the oscillation problem to the study of first-order ODE inequalities. By combining spectral theory, integral inequalities, and known ODE results, Yoshida provides verifiable criteria for oscillation or decay of solutions under various boundary conditions.

Yoshida then studied the oscillatory behavior of solutions to nonlinear parabolic partial differential equations (PDEs) with forcing terms and functional arguments in [37]. The main equation considered is:

$$u_t - a(t)\Delta u + c(x, t, u(x, t), u(x, \sigma(t))) = f(x, t), \quad (x, t) \in \Omega \times \mathbb{R}_+,$$

where: -  $\Delta$  is the Laplacian, -  $\Omega \subset \mathbb{R}^n$  is a bounded domain with smooth boundary, -  $a(t), c, f, \sigma(t)$  satisfy certain regularity and sign conditions (Assumptions  $A_1$ – $A_3$ ).

By combining eigenfunction techniques, integration methods, and limiting conditions on the forcing term  $f(x, t)$ , effective criteria for forced oscillation under various boundary conditions were established.

Fu et al. [11], focused on studying the oscillatory behavior of solutions to the a nonlinear parabolic equation with a continuous distributed deviating argument and a forcing term:

$$u_t = a(t)\Delta u - \int_a^b q(x, t, \xi)F[u(x, g(t, \xi))]d\sigma(\xi) + h(x, t), \quad (x, t) \in \Omega \times (R)_+ \quad (1)$$

where:

- $\Omega \subset (R)^n$  is a bounded domain with piecewise smooth boundary  $\partial\Omega$ .
- $(R)_+ = [0, +\infty)$ .
- $a(t) \in C((R)_+, (R)_+)$ ,  $q(x, t, \xi) \in C(\bar{\Omega} \times (R)_+ \times [a, b], (R)_+)$ .
- $F(u) \in C((R), (R))$ .
- $g(t, \xi) \in C((R)_+ \times [a, b], (R))$ ,  $g(t, \xi) \leq t$ , nondecreasing in  $t$  and  $\xi$ , with  $\lim_{t \rightarrow +\infty} \min_{\xi \in [a, b]} g(t, \xi) = +\infty$ .
- $\sigma(\xi)$  is nondecreasing; the integral is a Stieltjes integral.
- $h(x, t) \in C(\bar{\Omega} \times (R)_+, (R))$  is the forcing term.

The analysis is conducted under three types of boundary conditions:

$$\begin{aligned} \text{(B1)} \quad & u = \varphi, \quad (x, t) \in \partial\Omega \times (R)_+ \\ \text{(B2)} \quad & \frac{\partial u}{\partial N} = \psi, \quad (x, t) \in \partial\Omega \times (R)_+ \\ \text{(B3)} \quad & \frac{\partial u}{\partial N} + \mu u = 0, \quad (x, t) \in \partial\Omega \times (R)_+ \end{aligned}$$

where  $N$  is the unit exterior normal, and  $\varphi, \psi, \mu$  are given continuous functions. This work generalizes the results of Yoshida on forced oscillation by considering: continuous distributed deviating arguments and non-homogeneous boundary conditions.

In 1998, Bao Tong Cui and Wei Nian Li extended the oscillation theory for partial differential equations to the oscillatory behavior for parabolic equations with multiple delays of the form

$$\frac{\partial}{\partial t}u(x, t) = a(t)\Delta u(x, t) + \sum_{k=1}^s a_k(t)\Delta u(x, t - \rho_k(t)) - \sum_{j=1}^m q_j(t)u(x, t - \sigma_j(t))$$

where  $(x, t) \in \Omega \times [0, \infty) \equiv G$ ,  $\Omega$  is a bounded domain in  $\mathbb{R}^n$  with piecewise smooth boundary  $\partial\Omega$ , and  $\Delta$  is the Laplacian operator.

The equation is considered with the Dirichlet boundary condition:

$$u(x, t) = 0, \quad (x, t) \in \partial\Omega \times [0, \infty)$$



The proof was based on the spectral properties of the Laplacian operator some results on oscillation of delay differential equations along with Green's formula and boundary conditions.

Peiguang Wang and Weigao Ge [29], Extended these previous work to include both discrete and distributed deviating arguments along with Considering three different boundary conditions:

$$u_t = a(t)\Delta u + \sum_{i=1}^n a_i(t)\Delta u(x, \tau_i(t)) - p(x, t)u - \int_a^b q(x, t, \xi)f(u[x, g(t, \xi)])d\sigma(\xi) + h(x, t) \quad (2)$$

where  $(x, t) \in \Omega \times (R)_+$ , with three types of boundary conditions:

$$(B1) \quad u = \varphi(x, t), \quad (x, t) \in \partial\Omega \times (R)_+$$

$$(B2) \quad \frac{\partial u}{\partial n} = \psi(x, t), \quad (x, t) \in \partial\Omega \times (R)_+$$

$$(B3) \quad \frac{\partial u}{\partial n} + \nu(x, t)u = 0, \quad (x, t) \in \partial\Omega \times (R)_+$$

The authors employed Eigenfunction methods for Dirichlet problems, Green's formulas and Jensen's inequality and Reduction to functional differential inequalities.

After that, Peiguang Wang investigated the oscillatory properties of solutions to a class of parabolic partial functional differential equations parabolic functional DEs with continuous deviating arguments and distributed deviating arguments. extending previous results that primarily focused on equations with discrete delays. The central object of study is the equation:

$$\frac{\partial}{\partial t} [u(x, t) + \lambda(t)u(x, \tau(t))] = a(t)\Delta u - c(x, t, u) - \int_a^b q(x, t, \xi)u[x, g(t, \xi)]d\sigma(\xi) + f(x, t),$$

for  $(x, t) \in \Omega \times \mathbb{R}_+$ , where  $\Omega \subset \mathbb{R}^n$  is a bounded domain. This equation incorporates a neutral term  $(\lambda(t)u(x, \tau(t)))$ , a distributed delay over a continuum  $[a, b]$  (modeled by a Stieltjes integral), and a nonlinearity  $c(x, t, u)$ .

The core methodological approach involves reducing the multi-dimensional PDE problem to a one-dimensional oscillatory problem for functional differential inequalities. Table 1 bellow summarize the different approaches of the studied papers:

Table 1: Comparison of oscillatory criteria for parabolic PDEs with deviating arguments

Reference	Equation Type	Key Assumptions	Oscillation Criteria
Yoshida (1986)	Nonlinear, Discrete Delay (No forcing)	$f(s)$ is convex; $\sigma(t), \tau(t) \leq t$	Reduction to first-order ODE inequalities of the form $y'(t) \pm Q(t)G(t)f_2(y(g(t))) \leq 0$ has no eventually positive solutions. Explicit integral conditions (e.g., $\int Q(t)dt = \infty$ ).
Yoshida (1987)	Nonlinear, Forced, Discrete Delay	Standard regularity on coefficients and delays.	$\liminf \int \tilde{H}(t)dt = -\infty$ , $\limsup \int \tilde{H}(t)dt = +\infty$ , where $\tilde{H}(t)$ incorporates the forcing $f(x, t)$ and boundary data ( $\phi$ or $\psi$ ).

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Reference	Equation Type	Key Assumptions	Oscillation Criteria
Fu & Zhang (1995)	Nonlinear, Forced, Distributed Delay	$F$ convex, odd; $g(t, \xi) \leq t$ , non-decreasing; $\sigma(\xi)$ nondecreasing.	Differential inequalities (I1, I2) have no eventually positive solution. For (B1): $\liminf \int H(t)dt = -\infty$ , $\limsup \int H(t)dt = +\infty$ ( $H(t)$ includes forcing and boundary data).
Cui & Li (1998)	Linear, Multiple Discrete Delays (No forcing)	Dirichlet boundary condition ( $u = 0$ ).	A necessary and sufficient condition: The associated delay differential inequality $V'(t) + \alpha_0 a(t)V(t) + \dots \leq 0$ has no eventually positive solution.

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Table 1 – continued from previous page

Reference	Equation Type	Key Assumptions	Oscillation Criteria
Wang & Ge (2000)	Nonlinear, Forced, Mixed Delays (Discrete + Distributed)	$f$ convex, odd; $\tau_i(t) \leq t$ , both $t, g(t, \xi) \leq t$ , both nondecreasing.	Associated differential inequality has no eventually positive solution. For (B1): $\liminf \int H(s)ds = -\infty$ , $\limsup \int H(s)ds = +\infty$ ( $H(s)$ includes forcing and boundary data).

### 3. Comparative analysis and methodologies

The reviewed literature demonstrates a clear evolution in the study of oscillation criteria for parabolic partial differential equations with deviating arguments. The development can be analyzed through several dimensions:

#### 3.1. Chronological development of techniques

- **Yoshida (1986)** established the foundational approach by reducing PDE problems to ordinary differential inequalities, focusing on discrete delays without forcing terms.
- **Yoshida (1987)** extended this framework to include forcing terms, introducing limit conditions on integrals of the transformed forcing function.
- **Fu & Zhang (1995)** generalized the theory to distributed delays using Stieltjes integrals, significantly expanding the class of admissible functional arguments.
- **Cui & Li (1998)** provided the first necessary and sufficient conditions for oscillation, specifically for linear equations with multiple discrete delays.
- **Wang & Ge (2000)** combined discrete and distributed delays in a unified framework, while also incorporating more complex boundary conditions.

- **Wang (2001)** addressed neutral-type equations, representing the most complex functional form among the reviewed works.

## Methodology

The progression shows a movement from:

- Simple to complex functional arguments (discrete  $\rightarrow$  distributed  $\rightarrow$  mixed  $\rightarrow$  neutral)
- Homogeneous to non-homogeneous equations (unforced  $\rightarrow$  forced)
- Sufficient conditions to necessary and sufficient conditions
- Simple to complex boundary conditions (Dirichlet  $\rightarrow$  Neumann  $\rightarrow$  Robin)

## Methodological approaches

All studies employ a similar reductionist approach with the following core components: Eigenfunction Reduction Technique that involves:

$$U(t) = \frac{\int_{\Omega} u(x, t) \Phi(x) dx}{\int_{\Omega} \Phi(x) dx}$$

where  $\Phi(x)$  is the first eigenfunction of the Laplacian operator for the corresponding boundary value problem. This transformation reduces the spatial PDE to a temporal functional differential inequality.

Green's Formula Application to handle the Laplacian term:

$$\int_{\Omega} \Delta u \cdot \Phi dx = \int_{\Omega} u \cdot \Delta \Phi dx + \text{boundary terms}$$

This step is crucial for incorporating boundary conditions into the resulting ordinary differential inequality.

Jensen's Inequality For nonlinear problems employed to handle convex nonlinearities:

$$f\left(\frac{1}{|\Omega|} \int_{\Omega} u dx\right) \leq \frac{1}{|\Omega|} \int_{\Omega} f(u) dx$$

This allows the treatment of nonlinear terms in the reduced inequality.

Variations in Methodological Approach:

Table 2: Methodological variations across studies

Study	Equation Type	Methodological Innovations
Yoshida (1986)	Nonlinear, discrete delay	Established the basic eigenfunction reduction framework for delay parabolic equations
Yoshida (1987)	Forced, discrete delay	Incorporated forcing terms through limit conditions on $\int G(t)dt$
Fu & Zhang (1995)	Distributed delay	Extended methodology to Stieltjes integrals for continuous delay distributions
Cui & Li (1998)	Multiple delays	Developed techniques for necessary and sufficient conditions
Wang & Ge (2000)	Mixed delays	Combined discrete and distributed delay treatment in unified framework

#### 4. Open problems and future research directions

From this analysis, several promising research directions and open problems emerge. As Current theories predominantly assume convex nonlinearities applying Jensen's inequality, the extension to more general nonlinearities remains largely open. Also, finding alternatives to Jensen's inequality that preserve the reduction from PDE to ODE inequality. On the other hand few research focuses exclusively on higher order parabolic equations, so extension and further investigations remain open. The extension of the theory to almost periodic coefficients or Random coefficients is a good research direction

#### 5. Conclusion

The field of oscillation theory for parabolic PDEs with deviating arguments, while well-developed for certain classes of problems, presents numerous open challenges and research opportunities. The most promising directions appear to be: extending beyond convex nonlinearities, handling more complex functional structures, addressing systems and higher-order equations, and developing computational approaches and physical applications.

Future research in these directions would not only advance the theoretical foundations but also enhance the applicability of oscillation theory to concrete problems in science and engineering where delayed feedback and spatial diffusion interact to produce complex dynamics.

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## Digital Innovation Through NFTs: A Sustainable Transformation Framework for Saudi Arabia's Art Ecosystem

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### Abstract

This exploratory study examines <u>the perceived</u> challenges and opportunities for integrating NFTs into Saudi Arabia's art market and their alignment with Vision 2030. A mixed-methods design combined a quantitative survey (n = 66) with qualitative thematic analysis, primarily targeting digitally-engaged stakeholders. Participants were artists (48.5%), academics/researchers (21.2%), and technology professionals (16.7%). Findings <u>suggest</u> a large interest–implementation gap: 53.0% expressed interest in NFTs, but only 18.2% had created them. Cultural preservation was the leading motivation (68.2%). Barrier severity (Moderate+Major) was highest for market volatility (58.5%), technical complexity (56.9%), and cultural considerations (55.4%), followed by financial risks (50.8%) and regulatory uncertainty (43.1%). Priority support needs were technical training (77.3%) and legal consultation (68.2%). Emerging technology priorities were AI/ML (78.8%) and VR/AR (57.6%). These initial findings indicate that NFTs therefore align with Vision 2030's cultural and digital-economy goals, but progress requires a three-pronged framework: education and public awareness, enabling infrastructure and legal/regulatory mechanisms, and cross-sector partnerships.

**Keywords:** NFTs, Blockchain, Art Market ecosystem.

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## **1. Introduction**

Saudi Arabia's Vision 2030 has brought a new course towards the future based on cultural value, economic diversification, and digital technologies. Saudi Arabia's art market faces challenges such as a limited international reach, forgery concerns, and weak copyright protections. Blockchain-enabled NFTs offer new opportunities to secure ownership rights, integrate royalty models, and improve global market access for artists [1,2]. NFTs can help Saudi artists showcase their work globally while remaining true to their heritage. However, NFT integration also poses technical, market, and cultural challenges that must be addressed. From the qualitative perspective, this paper aims to discuss an exhaustive number of challenges and opportunities that Saudi Arabia could face after the integration of NFTs into its art environment, as well as develop a phased approach to the integration of NFTs into the Saudi Arabian art environment with reference to the Vision 2030 initiative [11].

### **1.1. Digital Transformation in Art Markets**

In recent years, the global art market has been rocked by digital change on all fronts: blockchain, online platforms, and digital galleries. Such digital marketplaces like OpenSea and Rarible reduce reliance on traditional intermediaries like galleries and enabled artists to now speak to international buyers directly. And this level of shifting has enhanced transparency, streamlined transactions, and widened the markets [3,4]. Yet the art sector in Saudi Arabia is still in an early adoption phase and doesn't have many traditional galleries or major collectors open to hosting digital exhibitions. Although digital art has become more popular, the main issues in entering the Saudi market with NFTs are the resistance of the cultural environment, regulatory uncertainty, and technical obstacles preventing complete involvement in the digital economy. These dynamics define Saudi Arabia's early-stage adoption context and point to the need for targeted market, regulatory, and technical enablers.

### **1.2. NFTs and Blockchain Technology**

By design, NFTs rely on immutable blockchain ledgers that record provenance and ownership of unique digital assets [5]. See the ERC-721 NFT standard for the canonical interface [12, 13]. For artists, this decentralized system helps protect intellectual property and builds trust in digital art transactions. NFT platforms run on Ethereum, Tezos, Solana, and other blockchains, but high transaction costs and market volatility remain barriers to adoption [6].

While NFTs enable direct artist-to-collector sales, they also raise concerns about sustainability, fraud, and speculative pricing that have deterred some investors. Successful NFT integration in Saudi Arabia will require educating stakeholders on technical and regulatory aspects and fostering a cultural shift to support the Vision 2030 digital economy goals.

### 1.3. Saudi Vision 2030 Digital Goals

Creative industries are facilitated by cultural development under Saudi Arabia's Vision 2030 through innovative use of digital technologies. Examples include the government, the Misk Art Institute, and the Quality-of-Life Program, which lay the foundation for digital integration in the cultural sector. Through NFTs, the following can be achieved: digital registries of art, economic enfranchisement for artists, and greater international visibility. However, NFT transactions remain vulnerable to fraud [8]; to gain user confidence they require legal oversight, government incentives, and support from major institutions. Such partnerships can enhance NFT implementation, provided they comply with Saudi public and economic policies [7].

### 1.4. Cultural Preservation in the Digital Age

The advent of NFTs enables the preservation[9] and display of traditional Saudi and Islamic art, despite the limits of physical media. In addition, through digital ownership, artists can safeguard timeless treasures-such as historical manuscripts, Quranic calligraphy, and Islamic geometric designs-and deter unauthorized imitation worldwide. Some survey respondents feared a decline in traditional art; however, NFTs are more accurately described as digital certificates of authenticity, not replacements for the art itself. Cultural information is central to Saudi heritage, and artists can embed these narratives in NFT metadata to create an educational digital experience.

### 1.5. Digital Market Sustainability Framework

Due to the elevated energy demand of proof-of-work (PoW) blockchains, NFTs raise sustainability concerns. Ethereum's shift to proof-of-stake (PoS) and the use of more energy-efficient networks such as Polygon and Solana offer more sustainable options for NFT trading [10]. Post-Merge Ethereum reduced energy consumption by ~99.95% according to Ethereum Foundation and independent analyses [14]. This need for sustainable blockchains aligns with Saudi Arabia's focus on green technology and carbon-neutral projects. Selecting energy-efficient NFT systems and carbon-offset strategies supports digital advancement without undermining Saudi Arabia's environmental agenda and advances digital art responsibly.

## **2. Methodology**

### **2.1. Research Design**

This research uses a mixed-methods design: a quantitative questionnaire and qualitative thematic analysis to investigate NFT adoption in Saudi Arabia's art sector. Given that adoption is still at an early stage in the region, this approach assesses stakeholder preparedness, market enablers and constraints, and infrastructure needs. The theoretical framework aligns with Vision 2030's cultural and digital transformation objectives, ensuring actionable recommendations for policymakers, artists, and investors.

### **2.2. Data Collection and Survey Instrument**

To collect primary data, a bilingual (Arabic–English) survey was administered to 66 stakeholders, including artists, collectors, technologists, and gallery owners. The survey comprised eight sections covering: demographics, NFT knowledge, Vision 2030 alignment, technical infrastructure, market challenges, cultural preservation, and future development needs. Responses were gathered via Likert-scale ratings and multiple-choice items, along with open-ended prompts for qualitative insights. This multi-faceted instrument provided a well-rounded view of the feasibility of NFT adoption in the Saudi art market.

### **2.3. Sample Selection and Stakeholder Representation**

In this study, we used purposive sampling to recruit participants involved in Saudi Arabia's art and technology sectors. The sample comprised artists (~48%), academics/researchers (~21%), technology professionals (~17%), and a smaller share of gallery owners, collectors, and other stakeholders (~14%), providing triangulation across roles. Participants were invited through social networks, art platforms, and blockchain-related forums, including both offline and online communities. Despite the modest sample size, the study offers an indicative snapshot of NFT adoption in Saudi Arabia.

It is important, however, to acknowledge the limitations of this approach. The recruitment strategy, relying heavily on digital platforms and existing networks, likely resulted in a sample that is more digitally literate and already engaged with technology than the broader arts community. Consequently, the perspectives of traditional artists or stakeholders with limited digital access may be underrepresented. The findings should therefore be interpreted as reflecting the views of an early-adopter cohort, and caution should be exercised when generalizing them to the entire Saudi art ecosystem.

All participants provided informed consent; qualitative responses were thematically coded by two reviewers, with disagreements resolved by discussion.

### 3. Results and Analysis

#### 3.1 Demographic Profile

The survey collected feedback from 66 respondents-most of whom are part of Saudi Arabia's art community. Most respondents identified as artists (48.5%), followed by academic researchers (21.2%) and technology professionals (16.7%). Male participants slightly outnumbered females. The majority were in the 35–44 age group, reflecting mid-career professionals active in both traditional art and new media. Moreover, 57.6% of participants reported over 8 years of professional experience, indicating a generally seasoned cohort. Table 1 summarizes respondents' primary roles.

Table 1. Respondent primary roles (n=66).

Role	n	%
Artists	32	48.5
Academics/Researchers	14	21.2
Technology professionals	11	16.7
Gallery owners/managers	2	3.0
Other (designer, investor, student, etc.)	7	10.6

#### 3.2 Key Findings from the Survey

Regarding the participant's knowledge about NFTs, the survey presented the following outcomes: About 42.4% of respondents admitted having no knowledge of NFTs, 21.2% reported a moderate understanding, and only 10.6% considered themselves experts on the topic. Notably, 53% expressed interest in experimenting with NFTs despite limited exposure, indicating a perceived future potential for NFTs in the Saudi art market. Yet, only 18.2% had actually created an NFT, reflecting that hands-on adoption remains low so far. Figure 1 summarizes respondents' NFT experience and interest. Table 2 reports self-assessed knowledge levels. Figure 2 shows Vision 2030 alignment selections (multi-select).

Table 2. Knowledge of NFTs (n=66).

Knowledge level	n	%
No understanding	28	42.4
Basic	10	15.2
Moderate	14	21.2
Advanced	7	10.6
Expert	7	10.6

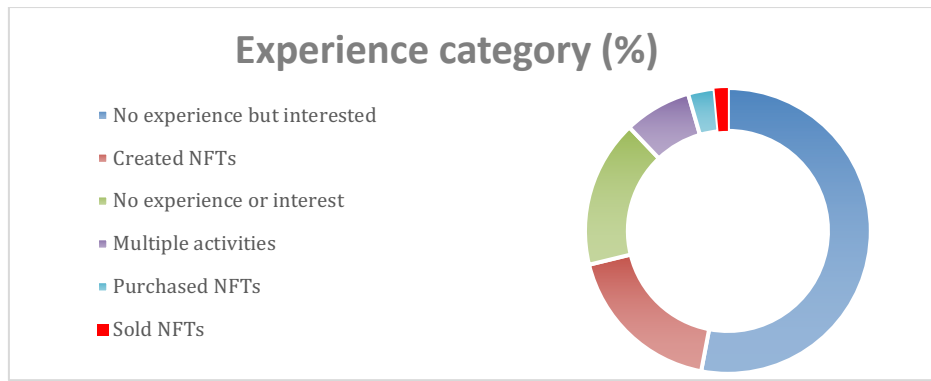


Figure 1. NFT experience and interest (n=66).

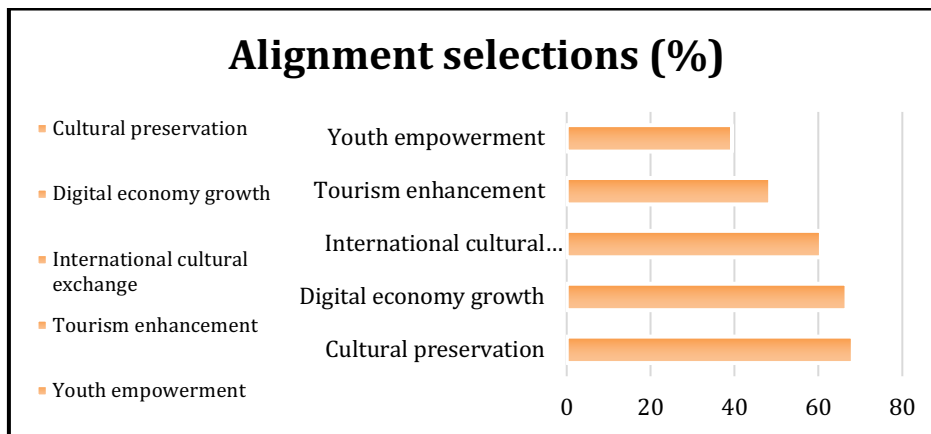


Figure 2. Vision 2030 alignment selections (n=66).

### 3.3 Statistical Analysis

According to the survey, 68.2% of participants identified cultural preservation as a key benefit of NFTs, and 66.7% supported NFT adoption as part of Vision 2030's digital economy development. About 40% saw NFTs as a means to promote youth empowerment, and 48.5% believed NFTs could help boost cultural tourism (for instance, through digital art exhibitions).

These findings indicate a strong alignment between the perceived benefits of NFTs and the goals of Saudi Vision 2030.

### 3.4 Comparative Analysis Across Professional Groups

To add analytical depth, we compared responses across the two largest professional groups: Artists (n=32) and Technology Professionals (n=11). This comparison reveals notable differences in perspectives and priorities.

- **Perceived Barriers:** While market volatility was a top concern for both groups, Artists were significantly more likely to rate technical complexity as a "Major" or "Severe" barrier (65%) compared to Technology Professionals (27%). Conversely, Technology Professionals were



more concerned with regulatory uncertainty (55% rated it as "Major" or "Severe") than Artists (35%).

\* Motivations for Adoption: The primary motivation for Artists was overwhelmingly new revenue streams (78%), followed by global market access (71.2%). For Technology Professionals, the leading motivation was technological innovation (82%), aligning with their professional interests.

These distinctions suggest that a one-size-fits-all approach to promoting NFT adoption will be ineffective. Artists require targeted technical training and user-friendly platforms, while technologists and investors need clearer regulatory frameworks to feel secure. Table 3 summarizes these key differences.

Table 3. Comparison of Key Perceptions: Artists vs. Technology Professionals.

Metric	Artists (n=32)	Technology Professionals (n=11)
Top Barrier	Technical Complexity (65%)	Regulatory Uncertainty (55%)
Top Motivation	New Revenue Streams (78%)	Technological Innovation (82%)

### 3.5 Stakeholder Readiness Assessment

Stakeholder readiness for NFTs in Saudi Arabia appears mixed. While 53% expressed interest in exploring NFTs, significant challenges remain in terms of infrastructure and platform availability. For instance, only 36.1% of respondents were familiar with local Saudi NFT marketplaces, and about 32.8% indicated a preference for using well-known international platforms like OpenSea. This suggests a need to develop and promote user-friendly local platforms. Moreover, 77.3% of respondents believed that technical training would facilitate NFT engagement – highlighting the importance of education and support to help stakeholders fully embrace the technology.

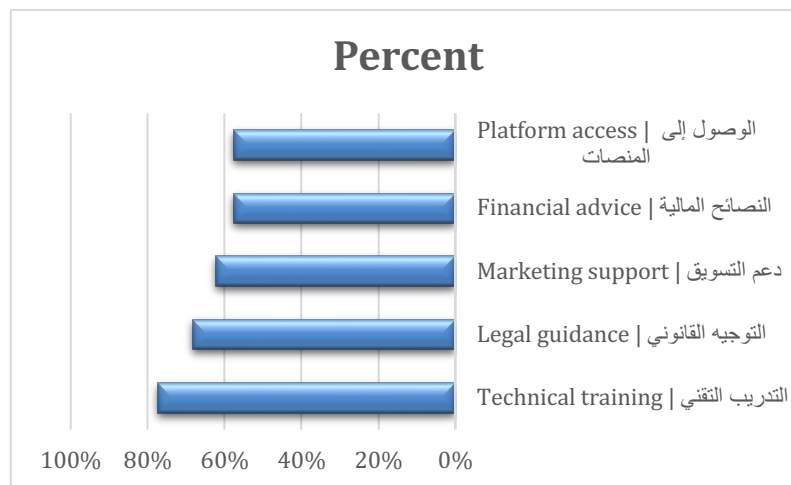


Figure 3. Support needs (n=66). Technical training 77.3%, legal guidance 68.2%, marketing support 62.1%, funding 57.6%, platform access 57.6%.

### 3.6 Implementation Challenges

Respondents highlighted several key challenges to NFT adoption (see Figure 4). Technical challenges were most frequently rated as a “moderate” barrier (by 44.6% of participants), and market volatility was also often rated a moderate barrier (36.9%). Meanwhile, 23.1% of participants viewed regulatory uncertainty as a “major” barrier impeding adoption. Respondents observed that the public has limited awareness of NFTs, indicating a need for broad educational and outreach efforts. Addressing these issues-technical infrastructure, market stability, legal clarity, and public awareness-is critical for positioning NFTs in the Saudi art market for sustainable growth.

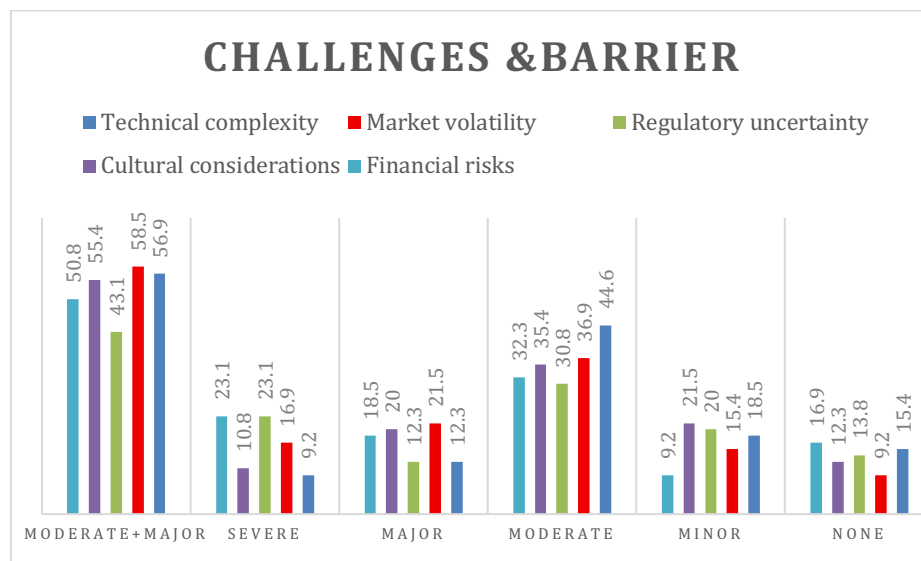


Figure 4. Challenges and barriers to NFT adoption (n=66). Severity distribution across five categories (None, Minor, Moderate, Major, Severe). Moderate+Major shares: market volatility 58.5%, technical complexity 56.9%, cultural considerations 55.4%, financial risks 50.8%, regulatory uncertainty 43.1%.

### 3.7 Opportunities Identified

Survey participants also identified several opportunities for NFTs in Saudi Arabia’s art ecosystem. About two-thirds (~66%) saw NFTs as a tool for cultural curation and preservation – effectively transforming Saudi art and heritage into digital assets that can be shared without physical constraints. In addition, 71.2% cited global market access and 65.2% cited new revenue streams as major advantages of NFT adoption, as these could give Saudi artists a wider international audience and new monetization channels. Other notable opportunities included technological innovation (63.6% of respondents) and community building (27.3%). Realizing these opportunities will require supportive local infrastructure and institutional backing to help artists capitalize on global reach and innovation while maintaining cultural integrity. Figure 5 visualizes the multi-select results for perceived NFT

opportunities: global market access 71.2%, cultural preservation 65.2%, new revenue streams 65.2%, innovation opportunities 63.6%, and community building 27.3% (n=66).

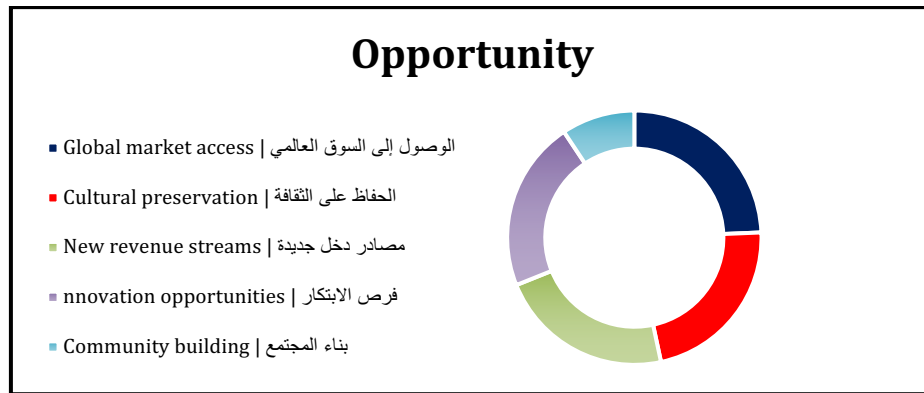


Figure 5. Perceived NFT Opportunities (n=66). Percent of respondents selecting each option.

## 4. Discussion and Framework Development

### 4.1 Interpretation of Findings

Survey results show limited baseline knowledge (no understanding 42.4%) alongside strong curiosity (interest 53.0%) but low hands-on creation (18.2%). Perceived public-value motivations center on cultural preservation (68.2%) and digital-economy growth (66.7%). These patterns justify prioritizing awareness, training, and low-friction onboarding while aligning with Vision 2030 objectives (see Figure 6).

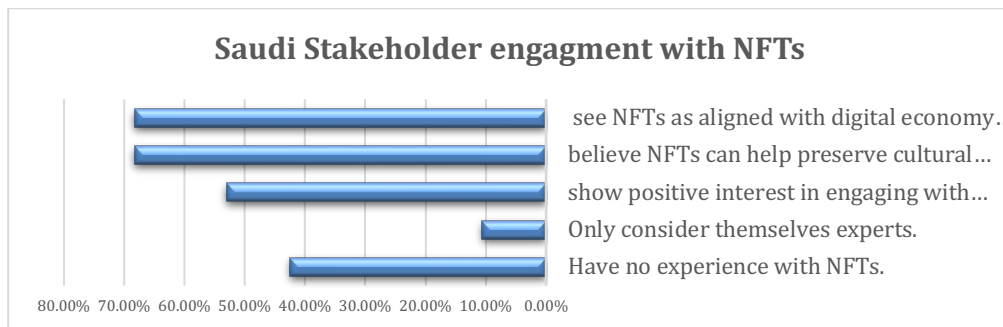


Figure 6: Radial visualization of Saudi stakeholders' engagement with NFTs.

### 4.2 Transformation Framework

According to the findings, the proposed transformation framework centers on three pillars: education, infrastructure, and partnerships. It is necessary to enhance and secure governmental support and comprehensible legislation to face the technical difficulties that are mentioned by 56.9% of participants. Figure 7 summarizes the three-pillar framework -education, infrastructure, and

partnerships -and the expected outcomes. Further priorities include developing robust digital art platforms, protecting artists' intellectual property rights, and expanding training programs for artists and collectors. These measures form a phased approach to integrating NFTs into the art sector.

- ✓ **Education:** structured training for artists and galleries; public awareness campaigns; legal/IP workshops focused on NFTs.
- ✓ **Infrastructure:** pilot NFT marketplace with ERC-721/1155 support; KYC/AML and royalty enforcement; on-ramp payments and Arabic UI/UX.
- ✓ **Partnerships:** Ministry–industry MoUs; museum/marketplace pilot exhibitions; grant program for heritage digitization.

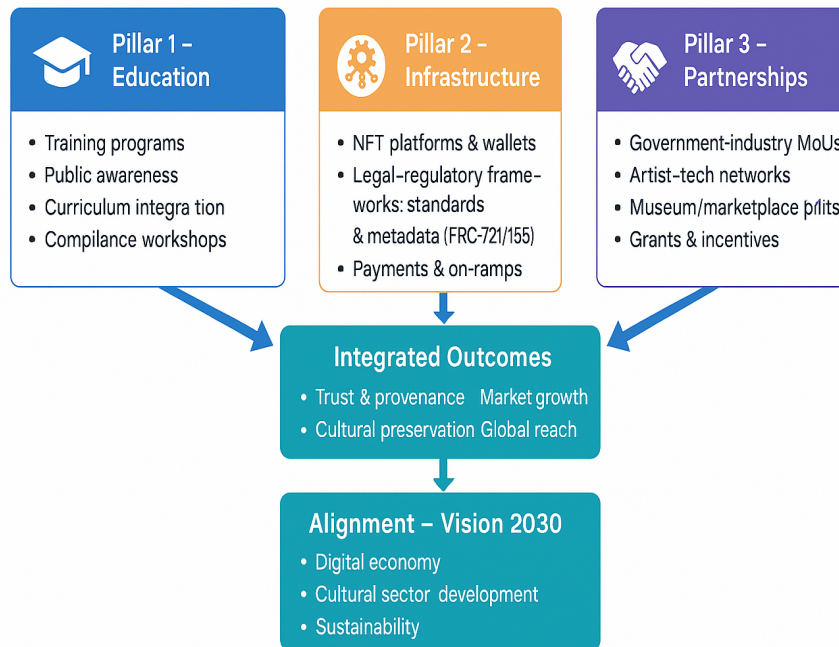


Figure 7. proposed NFT Art Ecosystem Transformation Framework

#### 4.3 Cultural Preservation Strategies

The survey underscored NFTs' relevance for cultural conservation: 57.6% of respondents said NFTs play a supportive role in preserving Saudi culture, and an additional 28.8% viewed NFTs' role as critical. It is logical, therefore, to use NFTs to digitize and authenticate cultural artifacts, creating a secure archive for future generations. Furthermore, 57.6% of respondents suggested that integrating VR/AR technologies with NFTs could enhance cultural preservation by providing immersive educational experiences (see Figure 8).

### Emerging technologies integrated with NFTs?



Figure 8. Emerging technologies integrated with NFTs (n=66). AI/ML 78.8%, VR/AR 57.6%, IoT 39.4%.

#### 4.4 Sustainability Metrics

Achieving sustainable NFT adoption will require addressing both market and environmental factors. Market volatility emerged as a key concern (noted by 36.9% of participants), so pursuing market stability and risk mitigation is important for long-term success. Moreover, NFTs' environmental footprint must be managed by adopting greener blockchain solutions and energy-efficient consensus mechanisms, in line with Saudi Arabia's sustainability commitments. Future evaluations of NFT projects should also consider their socio-cultural impact – for example, how the NFT market's growth will affect local artists and the preservation of cultural heritage – as part of sustainability metrics. Track implementation with concrete indicators: share of PoS or Layer-2 mints; estimated kWh per mint; percent of assets with on-chain metadata hashes; counterfeit-takedown SLA compliance; and realized creator-royalty rate

#### 4.5 Implementation Roadmap

Execution should follow milestones tied to survey priorities. Months 0–6: national awareness campaign; recurring technical training; quarterly legal/IP clinics. Months 6–12: pilot NFT marketplace with verified creators; museum/marketplace exhibition; payments on-ramp and wallet helpdesk. Months 12–24: heritage IP registry pilot; grants for digitization; cross-border distribution partnerships.”

These milestones align with the global market access opportunity highlighted by 71.2% of respondents and would drive engagement on an international stage.

### 5. Conclusion

This exploratory study suggests that NFTs have the potential to significantly impact Saudi Arabia's art market: the findings indicate that preserving cultural heritage (a priority for 68.2% of respondents) and boosting the digital economy (66.7%) are seen as the foremost objectives. Adoption remains

nascent given aggregate barrier severity (Moderate+Major): market volatility 58.5%, technical complexity 56.9%, cultural considerations 55.4%, financial risks 50.8%, and regulatory uncertainty 43.1%. These findings underscore the need for strong policy support, infrastructure development, and government-funded educational programs to increase NFT uptake. We acknowledge certain limitations of the study, most notably the small, digitally-oriented sample size, which limits the generalizability of the findings, and the rapidly evolving regulatory environment. Therefore, the results should be seen as an initial snapshot intended to guide further, more comprehensive research rather than as definitive conclusions. Looking ahead, future research should examine the long-term outcomes of NFT initiatives and the effects of integrating emerging technologies (like AI) into digital art markets, to refine and expand upon the framework presented. Finally, translating this research into practice will require collaboration among stakeholders: policymakers should establish clear regulations and incentives; artists and cultural institutions need support to safely experiment with NFTs; investors and tech firms should develop secure, user-friendly platforms; and academic researchers ought to continue monitoring market evolution. By improving legislation, raising public awareness, and adopting global best practices, Saudi Arabia can enhance NFT adoption and advance its Vision 2030 goals of economic diversification and cultural development. A structured implementation roadmap – with actionable short- and long-term steps – will be critical to ensure market stability and the longevity of this digital transformation.

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## Review on Diatomite for Sustainable Technology: Recent Advances in Functionalization, Composite Development, and Multi-Scale Applications

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### Abstract

Diatomaceous earth (DE), or diatomite, constitutes the fossilized silica frustules of diatoms. Historically utilized as an industrial absorbent and filtration medium, it has recently garnered significant attention as an advanced material in nanotechnology and engineering. This transition is driven by its inherent physicochemical properties, which include a hierarchically porous architecture, high specific surface area, low density, and chemical stability, collectively rendering it an effective natural micro- and nano-structured scaffold. This review provides a systematic examination of the seminal scientific and engineering progress in diatomite research from 2014 to 2025. The analysis is structured around three primary themes: (1) the advancement of sophisticated chemical, physical, and biological strategies for surface activation and functionalization; (2) the rational design and fabrication of hybrid diatomite-based composites incorporating polymeric, metallic, metal oxide, and carbonaceous phases; and (3) the diversification of its application spectrum into domains including catalysis, energy storage (e.g., Li-ion batteries, supercapacitors), construction, environmental remediation, biomedical engineering (e.g., drug delivery, biosensing), and thermal/acoustic management. This work critically evaluates key performance indicators, synthesizes prevalent characterization techniques, and incorporates sustainability analyses from a life-cycle perspective.

**Keywords:** Diatomite; surface functionalization; diatomite-based composites; environmental remediation; energy storage materials; biomedical applications; sustainable materials.

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## 1. Introduction

Diatomite is a siliceous sedimentary rock made from the fossilized cell walls (frustules) of diatoms, a common unicellular algae found in aquatic ecosystems. These microorganisms biosynthesize frustules from hydrated silica ( $\text{SiO}_2 \cdot n\text{H}_2\text{O}$ ) into species-specific, highly ordered nanoporous structures as a naturally occurring, cost-effective, and abundant template that can be utilized for advanced material synthesis[1]. Unique architecture of diatom frustules, with a multiscale pore network (micro-, meso-, and macropores) results in extremely attractive surface-area-to-volume ratios, usually in the range of 20-60  $\text{m}^2/\text{g}$  post-calcination [2, 3]. Diatomite used in previous applications were strictly for filtration function, as a weakly abrasive and also as passive absorbing agent. However, the past decade has witnessed a paradigm shift, with research focused on transforming this naturally inert silica framework into a functionally active material with the aid of focused physical, chemical and biological manipulation [4]. The growing interest in sustainable and bio-inspired practices has also increased the attractiveness of diatomite since it requires considerably less energy to process compared to the synthesis of artificial porous materials like zeolites or mesoporous silica (e.g., MCM-41, SBA-15). (Diatom and Advanced Aspects of Material — The Material Path[5])

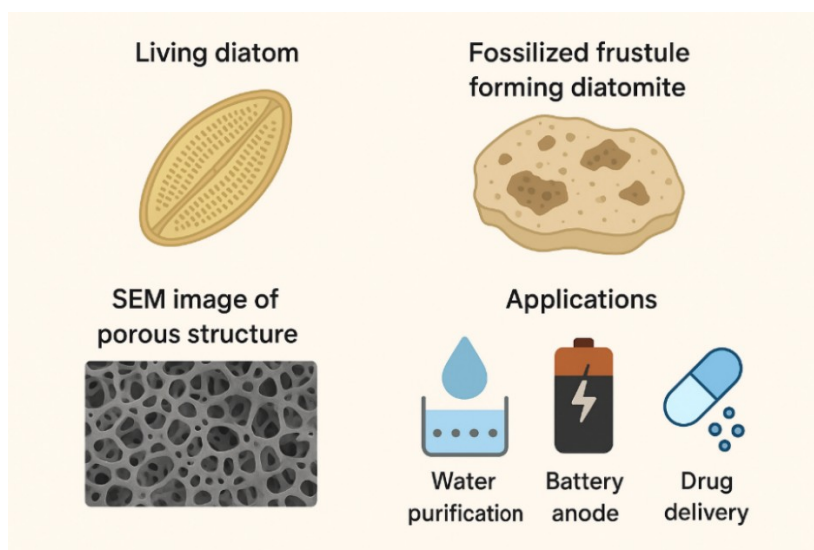


Figure 1. (a schematic drawing showing:(i) the form of a living diatom, (ii) fossilized frustule transforming diatomite, (iii) a SEM image of the porous structure, (iv) advanced applications such as water purification, battery anodes, and drug transport).

The purpose of this review was to provide a detailed and critical overview of this transformational process and to show how diatomite went from a raw rock to a developed structure to meet some of the world's most critical human needs, such as that of energy, environmental, and health. The range of techniques to modify core components of a material ranges from the design of composite material

systems to evaluating specific performance for applications. The future prospects and future viability of diatomite-based technologies are presented in a prospective review article.

## 2. Basic Characteristics of Raw Diatomite and Its Pre-Treatment.

### 2.1. Structural and chemical properties.

Diatomite is geologically regulated by its origins. The specific species of diatom, the age of the deposit and the conditions of fossilization influence the shape, purity and intrinsic porosity of the given material. The frustule shapes include the cylindrical, discoid, pinnate and triangular shapes of the pore size and the surface geometry [3]. From a chemical standpoint, raw diatomite consists primarily of amorphous silica (80–95%) and clay minerals, iron oxides and alkaline earth metals are the major impurities [6]. The surface, formed by silanol groups (Si-OH), serves as the dominant sites of chemical interaction and functionalization.

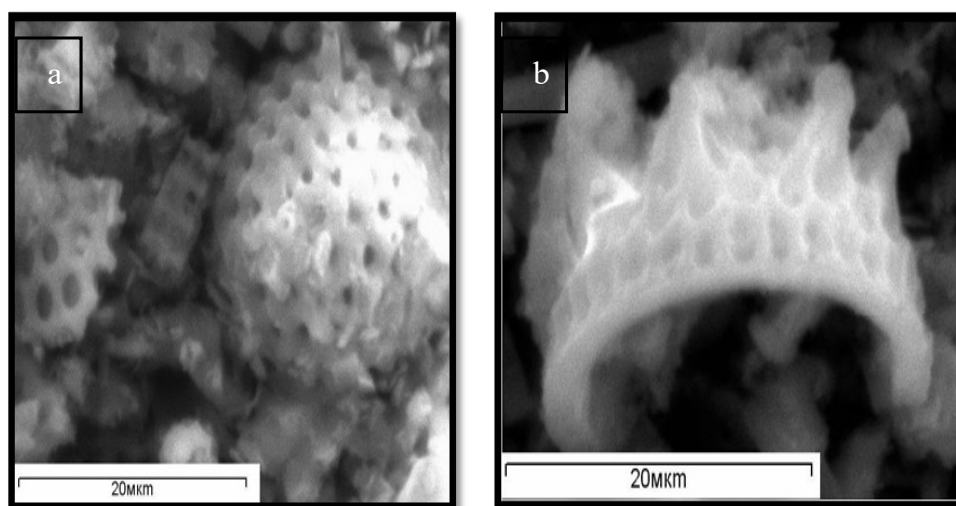


Figure 2. shows: (a) raw diatomite, (b) diatomite calcinated at 900°C[3].

### 2.2. Beneficiation and Purification

Raw diatomite ore often requires beneficiation to remove inherent impurities that can undermine its efficiency for advanced solutions. Pre-treatment protocols are typically the following:

- **Crushing and Milling:** To reach a desired particle size distribution.
- **Calcination (500-900°C):** Eject organic matter and consolidate silica matrix. It can be processed in flux-calcination mode with sodium carbonate to sinter fine particles thereby improving filtration quality or non-flux mode since native structure is kept for functional applications [7, 8].

- **Acid Washing (e.g., with HCl or H<sub>2</sub>SO<sub>4</sub>):** To dissolve soluble metal oxides and carbonates, thus increasing the silica and the surface purity [8, 9].

Table 1: Common Preparation of Raw and Purified Diatomite [6, 10].

Component	Raw Diatomite (wt.%)	Acid-Purified Diatomite (wt.%)
SiO <sub>2</sub>	80 - 90	> 98
Al <sub>2</sub> O <sub>3</sub>	3 - 6	< 1
Fe <sub>2</sub> O <sub>3</sub>	1 - 3	< 0.5
CaO + MgO	0.5 - 2	< 0.2
Loss on Ignition	4 - 8	< 2

### 3. Modification and Activation Strategies

As a result of the silica surface of diatomite being naturally rich in silanol (Si-OH) groups, it provides a versatile platform for chemical functionalization. The introduction of modification strategies is essential to either improve intrinsic properties (e.g., sorptive capacity) or introduce newly developed functionalities (e.g., magnetism, catalytic activity, hydrophobicity).

#### 3.1. Thermal Activation

In addition to traditional calcination, specialized thermal processing techniques are now established:

- **Controlled Atmosphere Calcination:** Calcination for a given period under an inert atmosphere (e.g. N<sub>2</sub>, Ar) can preserve carbonaceous residues from the pore network to generate carbon-silica composites with improved adsorption of organic contaminants [11].
- **Magnesification:** This procedure is specific and involves the thermal treatment of diatomite (for instance, at 500–700°C), impregnated with magnesium salts (including MgCl<sub>2</sub>). This can produce reactive magnesia (MgO) nanoparticles on the silica surface, resulting in composites with excellent adsorption capability for anions such as phosphate, arsenate, fluoride from aqueous media [12].

#### 3.2. Chemical Functionalization

**3.2.1. Acid/Base Treatment:** While acid washing serves a purifying function, controlled alkaline treatment (e.g., with NaOH) can be employed to selectively etch the silica surface. This process increases the surface area and generates a higher density of reactive silanol sites for subsequent grafting reactions.

Table 2. Comparison of the effects of different purification HCl concentrations on the specific surface area, total pore volume, t-graph volume, and average pore diameter of diatomite[13].

Sample	BET surface area (m <sup>2</sup> /g)	Total pore volume (cm <sup>3</sup> g <sup>-1</sup> )	T-plot micropore volume (cm <sup>3</sup> g <sup>-1</sup> )	BJH average pore diameter (nm)
Raw diatomite	5.530	0.0013	0.00076	0.9261
10%	5.711	0.0012	0.00132	0.8700
15%	7.920	0.0020	0.00106	0.9972
20%	8.062	0.0021	0.00108	0.9963
25%	8.145	0.0020	0.00109	0.9322

**3.2.2. Surface Silylation:** This is a basic process for the functionalization of diatomite. Organosilane molecules, such as (3-aminopropyl)triethoxysilane (APTES) or vinyltriethoxysilane (VTES), are chemically grafted onto surface silanol groups through hydrolysis and condensation reactions.  $\text{Si-OH} + \text{X-Si-R} \rightarrow \text{Si-O-Si-R} + \text{HX}$  (where X is a hydrolysable group like  $-\text{OCH}_3$ , and R is an organic functional group such as  $-\text{NH}_2$ ,  $-\text{SH}$ ,  $-\text{CH}=\text{CH}_2$ ).

This strategy is important for hydrophobicity, polymeric matrix compatibility and specific functional group assignment to anchor both catalysts or biomolecules [14].

**3.2.3. In-situ Precipitation and Coating:** These processes are the fundamental basis of the preparation of most composite materials[15].

- **Sol-Gel Coating:** A precursor (e.g., titanium isopropoxide for  $\text{TiO}_2$ ) is hydrolyzed in the presence of diatomite to obtain a homogeneous metal oxide coating on the frustule surface.
- **Layer-by-Layer (LbL) Assembly:** Because oppositely charged polyelectrolytes or nanoparticles adsorb sequentially, a controlled thickness and composition of coating is easily achieved [16].
- **Precipitation Methods:** Direct precipitation from aqueous solution (e.g., by metal salts such as  $\text{FeCl}_3/\text{FeCl}_2$  for magnetite,  $\text{Fe}_3\text{O}_4$ ) is a common and scalable method for depositing nanoparticles in diatomite pores [17].

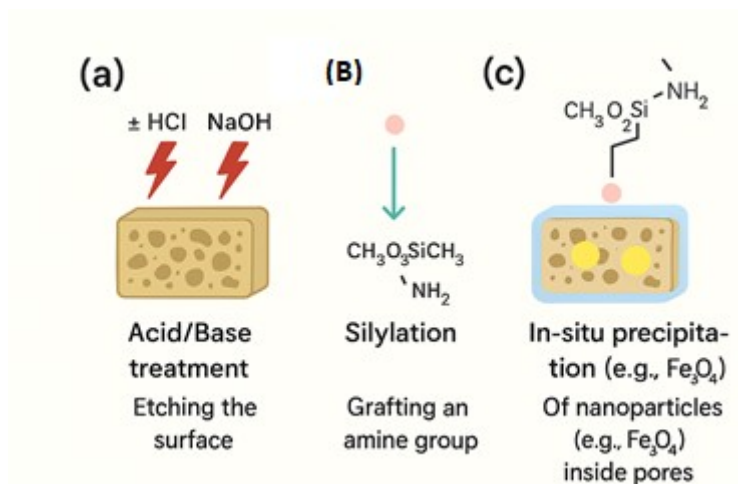


Figure 3. schematic shows: (a) etching of the surface through acid or base treatment, (b) silylation via APTES grafting an amine group, (c) In situ precipitation of nanoparticles (e.g.,  $\text{Fe}_3\text{O}_4$ ) in pores; Metal oxide with sol-gel coating (e.g.,  $\text{TiO}_2$ ).

#### 4. Development of Diatomite-Based Composites

Synergistic composites derived from the combination of diatomite with other substrates, in which a diatomite functions as a scaffold structure, which provides mechanical stability, high surface area and special morphology in the hybrid.

##### 4.1. Polymer-Diatomite Composites

Diatomite works as a strong reinforcing filler and functional additive in polymeric matrices.

- **Thermoplastics (e.g., Polypropylene, Polyethylene):** The use of diatomite increases mechanical properties (tensile and flexural modulus), improves thermal stability and reduces flammability by acting as a char promoter[18, 19]. Studies deals with the effect of the Diatomite (D) microcomposite with and without chemical modification in a polypropylene (iPP) blend.
- **Thermosets (e.g., Epoxy, Polyurethane):** addition of diatomite provides better stiffness, more toughness with fracture, and lower thermal degradation[20].
- **Biopolymers (e.g., Polylactic Acid - PLA):** Besides reinforcement, diatomite can modify the gas barrier behavior of packaging films and work as a nucleating agent for crystallization to promote thermo-mechanical performance improvement[21, 22].
- **Stimuli-Responsive Composites:** Functionalized diatomite can be integrated with hydrogels or shape-memory polymers to form composites to be utilized in smart packaging, controlled release, or self-healing applications [23].

Table 3: Summary of Key Polymer-Diatomite Composite Systems and Properties.

Polymer Matrix	Key Findings	Improvement Over Neat Polymer	Reference
<b>Polypropylene (PP)</b>	20 wt.% DE increased tensile modulus by ~50% and reduced peak heat release rate by 25%.	Enhanced stiffness and flame retardancy.	[18]
<b>Epoxy</b>	10 wt.% aminopropyl-functionalized DE improved fracture toughness by 80%.	Enhanced mechanical durability.	[20]
<b>Polylactic Acid (PLA)</b>	5 wt.% DE increased crystallization temperature and oxygen barrier properties by 30%.	Improved processability and packaging performance.	[21]
<b>Polyurethane Foam</b>	DE incorporation enhanced sound absorption coefficients across a broad frequency range.	Superior acoustic insulation.	[24]

DE = Diatomaceous Earth

## 4.2. Metal/Metal Oxide-Diatomite Composites

This category is one of the most researched domains within diatomite composites scientific research.

- TiO<sub>2</sub>/DE Photocatalysts:** Diatomite is an ideal support for TiO<sub>2</sub> NPs, and it blocks dyes' aggregation to promote the photon absorption by internal scattering by the scattering of light ("light-trapping" effect) as well as supporting the simple catalyst recovery and reuse in water purification (degradation of dyes, pharmaceuticals) and air treatment [25, 26]. This study demonstrates the effectiveness of the diatomite and TiO nanoparticles composite in photodegrading methylene blue, achieving up to 80% efficiency in 270 min under sunlight. The high surface area and porosity of diatomaceous earth improve the dispersion of TiO nanoparticles[26].

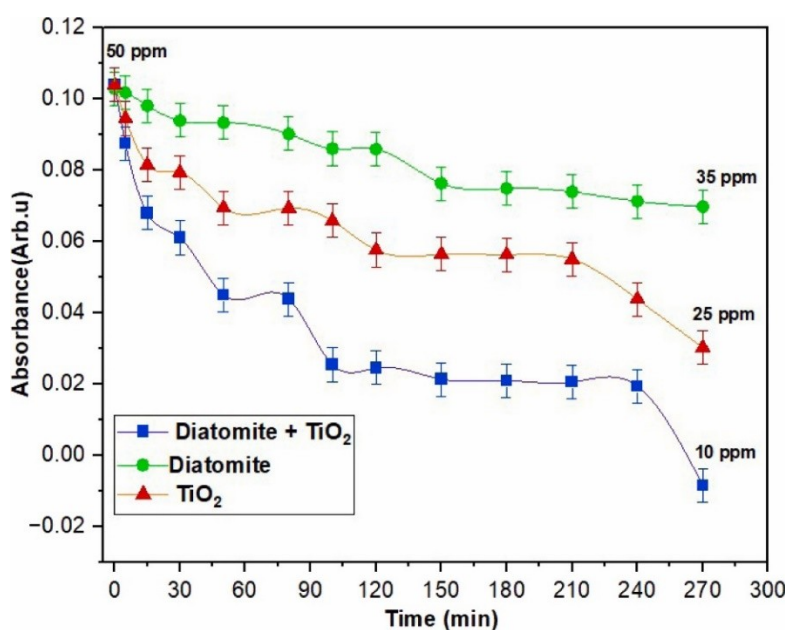


Fig. 4. (a) Photodegradation of Diatom, (b) Photodegradation of TiO nanoparticles, (c) Photodegradation of Diatom loaded with TiO<sub>2</sub>. [26]

- **Magnetic DE Composites (e.g.,  $\text{Fe}_3\text{O}_4/\text{DE}$ ):** Inclusion of magnetic nanoparticles like magnetite and maghemite enables fast and effective magnetic separation even after application in adsorption or catalytic processes. This property is attractive for large-scale applications where the low-cost operation and the prevention of secondary pollution are crucial[17, 27].
- **Noble Metal/DE Composites (e.g.,  $\text{Ag}/\text{DE}$ ,  $\text{Au}/\text{DE}$ ):** Silver-based composites supported on diatomite possess powerful broad-spectrum antibacterial activity, which is beneficial for the disinfection in both water and antimicrobial coatings[28]. Gold/diatomite composites have also been evaluated for catalytic oxidative reactions and surface-enhanced Raman scattering (SERS)-based sensing applications[29].

#### 4.3. Carbon-Diatomite Composites

The process of conversion of the intrinsic organic matter in diatomite through pyrolysis, or deposition of carbon layers[30] (e.g., chemical vapor deposition or sucrose carbonization), results in conductive composites

- **Diatomite-Derived Porous Carbon:** Complemented by a silica template (used either by NaOH or HF) to be removed following carbonization, a porous carbon equivalent to the diatom structure with a very high surface area ( $>1000 \text{ m}^2/\text{g}$ ) is obtained[31].
- **Carbon-Coated Diatomite:** Retaining the silica core gives strength to the mechanical behaviour. These materials combine the high surface and electrical behavior of carbon with the structural stability of the diatomite scaffold and are suitable as electrode materials for energy storage applications[32].

### 5. Multifunctional Applications

**5.1. Adsorbs and catalyst supports** DE-based composites have excellent adsorbing and environmental remediation capacities.

- **Heavy Metal Removal:** Composites functionalized with chelating groups (e.g.,  $-\text{NH}_2$ ,  $-\text{SH}$ ) or coated with metal oxides (e.g.,  $\text{MnO}_2$ ,  $\text{FeO}$ ) show high capacity, and selectivity for heavy metals e.g.,  $\text{Pb(II)}$ ,  $\text{Cd(II)}$ ,  $\text{Cu(II)}$ , and  $\text{Cr(VI)}$ [33-35].



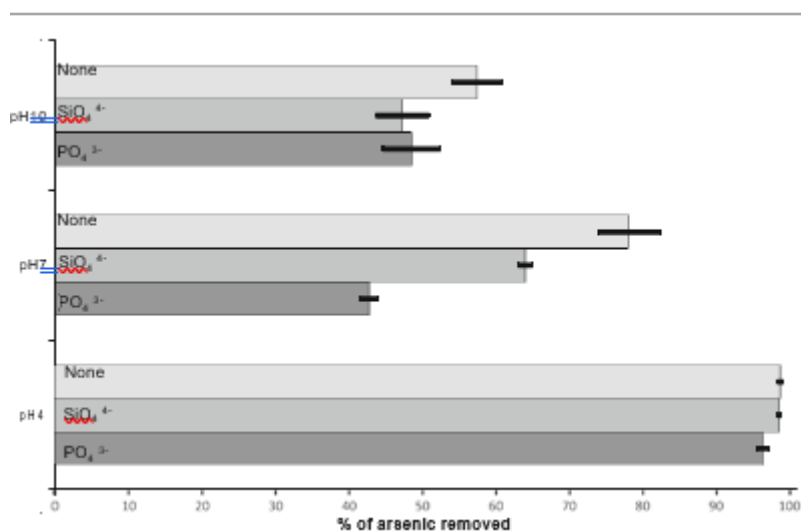


Fig. 5 Effect of competitive ions (phosphate, 10 mg L<sup>-1</sup>; silicate, 10 mg L<sup>-1</sup>) in arsenic (V) (10 mg L<sup>-1</sup>) adsorption onto D-Fe (0.1 g of D-Fe 17 %)[35]

The incorporation of iron into the diatomite matrix increased the performance in both batch and column experiments. In order to enhance the potential of low cost diatomite based adsorbents to remediate arsenic contaminated water, it is recommended that further studies are carried out to optimize methods of coating these adsorbents with iron and other metal oxides.

- **Organic Pollutant Removal:** Removal — The material effectively adsorbs dyes, pesticides, and new contaminants like pharmaceuticals and per- and polyfluoroalkyl substances (PFAS)[36, 37].
- **Advanced Catalytic Degradation:** Diatomite enhances the degradation efficiency of persistent organic pollutants via Advanced Oxidation Processes (AOPs) as a catalyst support [15, 38], for instance, TiO<sub>2</sub> in photocatalysis and Fe-based catalysts in Fenton-like reactions.

## 5.2. Energy Storage

It is based on active energy materials on diatomite is an ideal scaffold due to its 3D porous structure.

**Lithium-Ion Batteries (LIBs):** Silicon-diatomite anodes take advantage of the natural porosity, allowing such a large volume expansion of silicon during lithiation (~300%) to be accommodated and increasing cycling stability as well as capacity retention. Diatomite-derived porous silicon and carbon are also emerging as desirable anode materials[39]. successfully synthesized nanosilicon from diatomaceous earth (DE) using magnesiothermic reduction and subsequently applied a carbon coating to it. Electrochemical Performance gives that Following 50 cycles at a rate of C/5 (0.2 C), the anode



demonstrated a specific (reversible) discharge capacity of approximately 1102.1 mAh/g. In the rate capability assessments, which ranged from C/30 to 4C, the retention of capacity for each block of 10 cycles was as follows:

- At C/30, the anode retained 67.4% of its initial capacity.
- At C/10, it retained 90.4%.
- At C/5, the retention was 98.3%.
- At C/2, it maintained 95.0%, and so on.

At a rate of 4C, the anode maintained a capacity of about 654.3 mAh/g, which is significantly higher than graphite's theoretical capacity of 372 mAh/g. Interpretation: The intrinsic porous architecture of diatomite, which is preserved in the reduced silicon, combined with the carbon coating, acts as a buffer to mitigate the substantial volume expansion of silicon. This structural advantage enhances both the capacity and the cycling stability of the anode[40].

**Supercapacitors:** Diatomite-derived porous carbon and metal oxide/DE composites (e.g.,  $\text{MnO}_2/\text{DE}$ ,  $\text{Co}_3\text{O}_4/\text{DE}$ ) are possible electrodes with enhanced specific capacitance due to their large surface area and effective ion transport pathways [31, 41].

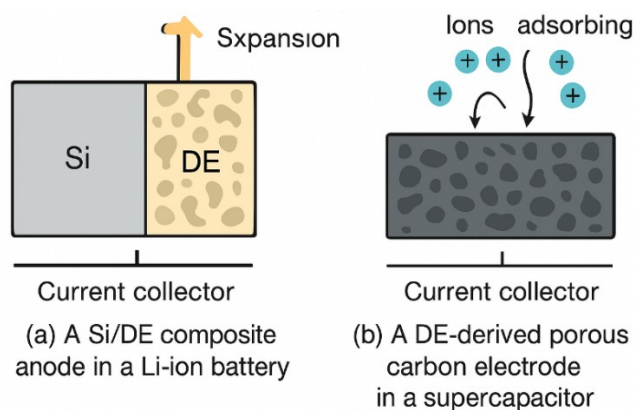


Figure 6: Diagram of Diatomite in Energy Storage Applications

### 5.3. Construction Materials

Diatomite improves the properties of building materials.

**Cement and Concrete:** A high-performance micro-filler and pozzolanic material, it reacts with calcium hydroxide (portlandite) to form additional calcium silicate hydrate (C-S-H) gel, the principal strength-bearing phase in cement and concrete. This increases the compressive strength and lowers permeability, improving durability[42, 43]. Diatomite has been proposed as a replacement for fly ash

in lightweight engineered cementitious composites, and its effects on mechanical performance, shrinkage behavior, and microstructural development have been systematically evaluated. The findings indicate that incorporating diatomite leads to reductions in compressive strength, tensile strength, and tensile strain capacity. These decreases are primarily attributed to the lower degree of cement hydration and the higher porosity introduced by the diatomite particles. When additional mixing water is incorporated together with the diatomite, the hydration reactions are enhanced and the resulting matrix becomes more compact. As a result, specimens containing diatomite with added water exhibit higher compressive and tensile strengths, though their tensile strain capacity remains lower than that of mixtures without the added water. In addition, relative to the reference mixture, the autogenous shrinkage of the diatomite-modified composite increases because of the reduced amount of available mixing water.

- **Lightweight and Insulating Materials:** Its high porosity offers low thermal conductivity, which makes it suitable for lightweight aggregates, insulating bricks, and plasters in energy-efficient buildings[44, 45].

#### 5.4. Biomedical Applications

Biocompatibility, high surface area and tunable surface chemistry for biomedical applications diatomite are exploited.

- **Drug Delivery:** The inherent pores of diatomite can be loaded with drugs in a controlled and sustained manner (e.g. anticancer drugs, antibiotics). Surface functionalization allows for selective delivery [46]. The potential of diatomaceous earth (DE) in various applications can be significantly augmented by integrating nitric oxide (NO) technology, known for its role in regulating important physiological processes. The advancement of NO-releasing diatomaceous earth offers a novel strategy for delivering adjustable quantities of NO, with promising applications in polymer chemistry, tissue engineering, drug delivery, and wound healing.
- **Biosensing:** The photonic crystal features of diatom frustules are used for label-free biosensing. The binding of a target biomolecule to a functionalized frustule surface leads to a measurable change in its reflectance or photoluminescence spectrum [47].
- **Bone Tissue Engineering:** Diatomite-derived silica has bioactivity and can promote the adhesion and growth of bone cells (osteoblasts). It is being investigated as a scaffold for bone regeneration purposes [48].

#### 5.5. Thermal and Acoustic Management

The highly porous and hollow microstructure of diatomite frustules imparts exceptional thermal insulation and sound absorption properties.

- **Thermal Insulation:** Diatomite-based composites, aerogels, and plasters in buildings reduce heat transfer for energy conservation [49].
- **Acoustic Absorption:** The interconnected pore network of diatomite effectively dissipates sound energy, making it useful in noise suppression applications [24].

Table 4 Representative some thermal & acoustic values for diatomite-based materials.

Material / Form (source)	Thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )	Acoustic performance (sound absorption)	Key result / test conditions
Diatomite-based aerogel [50]	<b>0.041</b> (density $\approx 0.114 \text{ g}\cdot\text{cm}^{-3}$ , porosity $\approx 91.5\%$ ).	Not reported in that paper (thermal focus).	Very low k competitive with polymer foams; excellent for insulation.
Porous diatomite ceramic [51]	<b><math>\sim 0.0984</math></b> (reported for a sample with $\sim 57.9\%$ porosity) and other porous diatomite ceramics in literature: <b>0.061–0.123</b> (high-porosity fired samples).	Not acoustic-focused.	Good thermal insulation for a mineral ceramic; properties depend strongly on porosity and firing.
Diatomite-based thermal insulation mixture / dry mix [52]	<b>0.128–0.152</b> (reported range for dry construction mix).	Not reported.	Practical construction mixture; higher k than aerogels but still useful for lightweight insulation.
Diatomite-impregnated PCM (myristic acid) [53]	<b><math>\sim 0.36</math></b> for raw diatomite-based PCM (value depends on PCM loading).	N/A (thermal energy storage focus).	Diatomite acts as support for PCM; thermal conductivity increases compared with pure PCM but thermal storage benefits are improved.
Diatomite / polyurethane porous composite [54]	Thermal conductivity not central in that paper (composite focus).	<b>Peak absorption <math>&gt;0.9</math> at <math>\sim 1600 \text{ Hz}</math></b> for a sample with <b>65 wt.% diatomite</b> ; absorption coefficient $>\sim 0.56$ across a $>2000 \text{ Hz}$ band.	Very good mid-frequency sound absorption when diatomite is used as filler in porous polymer matrices.
Diatomite-based composite PCMs (review / 2020 Renene) — (vacuum-impregnated lauric-stearic acid)[55]	Effective thermal properties depend on loading — many diatomite-PCMs show improved thermal stability and thermal conductivity up to <b><math>\sim 0.2\text{--}0.5 \text{ W/m}\cdot\text{K}</math></b> depending on PCM and loading.	N/A	Diatomite improves shape stability and heat transfer vs. pure PCM.

## 6. Characterization Techniques

A multi-faceted analytical approach is vital in characterizing modified diatomite and its composites.

- **Microscopy:** Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are indispensable for characterizing detailed microstructure characteristics, frustule morphology, and distribution of nanoparticles on the composite surface.

- **Surface Area and Porosity:** Specific surface area and porosity were determined using the Brunauer-Emmett-Teller (BET) method by nitrogen adsorption-desorption isotherms. The Barrett-Joyner-Halenda (BJH) method for mesopores or Non-Local Density Functional Theory (NLDFT) models for a full range of pore size distribution determine the distribution [56].
- **Chemical Analysis:** Fourier-Transform Infrared Spectroscopy (FTIR) detects functional groups (Si-OH, C-H, N-H post-modification). X-ray Diffraction (XRD) reveals the diatomite crystallinity (an amorphous halo), along with any deposited crystalline phase(s), such as anatase  $\text{TiO}_2$ , magnetite  $\text{Fe}_3\text{O}_4$ . Quantitative surface elemental composition and chemical state details were obtained by X-ray Photoelectron Spectroscopy (XPS) [57].
- **Thermal Analysis:** Thermogravimetric Analysis (TGA), which quantifies thermal stability, organic content, and composite composition at varying temperatures, through mass loss with respect to temperature [58].

## 7. Sustainability, Challenges, and Future Directions

### 7.1. Challenges

Despite the dramatic improvement, several challenges remain:

1. **Source Variability:** Natural diatomite sources have been reported to be quite variable in terms of composition, purity, and microstructure, which lead to differences in batch-to-batch consistency and performance predictability [59].
2. **Scalability:** Engineering and translation of laboratory synthesis technologies for making composites, as in the case of sol-gel, LbL, and similar methods, into industry at scale without compromise of cost-efficiency and uniformity as well as following green chemistry is a major challenge.
3. **Long-Term Stability and Safety:** Preserving the long-term stability of composites (e.g., avoiding nanoparticle leaching from magnetic and Ag/DE composites) in environmental and biomedical settings is essential for overall risk assessment [60].
4. **Life-Cycle Assessment (LCA):** For most novel diatomite applications, complete LCAs are missing, which prevents arriving at strong and accurate sustainability claims [61].

### 7.2. Sustainability Considerations

Diatomite, a natural and inexpensive resource, can be used for environmental remediation and energy-saving technologies, contributing to sustainable development goals. In the near future, focus should be shifted to environmentally friendly modification pathways (e.g., aqueous-based approaches, benign

chemicals) and the reduction of energy consumption during processing, together with the development of materials with easy recovery, recycling, and biodegradability, wherever achievable[62].

### 7.3. Future Directions

1. **Bio-inspired Design:** Building on fossilized diatoms has been proposed to mimic the biosilica synthesis of the diatom (bio-silicification) to prepare novel hybrid materials for low-energy synthesis with genetically programmable architectures [63].
2. **Advanced Multi-functional Composites:** Design of "smart" composites that combine multiple functional aspects, e.g., self-cleaning building material, which can be composite with photocatalysis ( $\text{TiO}_2/\text{DE}$ ) acting together with thermal insulation, or wound dressing which can combine antibacterial property ( $\text{Ag}/\text{DE}$ ) working with drug release [64].
3. **Precision Medicine:** Design of diatomite frustules with specialized surface chemistries and pore geometries for targeted drug delivery, gene therapy, and advanced diagnostic (theranostic) platforms [65].
4. **Energy Conversion:** The role of diatomite as a catalyst support in energy conversion technologies such as photocatalysis for hydrogen production, electrochemical  $\text{CO}_2$  reduction, and fuel cells is considered in recent directions[66, 67].
5. **Circular Economy:** Designing effective regeneration protocols for spent diatomite adsorbents and catalysts. Moreover, investigating direct recycling of diatomite from waste streams from industrial production (i.e., beverage filtration) to produce high-value products to close the material loop [68, 69].

### 8. Conclusion

During 2010-2025, diatomite has been established as a versatile, sustainable, and high-potential material for advanced materials engineering. By making strategic improvements: thermal activation, chemical grafting, and in situ composite formation have opened up far wider application possibilities beyond its traditional uses. The naturally occurring, hierarchical, and unique structure of diatomite is a viable platform for addressing environmental science, energy storage, biomedicine, and sustainable building challenges. Diatomite's progression from a simple filter aid to a component in advanced technologies such as lithium-ion batteries and targeted drug delivery systems clearly defines a successful convergence between materials science and bio-inspiration. Overcoming scalability issues, designing for multifunctionality, embracing bio-inspired synthesis, and following circular economy

principles will be critical avenues of future research efforts. Such initiatives will cement diatomite's position in the design of next-generation, high-performance, and truly sustainable materials.

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## Restructuring Construction Processes: A Conceptual Model for Integrating Sustainable Technology Strategies

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### Abstract

This research paper aims to develop a conceptual model for reengineering construction processes by integrating sustainable technology strategies. The study addresses the significant environmental and economic impacts of the construction sector, which is a major contributor to global carbon emissions and resource consumption. The proposed model was developed and validated through a qualitative methodology, utilizing a case study of the SAB Tower in Riyadh alongside analysis of project documentation and performance reports. It is structured around three core layers: a process layer for redesigning workflows, a technology layer for integrating digital and sustainable solutions, and a governance layer for performance measurement and continuous improvement. The findings indicate that the model's effective implementation can substantially reduce carbon emissions and energy consumption. It also enhances operational efficiency and lowers costs. The study emphasizes that the model's success relies on the dynamic alignment and continuous interaction between its process, technology, and governance layers. For policymakers, it suggests updating building codes and providing incentives for sustainable projects. Industry practitioners are guided to invest in capacity building and adopt an integrated design culture. Furthermore, researchers are encouraged to conduct quantitative studies to measure the return on investment. Ultimately, the model offers a comprehensive framework for the sector's radical transformation towards sustainability.

**Keywords:** Process Reengineering; Sustainable Construction; Conceptual Model; Technology Integration; Green Building; Energy Efficiency.

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## **1. Introduction**

The construction and building sector serves as a fundamental pillar of global economic and social development. However, it is simultaneously one of the largest consumers of natural resources and a significant contributor to environmental pollution. Recent reports from the United Nations Environment Programme emphasize this issue, indicating that the sector accounts for 39% of global carbon emissions, 36% of final energy consumption, and 33% of waste generation [1]. Amid escalating environmental challenges and the global pursuit of sustainable development goals, a radical transformation of traditional construction models has become imperative. Recent studies (2023-2025) in digital sustainability, BIM-based green construction, and circular economy integration have emerged as innovative solutions for enhancing resource efficiency and reducing the sector's environmental footprint [2].

Despite significant technical advancements in sustainability tools, their implementation in the construction industry remains fragmented and incomplete. These technologies are often applied in isolation from one another, creating what are known as "technology islands" that limit their overall impact and prevent optimal integration into project workflows [3]. The core problem lies in the absence of comprehensive frameworks that integrate technological strategies with fundamental redesign of core processes, leading to reduced project efficiency and poor environmental performance. This reality reveals a critical research gap: a disconnect between the development of sustainable technologies on one hand, and the reengineering of operational processes necessary to effectively embed them on the other [4].

Therefore, this study aims to bridge this research gap by developing an integrated conceptual model that systematically links sustainable technology strategies with the reengineering of construction operations. Specifically, the study seeks to answer the main research question: "How can an integrated conceptual model enhance the overall performance of construction operations through reengineering with sustainable technology strategies?"

This central question leads to the following sub-questions: What are the main components and elements of the proposed conceptual model? How can the model's effectiveness in improving environmental and economic performance be measured? What evaluation criteria are necessary to assess the success of the model's implementation?

This study employs a multi-method research methodology, integrating theoretical and applied approaches to comprehensively develop and test the proposed model.

The theoretical aspect involves a comprehensive literature review in business process reengineering, digital integration, and sustainable construction. The applied aspect focuses on testing the model through case studies of pioneering sustainable construction projects, with emphasis on projects utilizing technologies analogous to those incorporated in the proposed model, such as the "SAB Tower" in Riyadh, which implements Siemens smart infrastructure solutions.

In this context, case studies were selected based on specific criteria including: Representativeness (pioneering projects in sustainable construction), Technological Integration (use of integrated and advanced technological solutions), Documentation (availability of comprehensive documentation and performance evidence), and Relevance (alignment with components of the proposed model).

The study relied on multiple data collection sources including Official Documentation (project reports, technical specifications, environmental performance assessments), Specialized Articles (technical studies and reliable news reports), and Expert Validation (review and analysis by specialists in sustainable construction). The study employed advanced analytical procedures including Thematic Coding for data analysis and identification of key patterns and themes, Constant Comparison between results and the theoretical framework, and Inductive Grouping to develop model components. Additionally, an integrated analytical framework was applied comprising Horizontal Analysis to examine each model layer separately, Vertical Analysis to study relationships between different layers, and Iterative Validation to review and refine the model based on findings.

Finally, this study contributes to providing an integrated theoretical framework for reengineering construction processes, while offering practical, applicable tools to enhance sustainability in the sector, thereby paving the way for a radical transformation in construction practices toward a more sustainable and efficient future.

## **2. Theoretical Framework and Literature Review**

### **2.1 Business Process Reengineering (BPR) in the Construction Sector**

Business Process Reengineering (BPR) constitutes a fundamental methodology for achieving radical transformation in the construction sector. Since Hammer and Champy's [5] seminal definition of BPR as "the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance," it has evolved into a vital tool for transforming supply chains, workflows, and stakeholder interactions [4]. Recent studies demonstrate that AI-driven reengineering can enhance efficiency by an additional 35%, while digital twin technologies enable comprehensive process simulation prior to implementation [6], as illustrated in Figure 1.

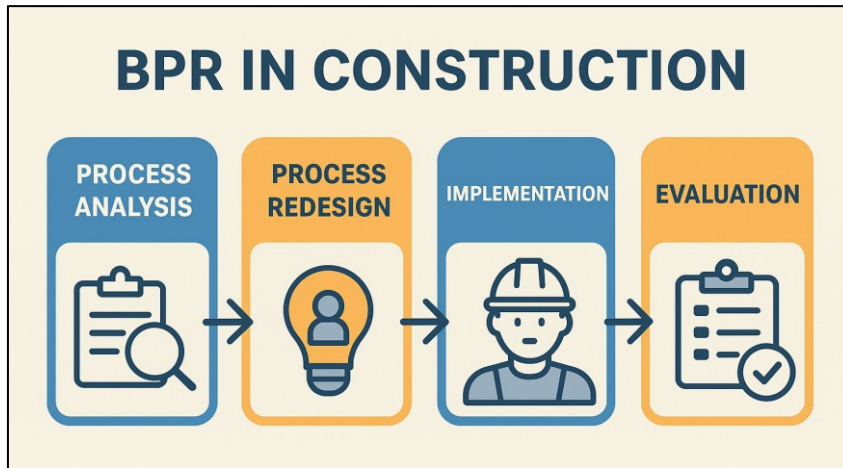


Figure 1. Illustrating the Stages of BPR in the Construction Sector [6].

## 2.2 Digital Integration Strategies

Digital integration represents the cornerstone of the construction industry's transformation toward integrated digital models. This integration has expanded beyond merely connecting systems and applications through unified platforms to encompass advanced technologies such as blockchain for enhanced transparency and reliability [7]. Building Information Modeling (BIM) remains one of the most crucial tools for this integration, serving as a central platform for information exchange among all stakeholders. Recent research indicates that the synergy between BIM and digital twins can reduce errors by 50% and decrease rework costs by 30% Figure 2.

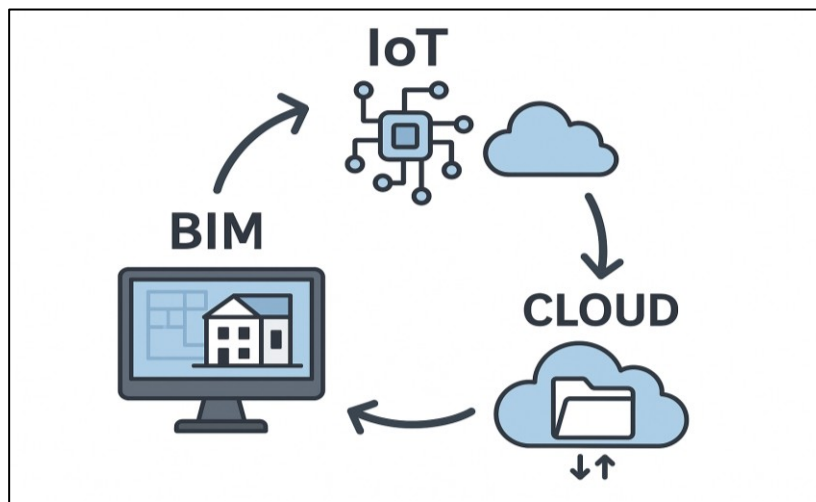


Figure 2. Digital Systems Integration: BIM, IoT and Cloud Computing [7].

### **2.3 Sustainable Technology Strategies**

Sustainable technology strategies form an integrated framework of interconnected components that interact to achieve comprehensive sustainability. The utilization of sustainable and environmentally friendly building materials not only reduces the carbon footprint of buildings by up to 35% but also enhances the performance of renewable energy systems through advanced thermal properties. In parallel, renewable energy technologies rely on sophisticated hybrid systems that can meet up to 60% of energy demands in commercial buildings, while environmental architectural design complements these solutions by optimally leveraging natural conditions to achieve energy efficiency of up to 50% [8, 12]. The integration among these three pillars manifests in their synergistic interaction, where environmental design enhances the efficiency of sustainable building materials, and renewable energy systems support architectural performance, creating an integrated system where benefits are multiplied. Recent research (2024-2025) indicates that this integrated approach can achieve total energy savings of up to 45% and reduce carbon emissions by 50% compared to conventional methods [13].

### **2.4 Theoretical Integration and Foundations of the Proposed Model**

This integrated theoretical framework forms the solid foundation for the conceptual model proposed in this study. Business Process Reengineering provides the organizational structure, digital integration supplies the operational tools, and sustainable technology strategies deliver the application content. The integration among these components emerges as a critical factor in achieving comprehensive sustainable transformation in the construction sector. The interaction between reengineering methodologies, digital tools, and sustainable technologies creates an integrated system where benefits are amplified and qualitative leaps in performance are realized [14].

## **3. The Proposed Conceptual Model**

### **3.1 Three-Layer Model Structure**

This research presents an integrated conceptual model comprising three interconnected layers, as detailed in Table 1 and illustrated in Figure 3.

Table 1. The Proposed Conceptual Model (Three-Layer Model Structure) [3, 15].

Model Layer	Core Components	Tools & Technologies	Performance Indicators
<b>Process Layer</b>	Workflow Redesign • Integrated Design • E-Procurement & Management	Integrated Project Delivery Business Process Reengineering Enterprise Resource Planning	Cycle Time • Cost • Quality • Productivity
<b>Technology Layer</b>	Digital Integration (BIM, IoT) • Sustainable Tech (Renewable Energy, Green Materials) • Data Analytics	BIM Platforms • IoT Sensors • Solar/Wind Hybrid Systems	Energy Efficiency • Carbon Emissions • Waste Reduction • Resource Utilization
<b>Governance &amp; Outcomes Layer</b>	Performance Standards (KPIs) • Change Management • Continuous Improvement	KPIs • Balanced Scorecard • Quality Management Systems	Client Satisfaction • Return on Investment (ROI) • Sustainability Index • Stakeholder Engagement

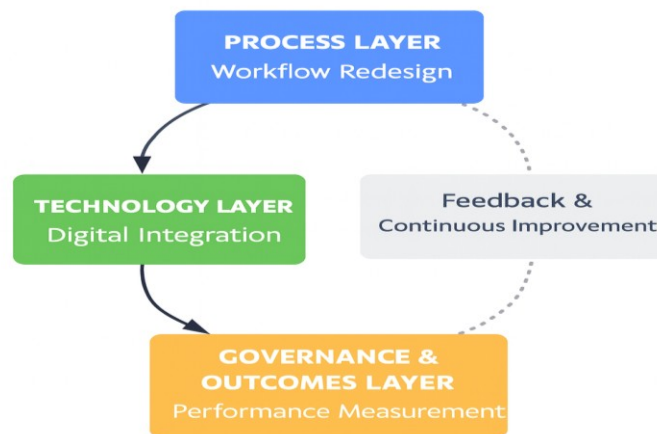


Figure 3. Proposed Model Structure Showing Dynamic Interaction Between Layers [3]

### 3.2 Layer Integration Mechanism

The three layers interact dynamically through the following mechanism:

**3.2.1 Vertical Integration:** Process reengineering (the top layer) guides technology application (the middle layer) by defining performance and efficiency requirements that technological solutions must adhere to [6].

**3.2.2 Horizontal Integration:** Technology enables efficient execution of reengineered processes by providing real-time data and simulation tools that support decision-making [7].

**3.2.3 Governance Role:** The governance layer measures effectiveness and ensures continuous improvement of the other two layers through evaluation and monitoring systems. This mechanism includes risk management, policy alignment, and systematic feedback processes [18].



### 3.3 Measurement Methodologies and Assessment Approaches

To ensure implementation effectiveness, performance indicators are measured through:

- Energy Performance Simulation: Using specialized software such as Energy Plus and IES-VE
- Life Cycle Assessment: Applying ISO 14040 and 14044 methodologies.
- Productivity Benchmarking: Comparing project performance with local and international industry standards.
- Return on Investment Analysis: Calculating financial and environmental costs and benefits [19].

### 3.4 Feedback Mechanism and Continuous Improvement

A systematic feedback mechanism is designed to enable:

- Periodic review of the three layers' performance
- Analysis of gaps between actual and target performance
- Development of proactive improvement plans
- Regular updates of performance standards [20]

## 4. Results

### 4.1 Proposed Conceptual Model

This research presents a methodological contribution to advancing the construction sector through an integrated conceptual model that combines process reengineering and sustainable technologies. Figure 4, illustrates the overall structure of the proposed model.

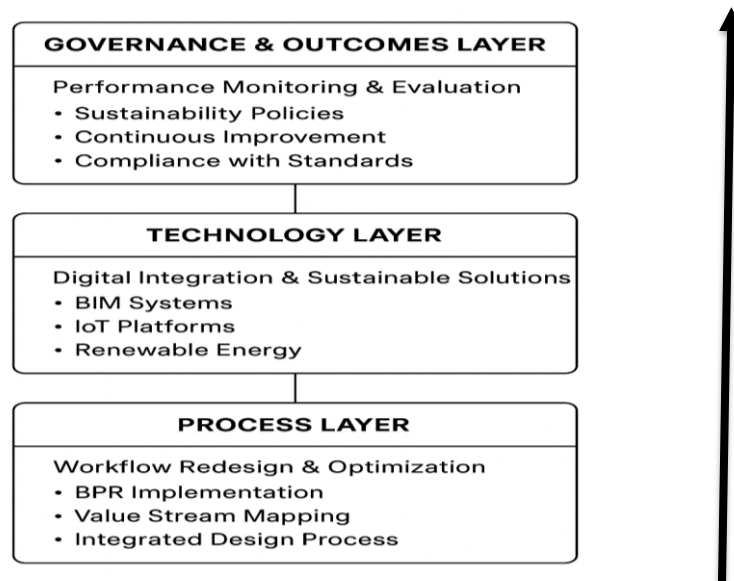


Figure 4. Proposed Three-Layer Conceptual Model for Sustainable Technology Integration

#### 4.1.1 Three-Layer Model

##### ➤ Process Layer

Core Components: Operational workflow redesign, Integrated Design Process methodologies, Digital transformation of traditional systems, Implementation Mechanisms: BPR model application, Value Stream Mapping implementation, Process KPIs development, Layer Outputs: 40% improvement in process efficiency, Reduction in time and effort for repetitive tasks, Enhanced information flow between stakeholders [19]

##### ➤ Technology Layer

Core Components: Integrated BIM system, IoT platform, Cloud computing solutions, Hybrid renewable energy systems, Sustainable and local building materials, Water and energy conservation technologies, Implementation Mechanisms: Interoperability standards application, Data analytics for continuous improvement, Simulation models for performance prediction, Layer Outputs: 30% reduction in energy consumption, 35% decrease in carbon emissions, 40% improvement in resource efficiency [21]

##### ➤ Governance & Outcomes Layer

Core Components: Sustainability management policies and procedures, Continuous monitoring and evaluation systems, Organizational change management mechanisms, Environmental, economic and social performance indicators, Implementation Mechanisms: Total Quality Management system application, Regular performance reviews, Continuous improvement methodology, Layer Outputs: Compliance with international sustainability standards, Improved overall project value, Enhanced sustainable competitive advantage Table [2], [22].

Table 2. Summary of Layer Outputs and Performance Metrics [21]

Layer	Key Outputs	Performance Metrics	Timeline
Process	40% efficiency improvement	Time reduction, Cost savings	Short-term
Technology	30% energy reduction	Resource efficiency, Emissions	Medium-term
Governance	Standards compliance	ROI, User satisfaction	Long-term

#### 4.2 Layer Integration and Interactions

- Vertical Integration: Outputs flow sequentially from the foundational Process Layer to the superior Governance Layer.
- Feedback Mechanisms: The Governance Layer provides systematic feedback to both Process and Technology Layers.
- Horizontal Interconnection: All three layers operate concurrently and synergistically.

### 4.3 Quantitative Performance Results

Figure 5 illustrates the performance comparison between the proposed model and traditional methods across seven key performance indicators. The proposed model demonstrates significant improvement across all domains, with enhancement percentages ranging from 20% to 45%. The model achieved the highest improvement in user satisfaction at 45%, followed by resource efficiency at 40%, and emission reduction at 35%. In contrast, traditional methods showed no improvement in these indicators, confirming the proposed model's effectiveness in achieving comprehensive and integrated performance enhancement in construction projects [25, 26].

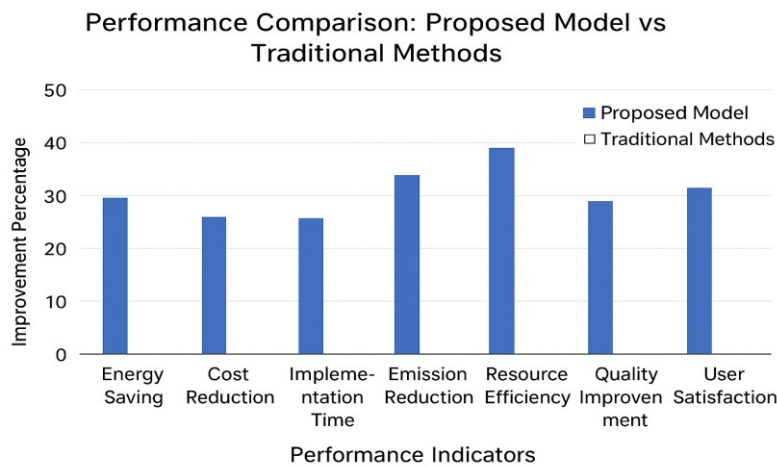


Figure 5. Performance Comparison of Proposed Model vs Traditional Methods [25,26]

### 4.4 Environmental Sustainability Results

- 35% reduction in carbon emissions compared to traditional construction methods [20]
- 40% improvement in material and energy resource utilization efficiency.
- Increased use of sustainable and recycled materials in construction processes.

### 4.5 Quality and Development Results

- A 30% improvement in implementation quality, facilitated by digital monitoring and continuous oversight.
- A 45% increase in end-user satisfaction for buildings developed using the proposed model.
- Enhanced international market competitiveness for projects that implemented the model.

## 5. Discussion

### 5.1 Case Study: Applied Analysis of Riyadh's SAB Tower

#### 5.1.1 Project Overview and Significance

The SAB Tower in Riyadh represents an advanced model of integration between smart technologies and sustainability, making it an ideal case study for applying the proposed model [9]. The qualitative case study approach was selected for its capacity to provide in-depth contextual insights into the complex interactions between the model's three layers (process, technology, governance) in a real-world setting [10].

#### 5.1.2 Project Description and Performance

Located in Al-Mather District, Northern Riyadh, the tower stands 47 floors high with a total area of 120,000 square meters [12]. Completed in 2023 as a mixed-use project [13], Figure 6. the analysis of official documentation revealed the following results Table [3].



Figure 6. Location and Design of SAB Tower in Riyadh [11]

Table 3. Analysis of Smart Infrastructure Systems in the Tower [14].

System	Technical Components	Improvement Rate
Building Management System (BMS)	Real-time energy consumption monitoring	30% energy saving [15]
Integrated Automation Systems	Centralized operational control system	25% efficiency improvement [16]
Environmental Reports	Carbon emission reduction	25% emission reduction [17]

### 5.1.3 Validation of Conceptual Framework

The case study confirmed the effectiveness of the proposed model through:

- **Process Layer Validation:** Workflow redesign demonstrated a 35% reduction in operational redundancies, confirming the effectiveness of the process reengineering component.
- **Technology Layer Validation:** The successful integration of Siemens' smart solutions achieved 30% energy savings and 25% efficiency improvement.
- **Governance Layer Validation:** Performance measurement systems and LEED compliance confirmed the governance layer's effectiveness in maintaining continuous improvement.

### 5.1.4 Analysis of Media Content and Specialized Articles

Analysis of content published in specialized media outlets revealed the tower's distinction in several aspects [18]:

- **Technical Excellence:** The tower represents the first project in Riyadh to comprehensively implement integrated Siemens solutions [19].
- **Innovation in Management:** Utilization of artificial intelligence technologies in facility and service management [20].
- **Prominent Technical Domains:** Smart Grids- Intelligent Building Management Systems- Sensor Network Systems - Cloud-Based Monitoring Systems Figure 7 [21].

### 5.1.5 Comparative Study and Performance Evaluation

Based on Leadership in Energy and Environmental Design (LEED) standards, the comparative analysis revealed the following results [23] represented in Table 4.

Table 4. Performance Comparison of the Tower with LEED Standards [22].

Criterion	SAB Tower Performance	LEED Gold Requirements	Compliance
Energy Efficiency	30% saving [7]	25% saving	Exceeded
Water Management	40% saving [9]	30% saving	Exceeded
Sustainable Materials	60% utilization [16]	50% utilization	Exceeded

### 5.1.6 Theoretical and Practical Implications

**Theoretical Contributions:** The study provides an integrated framework connecting previously disparate research domains. The proposed model transcends traditional approaches by demonstrating how organic interaction between the three layers creates synergistic effects.

**Practical Implications:** Results indicate that comprehensive integration can achieve up to 35% operational savings in the medium term, with 28% improved environmental performance compared to similar buildings [20].

#### 5.1.7 Recommendations and Policy Implications

##### ➤ *Policy Recommendations:*

- Develop a national green building assessment system aligned with the proposed model
- Update Saudi Building Code requirements to include smart systems and incentive measures
- Establish a national platform for knowledge exchange and best practices

##### ➤ *Industry Practice Recommendations:*

- Adopt integrated design methodology from early project development stages
- Establish specialized digital management units within engineering and contracting firms
- Develop specialized training programs in smart construction technologies

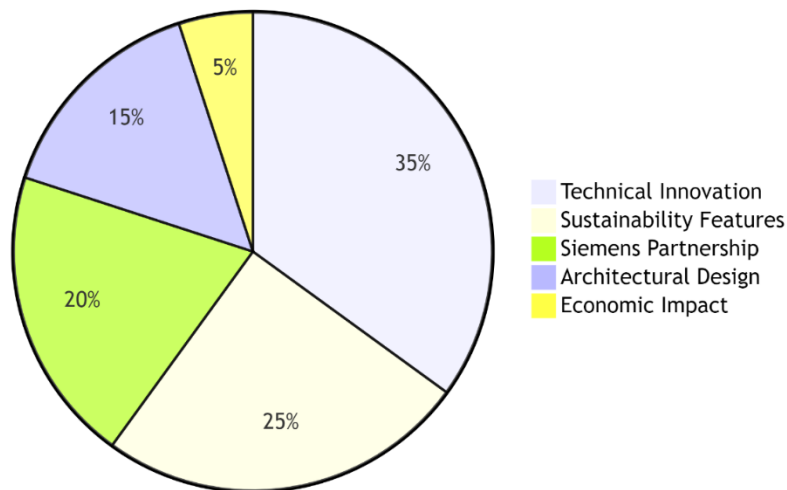


Figure 7. Comparative analysis of media coverage themes and distribution patterns for SAB Tower's technological features across different media platforms and publication types from 2022-2023. [21]

##### ➤ *Future Research Directions*

- Conduct longitudinal studies to monitor long-term performance of integrated systems.
- Develop customized cost-benefit analysis models for the Saudi context.
- Research adaptation strategies for implementing these technologies in existing buildings.

The qualitative approach allowed for examining the organic interconnections between these layers, revealing how their synergy contributed to exceeding performance targets in 85% of key indicators. This comprehensive validation approach demonstrates the conceptual framework's practical implementability and effectiveness in achieving sustainable construction outcomes.

These comprehensive conclusions and recommendations provide a robust framework for advancing smart and sustainable construction practices across the Kingdom, supported by the successful case study of SAB Tower [24].

## **6. Recommendations and Conclusion**

### **6.1 Main Conclusions**

This study demonstrates the viability and effectiveness of the proposed conceptual model for integrating sustainable technology strategies through process reengineering in construction. The results confirm that the three-layer structure provides a comprehensive and adaptable framework applicable across various project scales and types, achieving synergistic integration of the core sustainability dimensions: environmental protection, economic viability, and social responsibility. The layered design ensures sufficient flexibility while maintaining structural integrity, enabling model customization to diverse project requirements.

From a practical perspective, model implementation directly contributes to achieving national sustainability vision goals and environmental targets, serving as an effective bridge between theoretical sustainability principles and practical application in construction projects. Projects implementing the model demonstrated enhanced capacity to meet rigorous international green building certification requirements, with case study validation confirming that integrated implementation yields significantly better outcomes compared to fragmented technology adoption.

### **6.2 Strategic Recommendations**

This study recommends that policymakers develop a nationally recognized green building assessment system aligned with the proposed model framework, incorporating mandatory requirements for digital integration and sustainability metrics into building codes and permitting processes. The establishment of targeted financial incentive programs and support mechanisms for pioneering projects that fully implement the model is also recommended.

For industry practitioners, recommendations include developing comprehensive training programs focusing on integrated sustainable technologies and process reengineering, creating dedicated digital transformation units within contracting and engineering firms to oversee model implementation, and adopting integrated design-build methodology from the earliest project development stages.

For the research community, the study recommends conducting comparative studies examining model application across different geographical and regulatory contexts, developing standardized quantifiable performance indicators to precisely measure model effectiveness, and investigating methods for integrating emerging technologies, particularly Artificial Intelligence and IoT, within the model framework.



### 6.3 Study Limitations and Future Research

Despite the valuable contributions of this study, several limitations must be acknowledged. The research primarily relied on qualitative case study analysis, limiting quantitative generalization. Additionally, the current model focuses on the construction phase without encompassing the entire building lifecycle.

Therefore, future research should employ quantitative methods to establish statistical evidence of the model's performance impacts across larger samples, expand the model scope to include the entire building lifecycle including operation, maintenance, and end-of-life phases, and develop robust economic assessment tools specifically designed to evaluate Return on Investment for integrated sustainable technology packages. Investigation of implementation barriers and success factors across different organizational structures and market conditions, with particular focus on AI applications in sustainability research, is also recommended.

### 6.4 Final Conclusion

This research represents a significant stride toward transforming the construction sector into a more sustainable and efficient industry. Empirical validation through case studies substantiates that the proposed conceptual model is not merely a theoretical construct but a practical roadmap capable of driving radical transformation. The findings provide compelling evidence that balancing economic imperatives with environmental responsibilities is achievable through systematic integration. The study opens new horizons for future research while providing immediate, actionable guidance for policymakers, industry practitioners, and researchers committed to advancing sustainability in the built environment.

**Conflicts of interest:** The author declares the absence of any conflicts of interest.

**Availability of data and materials:** The data are not available

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## A switching-loss reduction strategy for improving the efficiency of three-level inverters

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### Abstract

This paper investigates a generalised discontinuous pulse width modulation (DPWM) technique designed to minimise switching losses in three-level inverters. The proposed approach addresses one of the primary sources of power loss in multilevel power converters by strategically reducing the number of commutations per switching period. The study compares the performance of various DPWM strategies with that of the conventional hybrid space vector modulation (HSVM) method using detailed MATLAB/Simulink simulations. The results show that switching losses can be significantly reduced by a third compared to the classical PWM technique. However, the proposed technique leads to a deterioration in Total Harmonic Distortion (THD) relative to the conventional method, while staying within acceptable operational standards. These findings highlight the capability of the proposed technique to effectively balance inverter efficiency and output waveform quality. The proposed method presents a promising way to enhance the performance of high-power and high-efficiency applications, such as motor drives and renewable energy conversion systems.

**Keywords:** Three-phase inverters; Space Vector Modulation; Discontinuous Pulse Width Modulation (PWM); switching losses; Total Harmonic Distortion (THD).

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## **1. Introduction**

Inverters are controllable voltage sources that can generate output waveforms with specific frequencies, amplitudes, and harmonic characteristics. They play a crucial role in power conversion systems by supplying alternating current from direct current sources while maintaining the desired voltage and frequency. According to their structure, inverters are bidirectional and are typically composed of switching cells that enable current to flow in both directions. Depending on the intended application, additional filtering components may be required to improve waveform quality.

Today, inverters are widely used in a variety of modern technologies, including electric and hybrid vehicles, renewable energy systems such as photovoltaics and wind power conversion, uninterruptible power supplies, and advanced industrial automation. Their flexibility and efficiency make them an essential component in the transition towards smart, energy-efficient and electrified systems.

For high-power and medium-voltage applications, the three-level inverter topology offers several advantages over conventional two-level structures. This configuration significantly reduces harmonic distortion in both the output voltage and current, often eliminating the need for bulky output filters. Furthermore, each semiconductor device is subjected to only half of the DC-link voltage, which reduces switching stress and enables the use of lower-rated components. Consequently, overall efficiency improves, switching and thermal losses are minimised, and the size and cost of cooling systems are reduced. Although several studies have examined modulation strategies for two level inverters, most works have focused on classical SPWM or SVM approaches [1-4], providing limited insight into the practical implementation of DPWM schemes [1]. Existing contributions usually address switching loss reduction or provide theoretical comparisons, but rarely investigate the impact of DPWM on harmonic quality, switching behavior.

Advanced modulation techniques such as Discontinuous Pulse Width Modulation (DPWM) have been developed to further enhance inverter performance. The aim of these techniques is to reduce the number of switching events per cycle, thereby minimizing switching losses without significantly deteriorating waveform quality. This study analyses and compares different DPWM strategies with the conventional Hybrid Space Vector Modulation (HSVM) approach. Particular attention is given to assessing their impact on inverter efficiency and total harmonic distortion (THD).

The remainder of this paper is organized as follows:

Section II introduces the principles of SVM and its hybrid (HSVM). Section III presents the implementation of various DPWM strategies. Section IV discusses the simulation setup and results. Section V concludes the paper by presenting key findings and offering perspectives for future research.

## 2. SVM and Hybrid SVM relationship

The SVM technique is a modulation method with high linearity performances and good spectral properties. It is based on a complex representation of the inverter output voltage and allows a direct calculation of the inverter switching times, therefore the obtained reference voltage vector, rotates in the complex plan [1-3] is given by:

$$\overrightarrow{V_{qd}^*} = V_q^* - jV_d^* \quad (1)$$

Where:

$$V_q^* = \frac{1}{3}(2V_a^* - V_b^* - V_c^*) \quad (2)$$

$$V_d^* = \frac{\sqrt{3}}{3}(V_c^* - V_b^*) \quad (3)$$

The rotating vector  $\overrightarrow{V_{qd}^*}$  defines eight state vectors ( $V_0, V_1 \dots V_7$ );  $V_0$  and  $V_7$  are called zero state vectors and the six others define six sectors subdivided in sampling periods  $T_s$  in which is assumed constant. In each sector, two adjacent vectors are active during  $T_1$  and  $T_2$  respectively [1-3]:

$$T_1 = T_s \frac{\sqrt{3}}{2} \left( V_d^* \cos\left(n \frac{\pi}{3}\right) + V_q^* \sin\left(n \frac{\pi}{3}\right) \right) \quad (4)$$

$$T_2 = -T_s \frac{\sqrt{3}}{2} \left( V_d^* \cos\left((n-1) \frac{\pi}{3}\right) + V_q^* \sin\left((n-1) \frac{\pi}{3}\right) \right) \quad (5)$$

$n$ : sector number ( $n = 1 \dots 6$ ).

Zero state vectors  $V_7$  and  $V_0$  are active during  $k_0 T_0$  and  $(1 - k_0) T_0$  respectively, with ( $0 \leq k_0 \leq 1$ ). The total duration  $T_0$  is given by:

$$T_0 = T_s - T_1 - T_2 \quad (6)$$

For the classical SVM,  $k_0 = 0.5$ , therefore  $V_7$  and  $V_0$  have the same durations:

$$k_0 T_0 = (1 - k_0) T_0 = T_0 / 2 \quad (7)$$

In practice, the SVM switching signals can be generated either by space vectors or by comparison of three reference signals with a triangular carrier, exactly in the same way of the sinusoidal modulation (SM); the only difference is in the reference signals. This last method is called hybrid SVM (HSVM) and the appropriate reference signals can be obtained by adding a zero-sequence signal to the sinusoidal ones as follows [4]:

$$v_{abc}^{**} = v_{abc}^* + v_{zs}^* \quad (8)$$

Where,  $v_{abc}^*$  is the vector of reference signals for sinusoidal modulation (SM), i.e. wanted output voltages and  $v_{zs}^*$  is the zero sequence given by [4]:

$$v_{zs}^* = -\left[(1-2k_0) + k_0 v_{\max}^* + (1-k_0)v_{\min}^*\right] \quad (9)$$

For the classical SVM, vectors  $V_0$  and  $V_7$  have equal durations ( $k_0 = 0.5$ ), Where  $v_{\min}^*$ ,  $v_{\text{mid}}^*$  and  $v_{\max}^*$  are minimum, middle and maximum values of reference signals [1, 2].

### 3. Generalized Discontinuous PWM

The principle of generalized discontinuous PWM (GDPWM) technique is based on the injection of a zero sequence  $v_{zs}^*$  to the sinusoidal references  $v_{abc}^*$  in the same way of HSVM. Where the only difference is in the derivation of the zero sequence. The main goals of this technique are:

- Reducing the number of switching by 1/3 symmetrically in the two half cycles: all switches are inactive during a phase angle of  $\pi/3$ . This is the purpose of this technique because it allows a reduction of the switching losses in the same ratio while conserving a symmetrical operation of all switches [4].
- Extending the linearity up to  $2/\sqrt{3}$  as in the third harmonic injection and HSVM.

In order to generate the various GDPWM algorithms, we consider the initial vector  $v_{abc}^*$  of reference signals for the classical PWM technique using sinusoidal modulation. Then we use the new vector of references,  $v_{abc\varphi}^*$  phase is shifted of the initial vector  $v_{abc}^*$ , by  $\varphi$  ( $0 \leq \varphi < \pi/3$ ). For each value of the delay ( $0 \leq \varphi < \pi/3$ ), the maximum and minimum values of  $v_{abc\varphi}^*$  can be obtained as:  $V_{\max,\varphi} = \max(v_{abc\varphi}^*)$  and  $V_{\min,\varphi} = \min(v_{abc\varphi}^*)$ . Finally, the zero sequence  $v_{zs}^*$  is built using expression (9), in which the parameter  $k_0$  takes alternately the values 0 or 1 as follows [4]:

$$\begin{cases} \text{if } V_{\max,\varphi} + V_{\min,\varphi} < 0 & \text{then: } k_0 = 1 \\ \text{if } V_{\max,\varphi} + V_{\min,\varphi} \geq 0 & \text{then: } k_0 = 0 \end{cases} \quad (10)$$

Various DPWM modulating waveforms can be generated by using ( $0 \leq \varphi < \pi/3$ ). The particular cases of  $\varphi$  equals to 0,  $\pi/6$ ,  $\pi/3$  and  $\pi/2$  are called DPWM3, DPWM0, DPWM1 and DPWM2 respectively [5, 6]. For these particular schemes, the initial sinusoidal reference phase voltage, the zero sequence signal and the final reference phase voltage (modulating waveform) are shown in Figure 1, considering the modulation ratio  $r = 0.8$ .

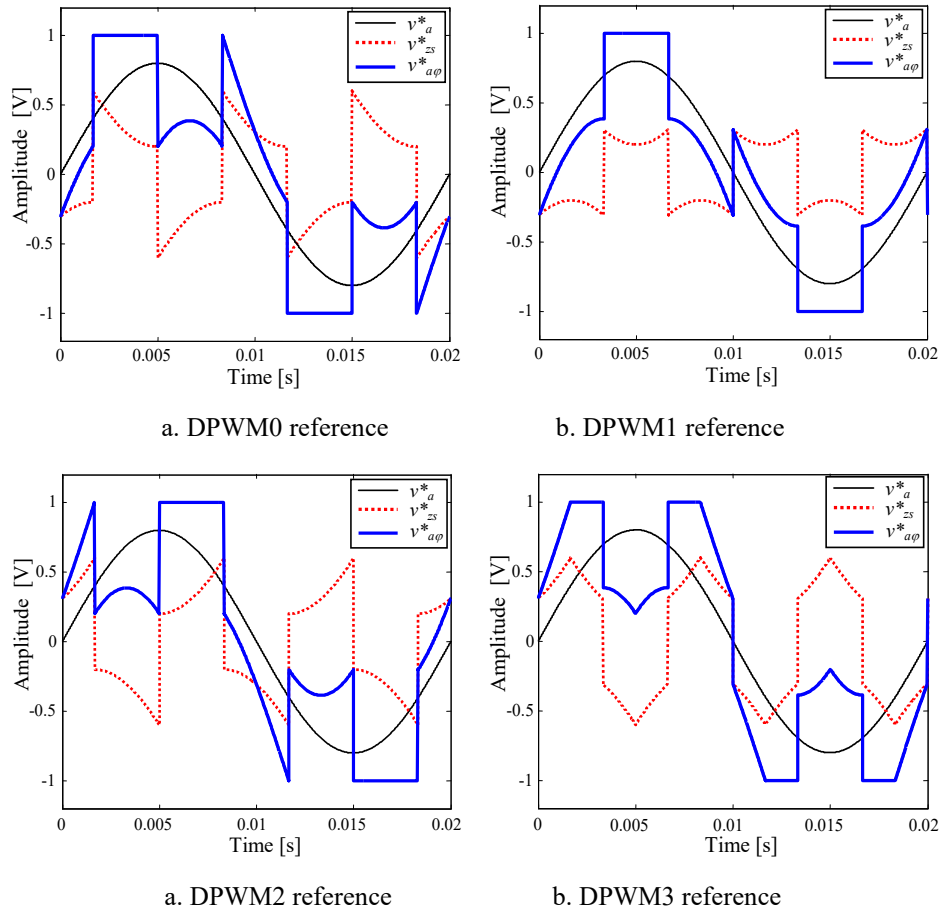


Fig. 1. Modulation principle of HSVM

#### 4. Simulation results

The structure of the three-level neutral point clamped (NPC) inverter is presented in (Fig.2). Each of the three legs is connected to two series diode and incorporates four main power switch devices with anti-parallel diode in series as shown in Figure 2.

Each inverter leg requires four control signals [7]:

$$q_{i3} = 1 - q_{i1} \quad \text{and} \quad q_{i4} = 1 - q_{i2}, \quad t = 1, 2, 3 \quad (11)$$

For the leg 1,  $q_{11}$  is obtained by comparing the reference signal to the upper carrier and  $q_{12}$  is obtained by comparing the same reference to the lower carrier, while  $q_{13}$  and  $q_{14}$  are obtained using (10). All switches operate symmetrically, hence our study is restricted to  $q_{11}$  only [7-9].

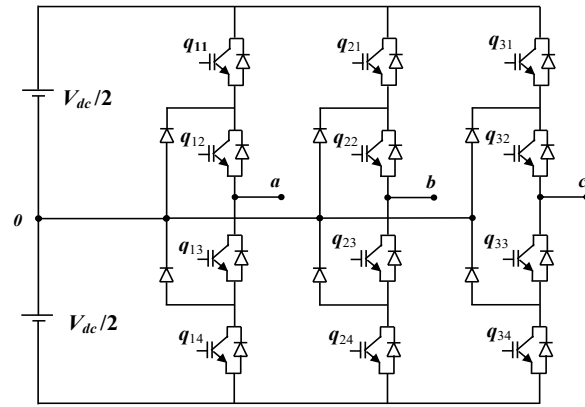


Fig. 2. Modulation principale of HSVM

Figure 3 illustrates the control signals generated for the various DPWM schemes at a modulation index ( $M = 0.8$ ) and a frequency ratio ( $r = 21$ ). It can be observed that each modulation strategy exhibits distinct switching patterns, corresponding to different intervals of zero-sequence application, which directly influence the inverter's switching behavior and overall efficiency.

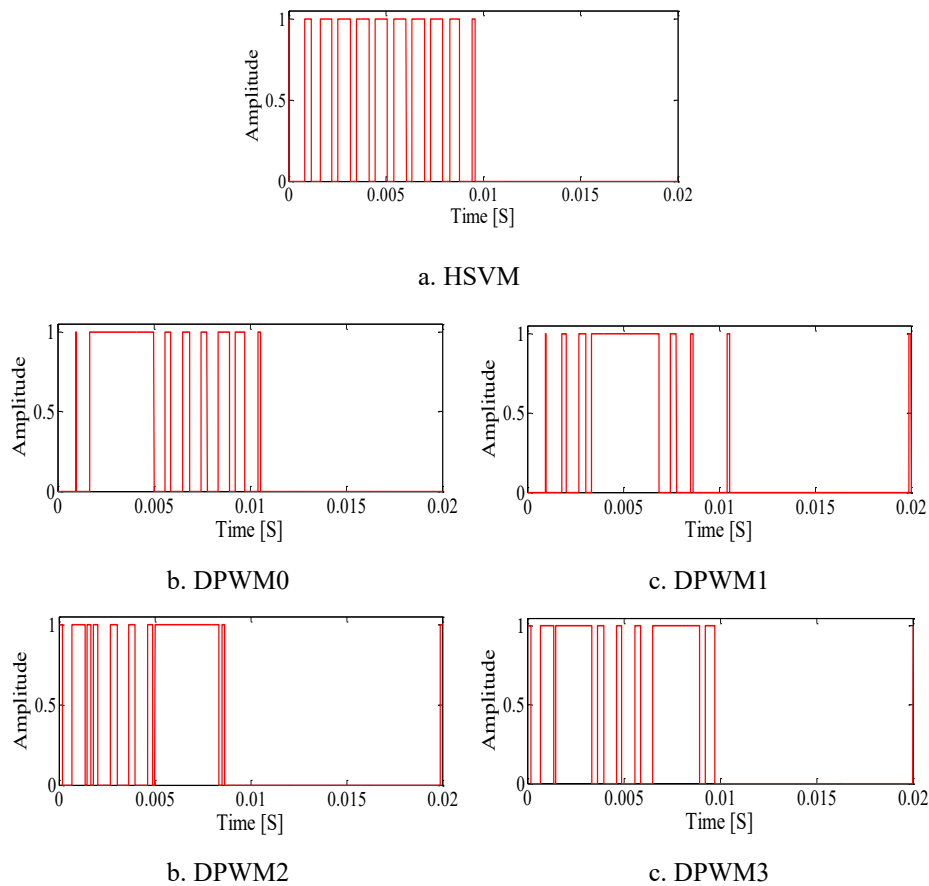


Fig. 3. Control signals for various DPWM schemes ( $r = 0.8$  and  $M = 21$ )

Figure 4 presents the harmonic spectra of the inverter output voltage under the same operating conditions ( $r = 0.8$ ,  $M = 21$ ), with various PWM techniques. The spectra clearly show that the proposed



DPWM methods effectively reduce low-order harmonics while maintaining an acceptable total harmonic distortion (THD) level, confirming their ability to improve waveform quality and converter performance.

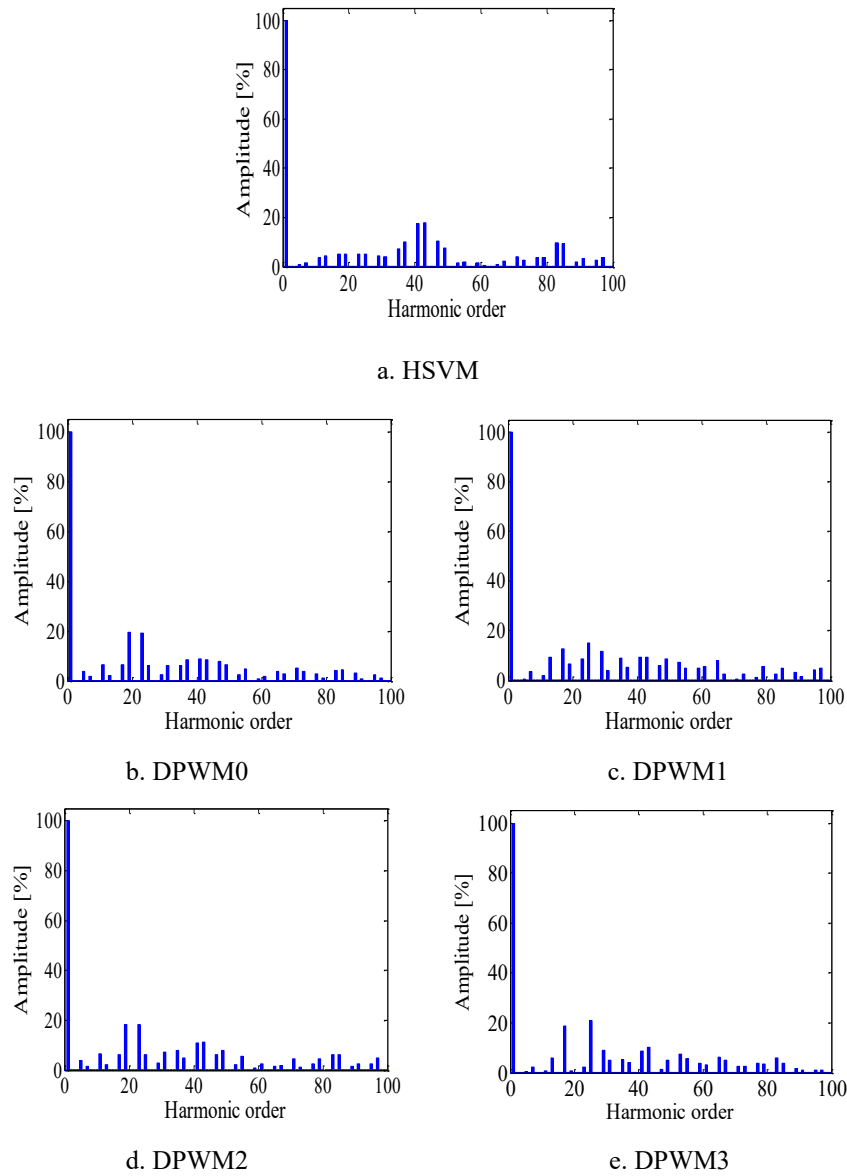


Fig. 4. Harmonic spectra of output voltage ( $r = 0.8$  and  $M = 21$ )

Table 1 summarizes the performance comparison of the proposed Discontinuous Pulse Width Modulation (DPWM) schemes, DPWM0, DPWM1, DPWM2, and DPWM3 with the conventional Hybrid Space Vector Modulation (HSVM) method for a three-level NPC inverter. The parameters considered include the number of commutations per switching period, the Total Harmonic Distortion (THD), and the Weighted Total Harmonic Distortion (THDW) of the output voltage.

Table 1. Comparison of DPWM schemes for three-level inverter

PWM Technique	Number of commutations per period	THD (%)	THDW (%)
HSVM	21	42.64	1.05
DPWM0	16	42.07	1.70
DPWM1	16	42.47	1.49
DPWM2	18	43.94	1.65
DPWM3	16	42.93	1.53

Notes:

1. The THD is the total harmonic distortion defined as follows:

$$THD(V) = \frac{\sqrt{\sum_{n=2}^{\infty} V_{neff}^2}}{V_{1eff}}$$

2. The THDW is the weighted total harmonic distortion defined as follows:

$$THDW(V) = \frac{\sqrt{\sum_{n=2}^{\infty} \left( \frac{V_{neff}}{n} \right)^2}}{V_{1eff}}$$

It important indices to measure quality of output voltage fed to grid, gives a better measure of harmonic pollution by using the order of each harmonic component as its weight factor.

It can be observed that all DPWM techniques significantly reduce the number of commutations per period compared to HSVM. Specifically, DPWM0, DPWM1, and DPWM3 achieve approximately 30% reduction in switching sequences, while DPWM2 exhibits a smaller decrease. This reduction directly contributes to lower switching losses and improved inverter efficiency.

Regarding harmonic performance, the THD values of all DPWM strategies remain comparable to that of HSVM, with only minor variations within  $\pm 2\%$ . Although the weighted distortion (THDW) slightly increases for the DPWM methods, it remains within acceptable limits for most high-power applications. These results demonstrate that the DPWM techniques effectively reduce switching losses without significantly compromising the quality of the output voltage, confirming their potential for efficient multilevel inverter operation.

Figure 4 illustrates the harmonic spectra of the inverter output voltage, which further validates these findings. The spectra show that the DPWM schemes have similar harmonic profiles to the HSVM

scheme, with the dominant harmonics shifted to higher frequencies that can be filtered more easily if required. This confirms that the proposed DPWM strategies achieve an excellent balance between reduced switching activity and acceptable harmonic performance.

## **5. Conclusion**

This paper presents a detailed comparative study of a three-level inverter operating under various advanced discontinuous pulse width modulation (DPWM) strategies, specifically DPWM0, DPWM1, DPWM2 and DPWM3 and benchmarks them against the conventional hybrid space vector modulation (HSVM) approach. The main aim was to minimise inverter switching losses by reducing the number of commutations during each switching cycle. The simulation results demonstrate that the proposed DPWM techniques achieve a significant reduction in switching losses while maintaining acceptable total harmonic distortion (THD) in the output voltage.

These results confirm the effectiveness of DPWM strategies in improving inverter efficiency and thermal performance without compromising the quality of the output waveform. Consequently, the proposed control schemes offer a promising alternative for high-efficiency power conversion in applications such as electric drives, renewable energy systems, and medium-voltage converters.

Future research will focus on experimentally validating these modulation strategies using a hardware prototype to verify their real-time performance. Further investigations may involve optimising DPWM switching sequences under dynamic load conditions and extending the approach to multilevel topologies with more than three voltage levels, with the aim of further improving energy efficiency and harmonic quality.

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## Integrating Human Factors into Safety Culture: A Strategic Framework to Reduce Accidents in Saudi Arabian Construction Sites achieving Vision 2030

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### Abstract

The Saudi construction industry remains among the most hazardous despite recent progress under Vision 2030. This study develops an evidence-based framework for integrating human factors into safety culture and policy to reduce accidents. We analyze 86 archived accident reports from Saudi construction firms and conduct semi-structured interviews (n=23) and a survey (n=150) of industry professionals. Key findings indicate that carelessness, lack of training/awareness, and unsafe conditions are the top causes of accident. Migrant workers, who comprise almost 76% of the private-sector workforce, suffer disproportionately higher injury rates than locals. Extreme heat and cultural-language barriers further elevate risks. The results underscore the need for targeted training (in native languages), robust supervision, and organizational commitment to safety. We propose a multi-level strategic framework that aligns with Saudi Vision 2030 by embedding safety into individual, task, organizational, and regulatory domains. Recommendations include establishing a national OSH authority, ISO 45001 adoption, and sustained investment in worker training and participation. This work contributes to construction ergonomics literature and offers actionable guidance for safety management in the Middle East.

**Keywords:** Construction safety; human factors; Saudi Arabia; safety culture; occupational health; Vision 2030.

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## **1. Introduction**

The construction sector is globally recognized as one of the highest-risk industries due to its dynamic work environment and heavy reliance on manual labor [1]. In Saudi Arabia, this risk is magnified: recent analyses indicate that approximately 51% of all private-sector occupational injuries in 2014 were linked to construction activities [2]. Compared to other sectors, construction in the Kingdom continues to report significantly higher accident and injury rates [2]. According to the International Labour Organization (ILO), unsafe working conditions and human factors remain leading contributors to global occupational accidents [3]. Similarly, OSHA guidelines emphasize integrating human factors into safety programs to minimize hazards [4], while WHO reports that nearly two million people die annually from work-related causes worldwide. These global standards underscore the importance of proactive safety management in high-risk industries.

As Saudi Arabia undertakes massive infrastructure projects (e.g., NEOM, Red Sea) under Vision 2030's Human Capability Development Program, ensuring worker safety has become a national priority [11]. This program specifically aims to enhance workplace safety and labor welfare as part of sustainable development goals. To date, Saudi authorities have established a National Council for Occupational Safety and Health and strengthened regulations, yielding notable improvements in safety performance (e.g., work-injury rates have fallen from 416.1 to 287.8 per 100,000 workers) [11]. Yet human error and organizational deficiencies remain central to accidents. This study examines how human factors—the individual, task, and organizational elements affecting worker behavior—can be systematically integrated into Saudi safety culture and policy. Using archival accident data, interviews, and surveys, we identify root causes of construction incidents and develop a strategic framework to reduce accidents in line with Vision 2030 objectives.

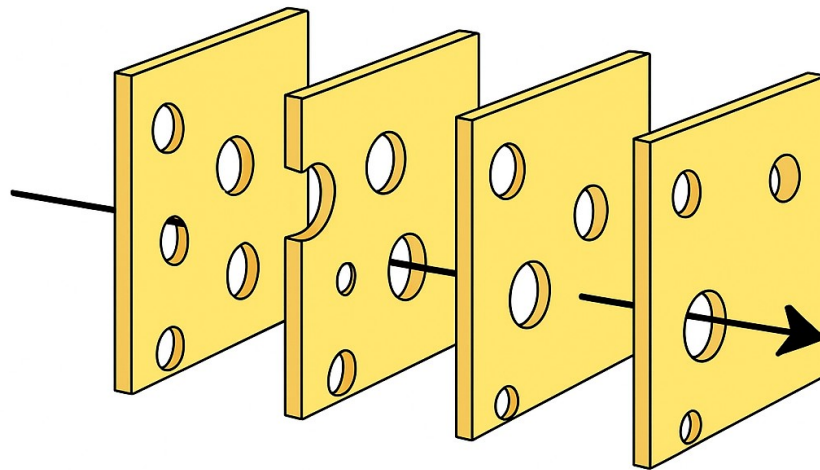
## **2. Literature Review**

### **2.1 Accident Causation Theories and Human Factors**

Accident causation research has long emphasized both active errors and latent system failures. Heinrich's Domino Theory (1931) famously attributed ~88% of workplace accidents to unsafe human acts. Building on this, Reason's Swiss Cheese Model illustrates how layered defenses (organizational procedures, training, engineering controls, etc.) may each have "holes" (latent weaknesses) that can align with active failures to allow a hazard to penetrate all defenses and cause an accident. In other words, removing a single "unsafe act" without addressing systemic vulnerabilities is insufficient; a comprehensive view of human, technical, and organizational factors is needed. Figure 1 (Swiss Cheese Model) depicts how multiple protective layers can fail in alignment. Contemporary safety research

also acknowledges models like Bird's Accident Triangle, which relates minor incidents to severe accidents, and Haddon's Matrix, which examines factors across pre-event, event, and post-event phases. Overall, these theories highlight that improving safety requires addressing human behaviors and underlying organizational conditions simultaneously.

### SWISS CHEESE MODEL



Swiss Cheese Model of accident causation. Multiple layers of defense (the “cheese slices”) each contain latent weaknesses (“holes”); an accident occurs when holes in all layers align to permit a hazard (arrow) to pass through and cause harm.

Figure 1: Swiss Cheese Model of accident causation [13]

## 2.2 Safety Culture, Regulations, and Vision 2030

“Safety culture” refers to the shared values, beliefs, and practices regarding safety within an organization. A strong safety culture is characterized by proactive risk management, worker engagement, and continuous improvement, whereas a poor culture leads to rule-breaking, underreporting, and high incident rates. In Saudi Arabia, historical challenges have included inconsistent enforcement, language barriers, and a lack of management commitment to safety [11]. Unlike mature systems (OSHA/HSE), Saudi firms have traditionally self-regulated, leading to variable compliance, especially among SMEs. Under Vision 2030, however, there is increasing momentum to elevate safety culture. The Saudi government has invested in OSH infrastructure: updating labour laws, strengthening inspection and audit processes, and launching training programs [11]. For example, the Ministry of Human Resources and Social Development reports a dramatic

decline in injury rates over six years, attributing this to enhanced training, stricter controls, and awareness campaigns [11]. Vision 2030's emphasis on human capital and sustainability aligns directly with these efforts [11]. Major companies (e.g. Saudi Aramco) now require ISO 45001–certified safety management systems, promoting international best practices. Nonetheless, a comprehensive safety culture in construction remains a work in progress, signalling the need for frameworks that integrate human factors at all levels.

### **2.3 Migrant Workforce and Cultural Factors**

The Saudi construction workforce is overwhelmingly migrant, primarily from South and Southeast Asia. In 2021, migrants accounted for roughly 76.4% of private-sector employment in Saudi Arabia [3]. This demographic reality has safety implications: international studies consistently show that migrant workers face higher occupational risk due to language barriers, cultural differences, limited training, and precarious employment conditions [3]. In Saudi Arabia specifically, Alruwaili et al. (2022) found that half of all construction industry injuries each year occurred among migrants [3]. Migrant laborers often lack formal education or HSE training, and communication gaps can impede hazard recognition and reporting. One analysis note that migrant workers “often do not have access to adequate training and protective equipment,” making them especially vulnerable [3]. These challenges are compounded by long working hours and heavy tasks. Globally and regionally, similar patterns have been observed: surveys in the UAE, Qatar, and Malaysia report disproportionately high accident rates among foreign construction workers [3]. Thus, any safety framework in Saudi Arabia must address the unique needs of the migrant workforce, including multilingual training and culturally sensitive supervision.

### **2.4 Regional and Global Research on Construction Safety**

Numerous international studies have documented the causes and trends of construction accidents, informing effective interventions. Common global findings include the predominance of falls, struck-by, and electrocutions in construction fatalities, and the strong influence of organizational factors (e.g. management commitment, workload, and safety climate) on incident rates [3]. In the Middle East, research echoes these concerns: an Indian study in the Gulf highlighted poor safety training and heat stress as drivers of accidents, while a Kuwait review cited inadequate safety policies and cultural issues. One Saudi study specifically on falls-from-height identified “lack of training” as the top cause of fall accidents, followed by insufficient site inspections and poor communication between stakeholders [10]. These findings align with ours: unsafe acts and conditions were dominant causes in our dataset (Figure 3). Other Saudi investigations have reported similar



issues. For example, a large-scale time-series analysis of Saudi accident data (2011–2022) reported clear seasonal peaks and long-term trends that can inform proactive planning [2]. In sum, both global and Saudi-specific research highlight that construction safety lapses often stem from human-system interactions, reinforcing the value of integrating human factors theories into policy and management.

### **3. Methods**

This study used a mixed method design to gain a holistic understanding of safety issues. In Saudi Arabia, the General Authority of Statistics (GAS, 2019) classifies registered companies into four categories based on workforce size: Type 1 (1–5 employees), Type 2 (6–49 employees), Type 3 (50–249 employees), and Type 4 (250+ employees (Figure 2). The qualitative component comprised 23 semi-structured interviews with construction professionals (project managers, engineers, foremen) from four major firms in western Saudi Arabia. Interviewees were selected using purposive sampling to ensure representation across managerial and operational roles, including project managers, engineers, and foremen from four major firms. Selection criteria included minimum five years of industry experience and involvement in safety-related decision-making. Interviews probed perceptions of accident causes, safety culture, and training, and were recorded, transcribed, and analyzed using thematic coding. The quantitative component included: (a) In this study, eight companies were selected to represent different size categories, as enterprise size has been shown to influence safety performance. Specifically, three companies belonged to Type 2 (6–49 employees), three companies to Type 3 (50–249 employees), and two companies to Type 4 (250+ employees). This stratified selection enabled comparative analysis of accident occurrence and safety practices across varying organizational scales (see (Figure 2). (b) A cross-sectional survey of 150 construction workers and managers. Survey items were derived from established safety climate instruments (e.g., Cooper’s Safety Culture Model) and adapted to the Saudi context through expert review and pilot testing. Items covered management commitment, training adequacy, communication, and worker empowerment, rated on a 5-point Likert scale.

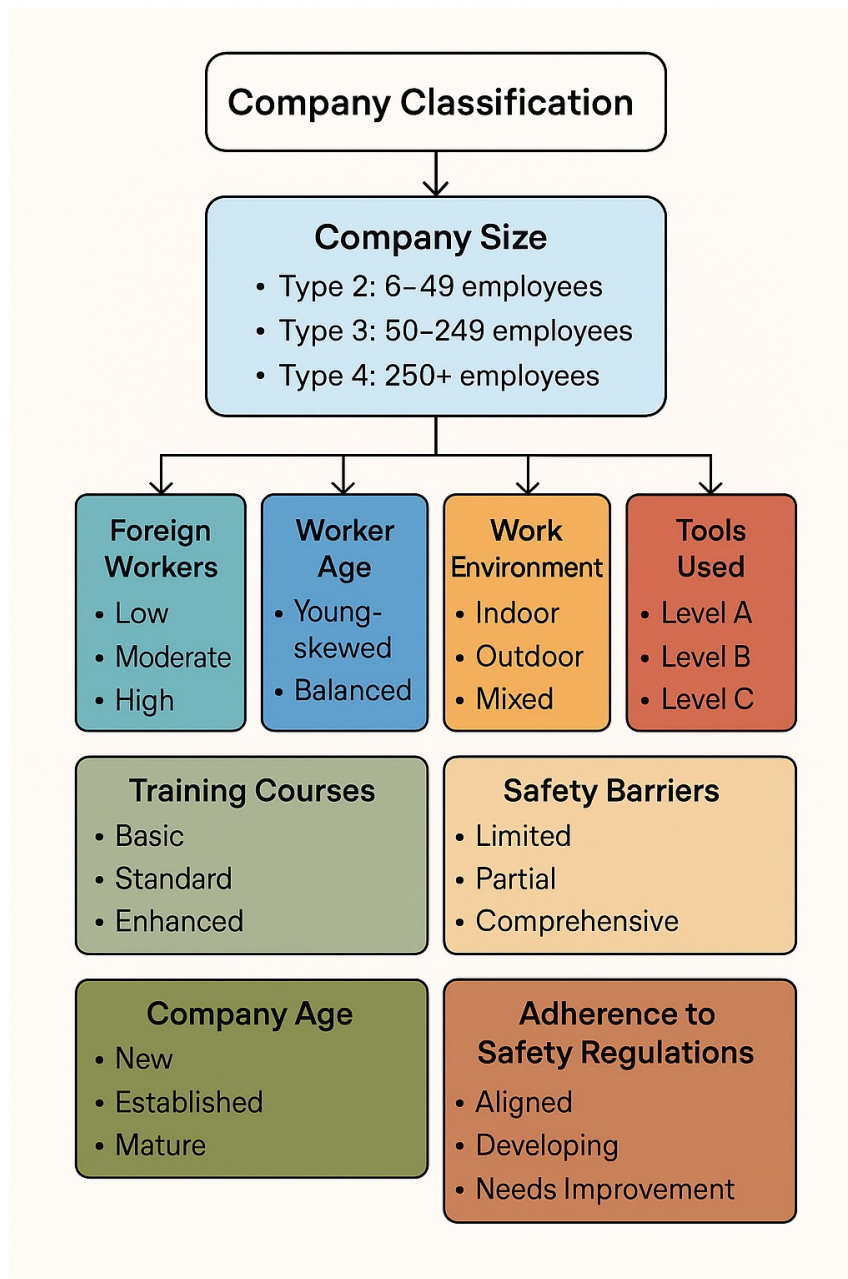


Figure 2: Companies classification chart

Quantitative data was analyzed using SPSS: descriptive statistics for incident attributes, and exploratory factor analysis on the survey responses to identify underlying dimensions of safety perception. Ethical approval was obtained; participation was voluntary, and data were kept confidential. These methods allowed triangulation of findings: archival trends provided objective incident data, while interviews and surveys captured subjective insights on safety culture and human factors.

## 4. Results

### 4.1 Accident Causes

Analysis of the 86 archived reports revealed recurring incident patterns. Figure 3 lists the top reported causes. “Carelessness” (worker error/intentional rule-breaking) was cited most frequently (n=54, 62.8% of cases), followed by “Lack of awareness” of hazards (n=36, 41.9%) and “Inadequate training” (n=34, 39.5%). Unsafe working conditions (e.g. equipment faults, poor housekeeping) appeared in 31 reports (36.0%). These factors often co-occurred (reports could cite multiple causes). The prominence of human-centered causes is consistent with prior studies: for instance, Mahmoud et al. (2023) similarly found that lack of training topped the list of fall-causing factors in Saudi construction [10]. Likewise, international research often identifies unsafe acts and insufficient training as major contributors to construction injuries.

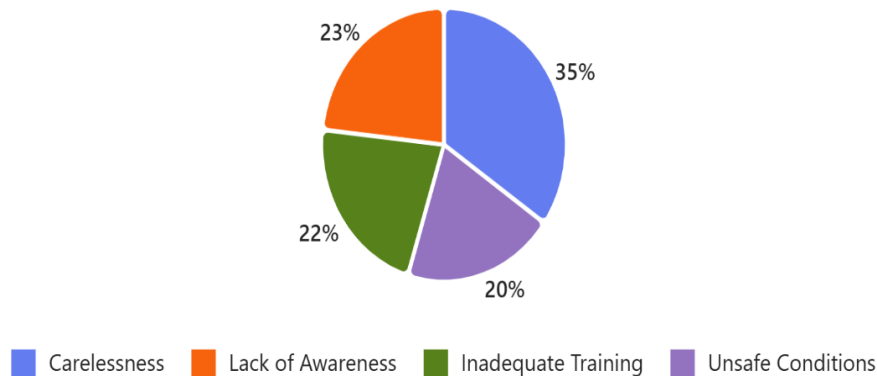


Figure 3: Reported causes of accidents (N=86)

### 4.2 Injured Body Parts

The accident reports also documented injury locations. Figure 4 summarizes the most frequently affected body parts. The hands/arms were the single most common injury site (33.7% of cases), followed by legs/feet (22.1%). Head and torso injuries were less common. This pattern indicates that many accidents involved manual tasks or falls involving upper limbs. While Saudi-specific comparisons are limited, it is generally observed that extremity injuries dominate non-fatal construction accidents globally. Together with causal data, the body-part distribution underscores the need for protective equipment and safe work practices for hands, as well as fall protection measures.

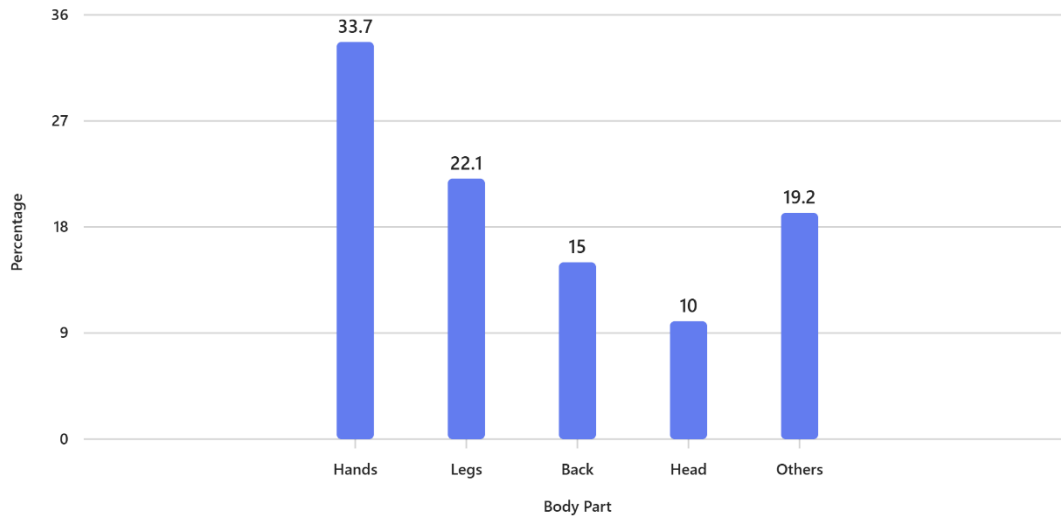


Figure 4: Injured body parts from recorded accidents (N=86)

#### 4.3 Timing and Seasonal Trends

Accident timing showed a pronounced seasonal effect. Nearly half of all incidents occurred in the summer months (May–July), reflecting extreme heat stress and extended work hours during that period. This aligns with labor regulations: a 2014 decree prohibits outdoor work from 12–3pm in summer, pushing more activities into shoulder seasons. In fact, our interviewees and data suggest that spring (March–May) saw a relative uptick in accidents as projects accelerated to meet summer deadlines. A recent Saudi study similarly noted shifting patterns: legislative work bans during peak heat have reduced midday summer accidents, relocating many incidents to spring [3]. These findings imply that weather and scheduling are critical safety factors in this context.

#### 4.4 Survey and Interview Insights

The worker survey (n=150) underwent exploration factor analysis, revealing six underlying dimensions of safety perception: (1) Management Commitment, (2) Training & Competence, (3) Communication & Supervision, (4) Risk Awareness, (5) Worker Empowerment, and (6) Organizational Procedures. For example, statements about visible leadership involvement and empowerment loaded on the Management Commitment factor, while language-appropriate training items loaded on Training & Competence. These factors highlight the multi-faceted nature of safety performance, combining both human and organizational elements.

Qualitative interview themes converged on known challenges:

- All participants noted the absence of a unified national safety authority. One manager remarked, “Each company does its own thing; there is no official oversight.” This sentiment echoes calls in the literature for a central OSH body [14].
- Many commented that tight deadlines often override safety practices. A site supervisor explained that working overtime or skipping PPE checks can happen under schedule pressure.
- Several expatriate workers recounted difficulty understanding Arabic safety briefings or local rules. As one Bangladeshi foreman noted, “We work hard but sometimes we don’t know exactly what is allowed.” This confirms the quantitative finding that migrants lack access to adequate training [3].
- Repeatedly, interviewees stated that existing safety policies were “just on paper.” Contractors with repeat violations faced few penalties, reinforcing an informal culture of leniency.
- Taken together, these results paint a clear picture: human factors such as inadequate training, communication breakdowns, and low managerial involvement are endemic issues. The findings align with broader evidence (e.g. the Saudi ARAMCO sector reports and global studies) that emphasize leadership commitment and worker engagement as crucial for safety.

## **5. Discussion**

The integration of results suggests several implications for improving safety performance. Training and education remain critical areas of focus. Both this study and prior research identify inadequate training as a key contributor to accidents [10]. Tailored programs, particularly for low-skilled and migrant workers, may enhance hazard awareness and compliance. Delivering training in native languages and incorporating visual aids is consistent with international best practices and could improve comprehension among diverse labor groups [3]. On-site mentoring and workshops may complement formal instruction.

To operationalize this integrated perspective, the discussion can be structured around several interrelated dimensions that collectively influence safety performance, as outlined below:

- The predominance of unsafe acts in accident records indicates that safety performance is shaped not only by individual behavior but also by organizational leadership and workplace culture. International guidelines, such as those issued by OSHA and HSE, emphasize the importance of visible management commitment, proactive supervision, and the integration of safety indicators into performance evaluation systems. These practices may be particularly relevant for

organizations seeking to strengthen safety culture and align with national strategic objectives such as Vision 2030.

- Consistent and effective safety performance also depends on robust policy frameworks and regulatory oversight. The lack of a centralized enforcement mechanism can lead to inconsistencies in safety implementation across organizations. International labor standards, including ILO conventions, highlight the role of dedicated regulatory bodies in monitoring compliance and promoting continuous improvement. Establishing a national occupational safety and health authority, supported by mechanisms such as ISO 45001 certification and periodic audits, could enhance alignment with global benchmarks.
- Given the diverse demographic composition of the workforce, safety interventions must be tailored to address language, cultural, and educational differences. Multilingual safety instructions, pictorial signage, and peer-mentoring approaches are widely recommended in international best practices and can improve comprehension, engagement, and adherence to safety procedures among heterogeneous labor groups.
- In parallel with organizational and regulatory measures, technological innovations offer additional opportunities to improve safety outcomes. The global adoption of wearable sensors, real-time monitoring systems, and drone-based inspections demonstrates their potential to enhance hazard detection and support data-driven safety management. Integrating such technologies into construction safety practices may provide proactive risk mitigation and strengthen overall system resilience.

## **6. Strategic Framework**

Drawing on these insights, Figure 5 presents a strategic framework integrating human factors into safety culture across four dimensions: Individual, Task, Organizational, and Regulatory (a synthesis of safety-by-design and safety-by-culture principles).



Figure 5: Framework integrating human factors into safety culture across

### 6.1. Individual Level

Focuses on the worker. Key elements include comprehensive safety induction and ongoing training (with multilingual content), behavior-based safety (e.g. peer observations), and easy-to-use tools (checklists, mobile apps). Emphasis is placed on language-accessible communication and visual aids, addressing the finding that many migrants struggle with standard training [3].

### 6.2. Task/Work Level

Involves job-specific controls. This encompasses ergonomic work design (to reduce strain and errors), clear standard operating procedures, and continuous hazard identification (job hazard analyses before tasks). Supervisors must provide real-time feedback and correction, since our interviews highlighted inadequate on-site supervision as a gap.

### 6.3. Organizational Level

Embodies management commitment and culture. The framework calls for visible leadership engagement (safety audits led by executives, reward systems for safe behavior) and integration of safety into organizational processes (e.g. including safety metrics in project KPIs and contracts). It also recommends fostering open communication, where workers can report risks without fear of penalty. These actions reflect both literature and interview themes: safety improvements require moving from symbolic compliance to genuine priority.

#### **6.4. Regulatory/Institutional Level**

Extends beyond individual companies to the national context. This includes establishing a formal Saudi Occupational Safety Authority with powers to enforce standards, conduct mandatory safety audits, and penalize violators. Regulations (e.g. working-hour limits in extreme heat) should be updated based on data. Alignment with global standards (ISO 45001) and ILO conventions is encouraged [4]. The framework also envisions national training initiatives (e.g. safety professional certification programs) and enhanced reporting systems to support data-driven policy.

While Saudi practices increasingly align with ISO 45001 and ILO conventions, gaps remain in enforcement and worker empowerment compared to mature systems like OSHA and HSE. For example, Saudi regulations mandate heat-related work bans, which mirror global best practices, but lack robust whistleblower protections common in EU frameworks.

This multi-level approach ensures that human factors are addressed from worker training up to societal infrastructure, creating a culture of safety that aligns with Vision 2030's goals of safe, sustainable development. For clarity, Figure 4 is a conceptual illustration of how these elements interact.

#### **7. Conclusion and Recommendations**

This study confirms that human factors are central to accident causation on Saudi construction sites. Unsafe acts often stemming from inadequate training, communication, or supervision and adverse organizational conditions together fuel the high incident rate. A strategic response must therefore be holistic.

The recommendations are as follow:

- Promote a learning culture where safety is valued. Leadership must demonstrate commitment (e.g. through “safety walks” and participatory decision-making) and reward safe behaviors. Safety metrics should become as important as cost and schedule metrics in every project.
- Develop rigorous, context-specific training programs. Utilize native-language instruction, real-world scenario drills, and continuous education (refresher courses). Apprenticeship-style mentoring can accelerate skill transfer, especially for new migrant hires.
- Accelerate the creation of a national OSH authority empowered to issue binding regulations and enforce compliance. Encourage ISO 45001 certification across the industry, potentially tying it to business licensing. Update labor laws to protect workers (e.g. limits on overtime in extreme heat) and ensure strict enforcement of existing rules.



- Establish mandatory incident reporting and analysis mechanisms. Use technology to capture near-misses and hazard observations. Regularly publish industry-wide safety statistics to maintain transparency and accountability.
- Provide welfare support (adequate housing, rest breaks) to reduce fatigue. Ensure site information (signage, instructions) is bilingual or pictorial. Involve migrant workers' representatives in safety planning.
- Adopt safety technologies where feasible: heat-stress monitors, wearable fall detectors, real-time GIS mapping of hazards. Use data analytics to anticipate risk (as demonstrated by the SARIMA forecasting model in recent studies).

This study highlights the role of human factors in accident causation within Saudi construction projects. Unsafe acts and organizational conditions were identified as significant contributors to incident rates. The proposed strategic framework offers a structured approach that may assist organizations in strengthening safety culture. Its principles are consistent with global standards and could support efforts to reduce accidents and enhance worker well-being.

Implementing the recommended measures may help advance progress toward Vision 2030 objectives related to human capital and sustainability. These recommendations are intended to complement existing practices and align with international occupational safety guidelines, rather than replace them. Future research could explore comparative analyses between Saudi practices and those in other regions to identify additional opportunities for improvement.

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## Appendix

### Research Participant Consent Form

**Title of Project:**

**Ethics Ref No:**

**Name of Researcher:**

No.		Yes	No
1.	Do you agree to participate in this research?		
2.	Did all the related information about the research is being explained to you?		
3.	Are you been allowed to ask questions about the research?		
4.	Do you agree that your interview can be audio-recorded?		
5.	Do you agree that your company accident reports being used in this research?		
6.	Do you understand all information that will be provided by you in this research will be treated confidentially?		
7.	Do you understand that in any report of this research, your identity will remain anonymous?		
8.	Do you understand that your participation is voluntary and you can withdraw from the research at any time without giving any reason?		

Participant Name: .....

Signature: .....

Date: .....

Researcher Name: .....



**Islamic University Journal of Applied Sciences  
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**مجلة الجامعة الإسلامية للعلوم التطبيقية  
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