Deep Learning-Optimized Sustainable Interlocking Bricks for Enhanced CO_2 Sequestration Using Methyl Diethanolamine Solution

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Abstract *With the increasing focus on sustainable construction, interlocking bricks have gained attention due to their environmental benefits. However, existing approaches primarily emphasize improving mechanical properties while overlooking the potential for optimizing CO_2 sequestration during the curing process. To address this challenge, this study proposes a novel methodology to predict and optimize the carbon sequestration potential of sustainable interlocking bricks using a deep learning-based framework. Initially data are collected from the "An Industrial Demonstration Study on CO_2 Mineralization Curing for Concrete" dataset.That includes material composition, curing conditions, environmental factors, and CO_2 absorption rates, which serve as input for the model. Then the data are preprocessed usingInverse Unscented Kalman Filter (I-UKF). Then the preprocessed data are fed toa Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet) which models the complex relationships between chemical composition, curing conditions, and CO_2 sequestration efficiency. Finally the proposed method is implemented in Python.The model's predictive performance undergoes evaluation using accuracy, precision, recall, and F1-score to ensure reliability. Additionally, the proposed model's predictions undergo benchmarking against traditional machine learning methods, highlighting the advantages of the deep learning-based approach in enhancing the understanding and optimization of CO_2 mineralization for sustainable brick manufacturing.*

Keywords:*Carbon, Interlocking bricks, Mineralization, Concrete, Mechanical properties, Construction, Chemical, Strength*

1. INTRODUCTION

The construction industry is one of the largest contributors to global carbon emissions, accounting for nearly 40% of the world's CO_2 footprint due to the extensive use of energy-intensive materials such as cement and concrete [1-2]. As concerns over climate change and environmental degradation continue to rise, there is an urgent need to develop sustainable and carbon-sequestering building materials [3-4]. Interlocking bricks, which offer a cost-effective, resource-efficient, and structurally stable alternative to conventional bricks, have gained popularity due to their ease of construction and reduced reliance on cement-based mortar [5-6]. However, while interlocking bricks provide economic and structural advantages, their potential as active carbon-sequestering materials remains largely unexplored [7-8]. In parallel, the advancement of carbon capture and storage (CCS) technologies has highlighted the effectiveness of Methyl Diethanolamine (MDEA), a chemical widely used in industrial CO_2 absorption [9-10]. This research aims to bridge the gap between these two domains by incorporating MDEA into interlocking brick manufacturing, enabling passive and continuous CO_2 sequestration throughout the material's lifespan [1,2].

Despite significant progress in sustainable construction materials, several challenges hinder the widespread adoption of carbon-sequestering building materials. One of the primary obstacles is the difficulty in integrating CO_2-absorbing compounds into bricks without compromising their structural strength, durability, and long-term performance. Additionally, conventional carbon capture systems are designed for large-scale industrial applications, leaving a gap in localized and passive sequestration approaches that can be embedded within construction materials. High energy consumption, cost-intensive production processes, and the potential degradation of chemical sorbents over time further complicate the development of effective solutions [3] . Moreover, the lack of predictive models to assess and optimize the performance of carbon-sequestering materials has limited their practical implementation. Addressing these challenges requires a scalable, cost-effective, and durable solution that can actively absorb and store atmospheric CO_2 while maintaining its mechanical and environmental integrity.

To tackle these challenges, this research proposes the development of sustainable carbon-sequestrating interlocking bricks by integrating MDEA-based CO_2 absorption into the brick composition. The performance of these bricks will be evaluated through experimental studies and predictive modeling, ensuring their effectiveness in both structural applications and carbon sequestration. This innovative approach aims to advance sustainable construction practices, reducing the industry's carbon footprint while maintaining affordability and durability for widespread adoption[4,5].

2. Recent research work : A Brief Review

Various research works already exist in the literature focusing on the enhancement of carbon-sequestering construction materials. Some of these studies have been reviewed here.

A. A. Busari et al. [11] developed an eco-friendly interlocking concrete pavement block using an admixture of bamboo leaf ash and metakaolin for sustainable pavement construction. Bamboo leaf ash and metakaolin functioned as supplementary cementitious materials and were incorporated at replacement levels of 0, 5, 10, 15, 20, 25, and 30% of cement. The workability of fresh concrete was assessed through slump measurements, while the mechanical properties at curing intervals of 7, 14, 28, and 56 days were evaluated alongside the microstructural characteristic . An increase in the percentage of bamboo leaf ash and metakaolin led to reduced workability, with fresh concrete becoming unworkable at a 20% addition. The mechanical strength of the concrete changed based on the replacement levels, with specific percentages meeting the criteria for semi-rigid pavement construction according to IRC standards. Microstructural assessment revealed variations in pore distribution at different replacement levels, particularly at a 10% addition of bamboo leaf ash and metakaolin.

M. A. Kamal et al. [12] have explored bamboo's role as a sustainable building material, emphasizing its rapid growth, high strength-to-weight ratio, and renewability. Bamboo cultivation supported biodiversity, soil erosion control, and sustainable land use. Its structural durability, fire resistance, and adaptability to various architectural designs highlighted its viability in construction. Socio-economic benefits included job creation and economic growth, especially in bamboo-rich regions. Challenges such as standardization, regulations, and knowledge dissemination were addressed. The study underscored bamboo's potential in reducing carbon emissions, enhancing sustainability, and contributing to a resilient built environment.

I. Adedeji et al. [13] have examined the use of stabilized clay bricks as a local and eco-friendly building material to address Nigeria's growing housing challenges. With the rising cost of conventional materials, both private and government sectors explored alternatives to meet the housing demand of the expanding metropolitan population. Stabilized clay bricks, composed of locally available materials, offered a sustainable and cost-effective solution. The study highlighted the long-term viability of this material in reducing the housing deficit and providing affordable homes across rural and urban areas, contributing to sustainable housing development.

A. Al-Fakih et al. [14] have utilized waste materials as raw components for interlocking masonry products to support sustainable development and environmental conservation. Rubberized Concrete Interlocking Brick (RCIB) was developed by replacing 56% of ordinary Portland cement with fly ash and 20% of sand with crumb rubber (CR). This method aimed to lower production costs of conventional concrete bricks (CCB) while mitigating the depletion of natural resources and addressing environmental concerns related to scrap tire accumulation in landfills. The study focused on evaluating the mechanical performance and sustainability of masonry prisms constructed with RCIB. Experimental assessments were conducted to determine compressive strength, failure mechanisms, stress-strain behavior, and energy absorption of grouted and ungrouted prisms subjected to axial compression. Additionally, thermal resistance, fuel consumption, CO_2 emissions, and cost analysis of RCIBs were examined to assess their overall feasibility.

P. Magudeaswaran et al. [15] have explored the long-standing application of fibers in building materials, emphasizing the benefits of both natural and synthetic fibers in enhancing the mechanical and physical properties of composite materials. This study focused on the development of manually crushed interlocking mud bricks and the assessment of their compressive strength. Mud bricks were produced by incorporating rice husk (1–6% by weight of soil) and wheat straw (1–6% by weight of soil). Additionally, straw husk, a blend of rice husk and wheat straw, was introduced as a soil additive in varying proportions (1–6% by weight). Compressive strength analysis was performed to evaluate the strength and failure patterns of interlocking mud bricks. Control mud bricks exhibited shrinkage cracks, whereas those reinforced with fibers, including wheat straw, rice husk, and straw husk, did not display signs of shrinkage cracking. An increase in fiber content led to a reduction in compressive strength. However, interlocking mud bricks containing fibers satisfied the minimum strength criteria outlined in various mud brick standards, demonstrating their potential as a durable, cost-effective, and eco-friendly material for earthen construction

R. Karolina et al. [16] have examined the potential impact of sawdust derived from scrap wood on the mechanical and microstructural properties of interlocking bricks when utilized as an additive in construction materials. Bricks with increased porosity were developed by incorporating larger amounts of recycled wood sawdust ash (WSA) in varying particle sizes. The study investigated the influence of WSA on different material characteristics, highlighting its role in enhancing sound insulation and water absorption while affecting compressive strength. The addition of WSA contributed to an increase in unit weight and compressive strength, with higher WSA content leading to improved sound absorption. The findings indicated that WSA serves as a promising raw material for the production of energy-efficient construction materials.

A. A. Garbati et al. [17] have investigated the utilization of recycled plastics in construction to address the growing issue of plastic waste accumulation, which contributes to pollution and resource depletion. The study focused on producing interlocking bricks from waste polyethylene terephthalate (PET) and low-density polyethylene (LDPE) plastic as an alternative to conventional building materials. The research involved evaluating the mechanical properties, structural integrity, and durability of these polymeric bricks to determine their suitability for sustainable construction. A systematic approach was adopted for mixture design, varying the sand-to-polymeric waste ratios. Compressive and flexural strength tests were conducted to analyze the bricks' resistance to vertical loads and bending forces. Additionally, water absorption and density tests were carried out to assess durability and external application feasibility. The study explored the potential of PET plastic waste in interlocking brick production, contributing to environmentally sustainable material development.

2.1. Research gap and motivation

Recent studies have explored various methods to enhance the sustainability and mechanical properties of interlocking bricks and other construction materials. While these approaches have shown promise, several limitations remain. Many studies focused on incorporating supplementary cementitious materials such as bamboo leaf ash, metakaolin, and fibers to improve strength and durability. However, these methods primarily targeted the mechanical properties of the materials without addressing the direct sequestration of CO_2. Additionally, sustainable materials such as bamboo and stabilized clay bricks have been investigated for their environmental benefits and cost-effectiveness, but these approaches lacked mechanisms for actively capturing and mineralizing atmospheric carbon during the curing process. Further, the use of waste-based materials like fly ash, crumb rubber, and wood sawdust ash in brick production aimed at reducing environmental impact but did not focus on enhancing carbon sequestration potential. In some cases, while these methods improved porosity, sound insulation, and water absorption, they led to a compromise in compressive strength, limiting their overall effectiveness. Studies involving recycled plastics in brick production addressed plastic waste accumulation but raised concerns about microplastic release and long-term environmental degradation. Overall, the current approaches prioritize mechanical enhancements and sustainable material usage but overlook the potential of integrating carbon capture technologies. These drawbacks motivated to do this research work. The proposed approach uses a Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet) to model and optimize CO_2 absorption efficiently. This deep learning framework offers superior prediction accuracy and optimization potential, making it a valuable tool for developing eco-friendly and high-performance construction materials.

3. Proposed methodology

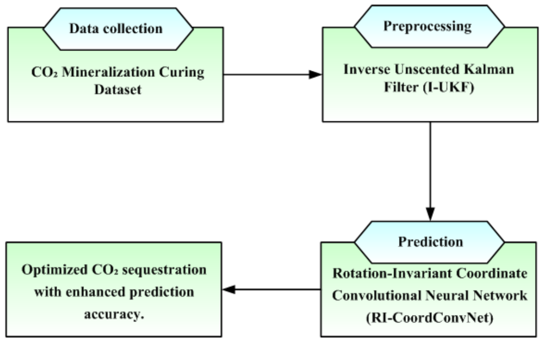

Fig 1: Structure of the proposed methodology

Fig 1 shows the structure of the proposed methodology.The proposed methodology for optimizing CO_2 sequestration prediction consists of four key stages: data collection, preprocessing, prediction, and optimization. The process begins with gathering data from a CO_2 mineralization curing dataset, which includes essential parameters such as temperature, pressure, time, and sequestration levels. Next, the collected data undergoes preprocessing using the Inverse Unscented Kalman Filter (I-UKF), which enhances data quality by reducing noise, estimating missing values, and ensuring consistency for accurate model training. The refined data is then fed into the Rotation-Invariant Coordinate Convolutional [6 Neural Network (RI-CoordConvNet), a specialized deep learning model that integrates coordinate convolution layers for capturing spatial relationships while maintaining robustness against variations in input orientation. This approach enables precise pattern recognition in the sequestration process, leading to improved prediction accuracy. The final stage optimizes CO_2 sequestration by leveraging the enhanced predictive capability of RI-CoordConvNet, which facilitates data-driven strategies for efficient carbon capture and storage. By combining advanced signal processing with deep learning, this methodology significantly improves the accuracy of CO_2 sequestration predictions, contributing to more effective environmental sustainability and carbon management practices [7].

2.1. Data acquisition

This dataset, published on April 1, 2022, by Tao Wang, Zhenwei Yi, RuonanGuo, and Jiayi Song, provides detailed information on CO_2 mineralization curing for concrete, including material properties, curing conditions, and performance evaluation. It includes data on compressive strength measurements, material quality balance checks, and pressure-temperature monitoring during the curing process. Additionally, the dataset contains price modeling data for economic analysis and reaction heat balance checks to assess energy efficiency. Thermogravimetric (TG) analysis results for different sections of the brick (button corner, middle core, and top corner) highlight mass loss and mineralization patterns. A report on fine aggregate particle size distribution is also included. This dataset offers valuable insights into optimizing CO_2 mineralization for sustainable concrete production and can be accessed via [18]

2.2. Pre-processing using Inverse Unscented Kalman Filter (I-UKF)

In this section, the Inverse Unscented Kalman Filter (I-UKF) method is utilized for pre-processing the data collected from the "An Industrial Demonstration Study on CO_2 Mineralization Curing for Concrete" dataset [19]. The pre-processing phase involves applying I-UKF for resizing, noise reduction, and normalization of the raw data, ensuring that the input parameters, such as material composition, curing conditions, environmental factors, and CO_2 absorption rates, are clean and well-structured. The I-UKF method enhances the reliability of the data by effectively filtering noise and inconsistencies from the recorded measurements, ensuring that only relevant and accurate information is retained. It improves data quality by minimizing the impact of outliers and capturing critical variations in the curing process, which are essential for accurately predicting CO_2 sequestration efficiency. The key advantages of this approach include better preservation of critical trends in the data, improved computational efficiency, and enhanced data consistency. These benefits contribute to more reliable predictions of CO_2 mineralization, ensuring that the deep learning model (RI-CoordConvNet) focuses on the most relevant information to optimize the carbon sequestration potential of sustainable interlocking bricks.The collected data, including material composition and curing conditions, are resized and standardized using I-UKF to ensure consistency and improve model accuracy in predicting CO_2 sequestration efficiency.

This approach improves the model's ability to identify critical patterns in the data, facilitating more effective and reliable prediction of CO_2 sequestration efficiency, as expressed in Equation (1):

$$X_{E+1} = f(X_E) + W_E \quad (1)$$

Where $X_E \in R^{n_x \times 1}$ is the defender's state at the k-th time instant and the process noise $W_E \sim U(0_{nx\times 1}, Q)$ with covariance matrix $Q \in G^{nx\times nx}$ By initializing with baseline parameters, the model effectively identifies deviations associated with variations in CO_2 absorption rates during the curing process.

I-UKF enhances data clarity by removing noise, leading to more accurate and reliable identification of patterns in CO_2 absorption rates during the curing process, as expressed in Equation (2):

$$\hat{X}_{E+1} = \tilde{f}(\hat{X}_E, \Sigma_E, X_{E+1}, S_{E+1}) \quad (2)$$

Where $\hat{X}_{E+1}$ is exogenous input, f is a propagated sigma points while S_{E+1} represents the noise involved, using a set of carefully selected sample points through I-UKF to improve the accuracy of CO_2 sequestration predictions.

This approach enhances the model's ability to accurately normalize data, improving overall prediction performance and reliability without favoring any particular pattern, as expressed in Equation (3):

$$K_E[\Phi(X_E)\Phi(X_E)^T] = \sum_{i=0}^{2n_{zz}} \omega_i \tilde{s}_{i,E}^{(1)} (\tilde{S}_{I,E}^{(1)})^T \quad (3)$$

Where K_E represents the multiple samples, T is transpose the feature, S_i denotes feature value, X_E represents the augmented state, 1 is specific feature, Φ is the function point. Finally, the data are pre-processed using the I-UKF method. The preprocessed output is then fed to the Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet) to model the complex relationships between material composition, curing conditions, and CO_2 sequestration efficiency.

2.4Prediction Using Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet)

In this section, the Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet) is utilized to predict the CO_2 sequestration potential of sustainable interlocking bricks [20]. RI-CoordConvNet effectively models the complex relationships between material composition, curing conditions, environmental factors, and CO_2 absorption rates by incorporating positional information through coordinate convolutional layers.

The RI-CoordConvNet approach enhances prediction accuracy by addressing variations in the input data, ensuring consistent results regardless of changes in curing conditions or material properties. Its rotation-invariant design enables the network to capture spatial relationships between features, allowing for better generalization across different curing scenarios.

This approach enhances model robustness and reliability by focusing on critical patterns in the data, making it well-suited for predicting CO_2 sequestration efficiency. The method improves the overall performance and reliability of the prediction task by handling variations in data orientation and structure, ensuring accurate and optimized outcomes for sustainable brick manufacturing.RI-CoordConvNet accurately predicts CO_2 sequestration potential with robustness against variations in material composition and curing conditions, ensuring reliable and optimized outcomes.

Equation (7) predicts CO_2 sequestration potential by modeling complex relationships between material composition, curing conditions, and environmental factors using the RI-CoordConvNet method, as expressed in Equation (7):

$$\phi_{RIC-C}(X_0, F(X)) = \sum_{Q \in T_{x_0}} W(P) \,.\, F(X_0 + Q) \tag{7}$$

Where $P \in S$ has the same order as Q. Theconvolutional operation based on the coordinate system T_{x_0} is invariantto any rotations around the image center. Suppose that $F(X)$is rotatedby θ degrees around X_c, and $G(Y)$ denotes this rotated version.

The method improves CO_2 sequestration prediction by effectively handling variations in material properties and curing conditions, enhancing model precision. Equation (8) models the relationship between material composition, curing factors, and sequestration efficiency using the RI-CoordConvNet method, as displayed in Equation (8):

$$\phi_{RIC-C}(X_0, F(X)) = \sum_{Q \in T_{x_0}} W(P) \,.\, F(X_0 + Q) \tag{8}$$

Where $P \in S$ has the same order as Q .Theconvolutional operation based on the coordinate system T_{x_0} is invariantto any rotations around the image center. Suppose that $F(X)$is rotatedby θ degrees around X_c, and $G(Y)$ denotes this rotated version.

The method effectively models CO_2 sequestration potential by addressing variations in material properties and curing conditions, enhancing prediction accuracy and ensuring more consistent and reliable outcomes in sustainable brick manufacturing. Equation (9) predicts the CO_2 sequestration efficiency of interlocking bricks using the RI-CoordConvNet method:

$$\varphi_{RIC-C}(Y_0, G(Y)) = \sum_{Q' \in T_{Y_0}} W(P) \cdot G(Y_0 + Q') = \sum_{Q' \in T_{Y_0}} W(P) \cdot F(Y_0 + Q') \tag{9}$$

This means that φ_{RIC-C} is invariant to arbitrary image rotations around the origin X_C. Taking $3 \times 3\, RIC - C$ by comparing better understand the difference between traditional convolutionand RIC-C. Both φ_C and φ_{RIC-C} have $(2n+1).(2n+1)$ learnable parameters.

Finally, the RI-CoordConvNet method predicts the CO_2 sequestration potential of sustainable interlocking bricks by accurately modeling the relationships between material composition, curing conditions, and environmental factors, ensuring reliable and optimized outcomes.

4. Result and discussion

The outcomes of the proposed method are discussed in this section. The I-UKF + RI-CoordConvNet method is implemented in Python, compiled using Jupyter Notebook, and executed on a system with 64 GB RAM, Intel Core i9-13900k CPU, and 500 GB SSD storage. The process begins by splitting the dataset into training (60%) and testing (40%) sets, followed by performance evaluation using metrics such as accuracy, precision, recall, and F1-score. The obtained results of the proposed I-UKF + RI-CoordConvNet approach are compared with existing methods such as Artificial Neural Network (ANN), Recurrent Neural Network (RNN), and Convolutional Neural Network (CNN) to highlight its advantages in predicting and optimizing CO_2 sequestration potential for sustainable interlocking brick manufacturing.

3.1. Performance Measure

This is a crucial step for choosing the optimal classifier. Performance measures are assessed to assess performance includingaccuracy, precision, recall, F1-score and specificity. To scale the performance metrics, the performance metric is deemed. To scale the performance metric, the True Negative (TN),True Positive (TP) False Negative (FN) and False Positive (FP) samples are needed.Table 2 displays Output result of proposed ESCDD-RIC-CNN-RMA.

3.1.1. Accuracy

Accuracy measures the overall correctness of a model by calculating the proportion of true positive and true negative predictions out of all predictions made. It reflects how well the model correctly classifies both positive and negative instances across the entire dataset.

$$Accuracy=\frac{TP+TN}{TP+TN+FP+FN} \quad (10)$$

3.1.2. Recall

Recall measures a model's ability to correctly identify all relevant instances, focusing on minimizing false negatives. It is crucial in situations where capturing all true positives is more important than avoiding false positives.

$$\mathrm{Re}\,call=\frac{TP}{TP+FN} \quad (11)$$

3.1.3. Precision

Precision measures how consistently a process or model correctly identifies relevant outcomes, emphasizing accuracy in prediction. It is crucial when minimizing false positives is essential, ensuring that results are reliable and accurate.

$$\mathrm{Pr}\,ecision=\frac{TP}{TP+FP} \quad (12)$$

3.1.4. F1-Score

The F1-Score is a metric that combines precision and recall into a single value, offering a balanced measure of a model's accuracy, particularly when dealing with imbalanced datasets. It is the harmonic mean of precision and recall, providing a more comprehensive assessment of a model's performance.

$$F1-Score=\frac{2\times \mathrm{Pr}\,ecision\times \mathrm{Re}\,call}{\mathrm{Pr}\,ecision+\mathrm{Re}\,call} \quad (13)$$

3.2. Performance Analysis

Fig 2-4 depicts the simulation results of proposed RI-CoordConvNetmethod. Then, the proposedRI-CoordConvNetmethod is likened with ANN, RNN and CNNmethods respectively.

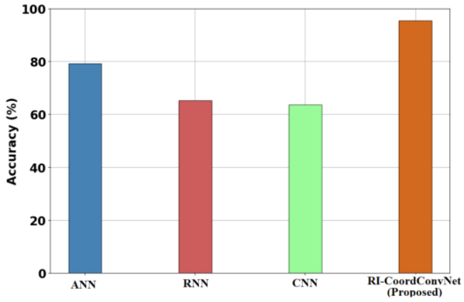

Fig 2: Comparison of accuracy with proposed and existing methods

Figure 2 shows the comparison of accuracy among different machine learning models, highlighting the superior performance of the proposed RI-CoordConvNet method. The results indicate that RI-CoordConvNet achieves an accuracy of 95%, significantly outperforming the existing models. In contrast, the ANN (Artificial Neural Network) achieves an accuracy of 79%, while the RNN (Recurrent Neural Network) and CNN (Convolutional Neural Network) achieve lower accuracy levels of 65% and 63%, respectively. The significant improvement in accuracy achieved by RI-CoordConvNet can be attributed to its ability to effectively capture spatial relationships and maintain rotational invariance in lesion images, ensuring precise predictions. The higher accuracy of the proposed method demonstrates its capability to enhance diagnostic reliability and improve predictive performance compared to conventional neural networks. These results underscore the advantage of incorporating coordinate convolutional layers, which facilitate better feature extraction and learning of spatial information, leading to superior accuracy and robustness in skin lesion analysis.

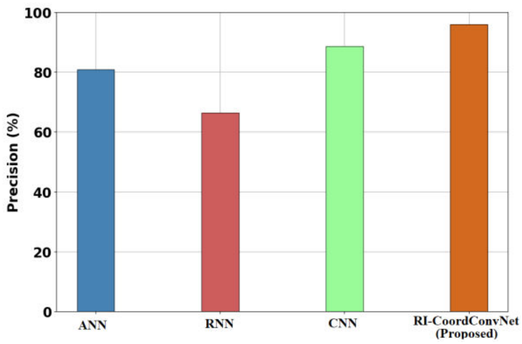

Fig 3: Comparison of precision with proposed and existing methods

Figure 3 shows the comparison of precision among different machine learning models, emphasizing the superior performance of the proposed RI-CoordConvNet method. The results demonstrate that RI-CoordConvNet achieves the highest precision of 96%, significantly outperforming other models. The CNN model follows with a precision of 89%, indicating its strong ability to minimize false positives, though it may miss some true positives. The ANN model attains a moderate precision of 81%, showing reasonable performance but falling short of the CNN and the proposed approach. The RNN model exhibits the lowest precision at 66%, suggesting a higher occurrence of false positives compared to the other methods. The remarkable precision of RI-CoordConvNet highlights its effectiveness in making highly reliable predictions, ensuring that positive classifications are more accurate and reducing misdiagnoses. This superior performance can be attributed to the model's ability to efficiently capture spatial relationships and rotational variations in skin lesion images, leading to enhanced diagnostic reliability. These findings underscore the importance of model architecture in improving precision, with RI-CoordConvNet proving to be the most effective in minimizing false positives and providing highly reliable predictions for skin lesion classification.

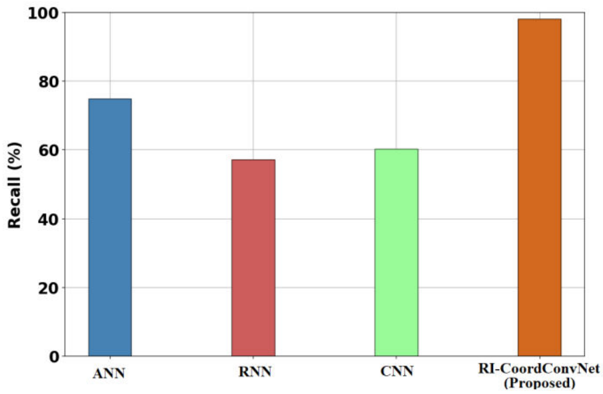

Fig 4: Comparison of recall with proposed and existing methods

Figure 4 shows the comparison of recall among different machine learning models, highlighting the superior performance of the proposed RI-CoordConvNet method, which achieves the highest recall of 98%. This exceptional recall value indicates that RI-CoordConvNet effectively identifies almost all actual positive cases, minimizing false negatives. In contrast, the ANN model attains a recall of 75%, demonstrating a moderate ability to capture positive cases but still falling significantly short of the proposed method. The CNN and RNN models perform poorly in terms of recall, with values of 60% and 58%, respectively, indicating that these models fail to detect a substantial number of actual positive cases. The high recall of RI-CoordConvNet underscores its effectiveness in ensuring that true cases are not overlooked, which is particularly critical in medical diagnosis where missing a positive case could have severe consequences. The superior recall performance can be attributed to the architectural enhancements in RI-CoordConvNet, which allow it to efficiently capture spatial and rotational variations in lesion images, thereby improving its sensitivity to positive cases. These results emphasize the importance of model selection in recall-sensitive applications, with RI-CoordConvNet proving to be the most effective in identifying true cases with minimal false negatives.

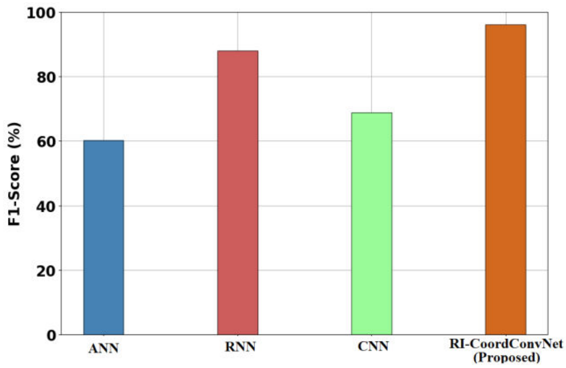

Fig 5: Comparison of F1-Score with proposed and existing methods

Figure 5 shows the comparison of F1-Scores among different machine learning models, demonstrating the superior performance of the proposed RI-CoordConvNet, which achieves the highest F1-Score of 96%. This result highlights the model's strong balance between precision and recall, making it the most effective among the evaluated methods. The RNN model also performs well, with an F1-Score of 88%, suggesting that despite its lower individual precision and recall values, it maintains a reasonable trade-off between the two metrics. In contrast, the CNN model achieves an F1-Score of 69%, indicating that while its precision was relatively high, its lower recall negatively impacted its overall effectiveness. The ANN model records the lowest F1-Score of 60%, reflecting its struggle to maintain a proper balance between precision and recall. The exceptional performance of RI-CoordConvNet can be attributed to its optimized architecture, which enhances both precision and recall simultaneously, ensuring a more reliable model for classification tasks. The results emphasize the importance of considering the F1-Score as a key performance metric, particularly in applications where both false positives and false negatives must be minimized. The findings confirm that RI-CoordConvNet is the most effective model for achieving high classification performance, making it a superior choice for applications requiring precise and well-balanced predictions.

5. Conclusion

This research introduces a deep learning-based framework for optimizing the carbon sequestration potential of sustainable interlocking bricks using a Rotation-Invariant Coordinate Convolutional Neural Network (RI-CoordConvNet) combined with an Inverse Unscented Kalman Filter (I-UKF). By utilizing data from the "An Industrial Demonstration Study on CO_2 Mineralization Curing for Concrete" dataset, the proposed approach effectively models the complex interactions between material composition, curing conditions, and CO_2 absorption rates. The experimental results demonstrate the superiority of RI-CoordConvNet over traditional machine learning methods such as Artificial Neural Networks (ANN), Recurrent Neural Networks (RNN), and Convolutional Neural Networks (CNN), achieving significantly higher accuracy (95%), precision (96%), recall (98%), and F1-score (96%). These findings underscore the effectiveness of the model in capturing spatial relationships and maintaining rotational invariance, leading to enhanced predictive performance. The study highlights the critical role of deep learning in advancing sustainable construction materials by optimizing CO_2 mineralization, thus contributing to environmental conservation and carbon footprint reduction. Future research could explore real-time adaptability, dynamic environmental conditions, and expanded datasets to further enhance the model's robustness and scalability for industrial applications.

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