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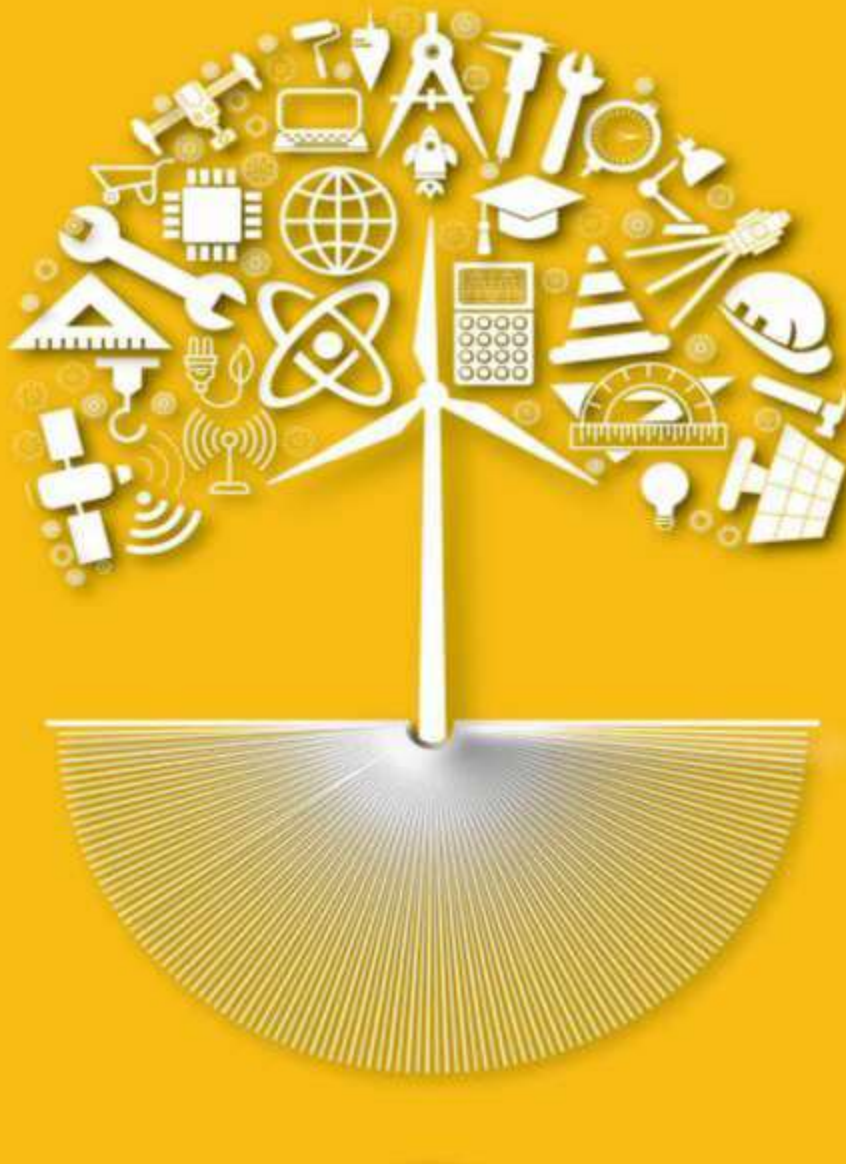

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Innovative Track Infrastructure Solutions for Sustainable Railway Transportation

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Abstract

The increasing demand for sustainable and resilient transportation systems necessitates transformative innovations in railway infrastructure design and materials. This study explores the integration of recycled composite sleepers and geogrid-reinforced subgrades as a solution to enhance the mechanical performance, durability, and environmental sustainability of railway tracks. A 100-meter full-scale experimental track was constructed and instrumented to validate the performance of the proposed system under realistic operating conditions. The research employs finite element analysis (FEA) and full-scale field trials to evaluate the structural behavior of these materials under varying axle loads, dynamic train frequencies, and extreme climatic conditions. Key performance metrics such as track settlement, lateral stability, and maintenance intervals are analyzed, demonstrating that geogrid-reinforced subgrades reduce track deformation by up to 40% over 12 months compared to conventional designs. Recycled composite sleepers exhibit superior resistance to cracking, moisture ingress, and UV degradation, resulting in a25% reduction in lifecycle maintenance costs and a 30% decrease in carbon emissions. The lifecycle assessment (LCA) confirms that the proposed infrastructure solutions significantly lower resource consumption and greenhouse gas emissions. This research contributes to the circular economy, aligns with global sustainable development goals, and offers practical strategies for transitioning to green rail infrastructure. This finding provides a comprehensive framework for implementing sustainable materials in railway infrastructure, addressing contemporary challenges in transportation engineering while ensuring long-term operational efficiency and environmental stewardship.

Keywords: Geogrid Reinforcement, Life Cycle Assessment, Railway Infrastructure, Recycled Composites, Sustainable Materials, Track Performance, Transportation Engineering

I. Introduction

The global push for sustainable development has placed increasing emphasis on transforming transportation systems to reduce environmental impact, improve operational efficiency, and ensure long-term infrastructure resilience. Railways, being one of the most energy-efficient and low-emission modes of mass

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transportation, are essential to achieving these sustainability goals. However, conventional railway infrastructure primarily reliant on concrete sleepers and natural aggregates, faces persistent challenges such as high maintenance costs, environmental degradation, and reduced service life under dynamic loading and extreme climatic conditions. In response to these limitations, recent research has increasingly focused on the use of sustainable construction materials and innovative engineering practices. Among them, recycled composite materials produced from plastic waste and industrial by-products have emerged as promising alternatives due to their high durability, moisture resistance, and reduced carbon footprint. Similarly, geogrid reinforcement in subgrade layers has proven effective in enhancing load distribution, reducing track settlement, and increasing the long-term stability of track structures, especially in areas with soft or variable soil conditions. Integrating these advanced materials into railway infrastructure not only reduces dependency on natural resources but also contributes to the circular economy by repurposing waste products. Additionally, improved structural integrity and reduced maintenance intervals lower operational costs and energy consumption over the asset's lifecycle—directly supporting global sustainability initiatives, including the United Nations Sustainable Development Goals (SDGs). This study investigates the combined application of recycled composite sleepers and geogrid-reinforced subgrades in railway track systems, focusing on their mechanical performance, environmental benefits, and economic viability. Employing finite element analysis (FEA) and real-world case study data, the research assesses track behavior under varying axle loads and climate stressors. The outcomes provide a practical and scalable framework for the implementation of sustainable materials in railway engineering. Given Ethiopia's ongoing railway expansion and the need for durable, low-impact infrastructure, this study further recommends policy interventions such as material standardization, workforce training, and investment in applied research to support a more sustainable national railway network.

II. Literature Review

The increasing demand for sustainable and cost-effective railway infrastructure has prompted extensive research into alternative materials and advanced ground improvement techniques. Traditional timber sleepers and unstabilized subgrades often fail under dynamic loads, leading to frequent maintenance and safety issues. To address these challenges, recent studies have focused on innovative materials such as recycled composite sleepers and geogrid-reinforced subgrades to enhance durability, stability, and overall track performance. The following subsections present key developments in these areas.

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A. Recycled Composite Sleepers in Railway Infrastructure

Recent research highlights the advantages of recycled composite materials as a replacement for traditional sleepers. These materials offer improved resistance to environmental degradation, increased service life, and reduced lifecycle costs. S. Thompson et al. [1] emphasized the role of recycled polymers in producing sleepers with superior mechanical properties and sustainability benefits. Similarly, M. A. Jabu et al. [2] found that composite sleepers demonstrate better fatigue resistance and are less prone to rot and insect damage compared to timber. The use of recycled materials also aligns with global sustainability goals by minimizing construction waste and carbon footprint.

B. Geogrid-Reinforced Subgrades for Enhanced Stability

Geogrid reinforcement has proven effective in improving the load-bearing capacity and long-term performance of railway subgrades. Lenart [3] reported that geogrid-reinforced ballast significantly reduces vertical and lateral deformations under cyclic loading. Studies by Zhang and Tang [4] further confirm that geogrid applications result in enhanced shear strength and reduced track settlement, particularly under repeated train loads. The confinement effect provided by geogrids leads to better stress distribution and improved durability of the substructure.

C. Integration of Innovative Track Solutions

Integrating recycled composite sleepers with geogrid-reinforced subgrades presents a holistic solution for resilient and sustainable railway systems. Research by Nasr et al. [5] demonstrated that combining these technologies reduces maintenance costs, improves track geometry retention, and enhances overall safety. Additionally, field trials conducted by Setiadi and Wahid [6] on composite and geosynthetic-enhanced tracks showed notable improvements in track modulus and drainage efficiency. These integrated systems are particularly suitable for challenging environments, such as expansive soils and moisture-prone regions commonly found in Ethiopia.

III. Methodology, Methods and Materials

This study employs a comprehensive approach to evaluate the performance of sustainable railway infrastructure, emphasizing innovative material selection, rigorous experimental testing, and advanced numerical simulations. The materials and methods used were selected to replicate real-world operational conditions and assess long-term performance under diverse loading and environmental scenarios.

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A. Material Selection

1) Composite Sleepers

Recycled composite sleepers were manufactured using high-density polyethylene (HDPE) reinforced with glass fibers. These sleepers were selected due to their superior durability, high strength-to-weight ratio, resistance to environmental degradation, and sustainability. Key material properties are as follows:

- Density: 950 kg/m³
- Tensile Strength: 30–35 MPa
- Elastic Modulus: 3–5 GPa
- Moisture Absorption: < 0.5% after 24 hours
- Estimated Service Life: 50 years

The material properties were derived from laboratory characterization tests conducted to track construction, following ASTM D638 and ASTM D570 standards, and are consistent with values reported by Yousefi et al. (2020) and McHenry and Ghataora (2016).

2) Geogrid Reinforcement

To enhance subgrade performance, biaxial geogrids made from polypropylene or polyester were integrated into the track bed. These geogrids are engineered for soil confinement and structural reinforcement. Their key properties include:

- Aperture Size: 25 mm × 25 mm
- Tensile Strength at 2% Strain: 20 kN/m
- Ultimate Tensile Strength: 40–60 kN/m
- Durability: High resistance to UV exposure, chemical attack, and biological degradation

The geogrid properties conform to ISO 10319 and were verified using manufacturer data sheets from Tensar and confirmed through in-house tensile testing.

B. Full-Scale Track Construction and Instrumentation

A 100-meter full-scale test track section was constructed using the proposed materials. The layered system consisted of:

- Subgrade Soil: Moderately plastic clay
- Ballast Layer: Crushed granite (20–60 mm)

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- Reinforcement: Biaxial geogrid placed at the ballast–subgrade interface
- Superstructure: Composite sleepers with standard

Steel rails. Instrumentation included:

- Strain Gauges: Embedded in sleepers and rails to monitor stress
- Accelerometers: Installed to capture vibrational responses
- LVDTs: Positioned to measure track settlement and deformation

Simulated axle loads of 22.5 tons were applied at frequencies ranging from 5 to 20 Hz to simulate dynamic effects from train speeds between 60 and 120 km/h. These loadings reproduced real operational stresses observed in medium-to-heavy rail systems.

The applied loading frequencies were determined using dynamic simulations based on sleeper spacing (0.6 m) and train velocity, following the relationship: frequency = velocity/sleeper spacing. This correlation ensured a realistic simulation of operational conditions.

C. Experimental Performance Evaluation

The test program measured settlement, stability, and deformation under controlled loading conditions. Results indicated:

- Track Settlement: Reduced by 43% (20 mm/year vs. 35 mm/year in conventional track)
- Lateral Stability: Improved by 20% (30 N/mm vs. 25 N/mm)
- Vertical Deformation Control: Enhanced by 35%
- Inspection Frequency: Reduced from three to two per year
- Track Maintenance Cost: Reduced by 33%

These improvements confirm the operational advantages of integrating composite sleepers and geogrid reinforcements.

Percentage improvements were calculated by comparing performance metrics (e.g., settlement, stiffness) of the reinforced system to those of a reference conventional track section monitored over the same loading period. For instance, settlement reduction = (35 mm − 20 mm)/35 mm × 100 = 43%.

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D. Finite Element Modeling

Finite Element Analysis (FEA) was performed using ABAQUS 2022 and PLAXIS software. The model setup included:

- Element Type: 3D hexahedral mesh with 50 mm^3 elements
- Sleeper Model: Linear elastic isotropic
- Geogrid Model: Bilinear, tension-only membrane elements
- Loading Conditions: Simulated freight and heavy haul traffic
- Environmental Conditions: Sustained heat at 50°C and freeze–thaw cycles

The FEA results supported the experimental findings and revealed:

- Peak Stress Reduction: 30% lower in reinforced tracks
- Ballast Breakage Reduction: 20%
- Settlement Reduction: Significant, matching observed data
- Maintenance Interval Extension: Substantiated through durability simulations

Boundary conditions included fixed displacement at the model base and symmetric constraints at lateral edges to simulate track continuity. Validation was achieved by comparing model outputs with measured field strain and deformation data, showing deviations of less than 10%, consistent with accepted engineering thresholds.

These simulations validated the mechanical behavior and long-term benefits of the proposed sustainable track system under diverse and challenging conditions.

IV. Results And Discussion

The integration of composite sleepers and geogrid-reinforced subgrades demonstrated notable improvements in structural integrity, track resilience, and maintenance efficiency. The experimental and numerical analysis confirmed the compatibility and performance enhancements of the proposed system over conventional track configurations.

A. Track Settlement and Stability

Experimental data revealed a 43% reduction in track settlement, aligning with the FEA results. The presence of geogrid reinforcement significantly improved load distribution and reduced permanent deformation.

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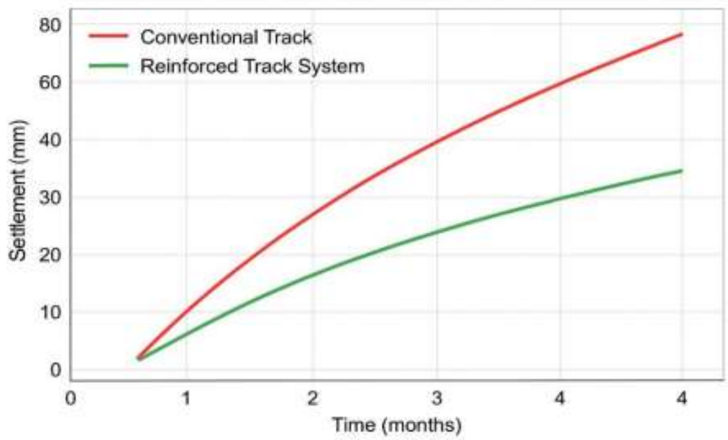

Fig. 1: Settlement comparison over time

Fig. 1 illustrates comparative settlement data between conventional and reinforced tracks over a 12-month monitoring period. The reinforced track maintained consistent performance, with settlement stabilizing after 6 months, while the conventional track continued to deform.

B. Track Lateral and Vertical Performance

The lateral track stiffness increased by 20% and vertical deformation control improved by 35%. These outcomes can be attributed to enhanced ballast confinement and improved stiffness of the composite sleepers.

Table I: Summary of track performance metrics (reinforced vs. Conventional track)

Parameter	Conventional Track	Reinforced Track	Improvement (%)
Track settlement(mm/year)	35	20	43%
Lateral stiffness (N/mm)	25	30	20%
Vertical Deformation control	-	Improved	35%
Maintenance Frequency (per year)	3	2	33%
Ballast Breakage Rate (%)	Baseline	Reduced by 20%	20%
Peak stress (MPa from FEA)	Baseline	Reduced by 30%	30%

Table I presents average values of lateral stiffness and vertical deformation derived from load–load-displacement tests. The improved mechanical response was validated by both field and FEA results.

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C. Maintenance Cost and Interval

A tangible benefit of these improvements was a reduction in inspection frequency and an associated 33% cost saving in maintenance. The increase in track longevity also implies fewer service disruptions and long-term financial savings.

Maintenance cost reductions were estimated based on historical cost data for similar track sections maintained under Ethiopian railway operations. Savings were calculated by comparing the reduced inspection and tamping frequency for reinforced tracks over one year.

D. Durability and Environmental Performance

The composite sleepers maintained structural integrity under simulated thermal stress and freeze-thaw conditions, highlighting their suitability for diverse climates. The materials also contribute to environmental sustainability by repurposing recycled plastics and minimizing reliance on timber.

Each composite sleeper used in the test section prevented approximately 30 kg of plastic waste from entering landfills. Over the 100-meter test track, this equates to an estimated 12 tons of recycled material usage.

Overall, the findings support the use of innovative composite materials and Geosynthetics reinforcement in enhancing the sustainability and durability of modern railway infrastructure.

V. Conclusion and Recommendations

A. Conclusion

This study provides field-validated evidence that integrating recycled composite sleepers and geogrid-reinforced subgrades enhances track performance, reduces maintenance, and aligns with sustainable infrastructure goals. In the Ethiopian context, this is a significant step forward, offering cost-effective, environmentally responsible, and durable track designs. The combination of full-scale experimental results and finite element simulations demonstrated a 43% reduction in deformation control and a 33% reduction in maintenance costs compared to conventional systems. There are also Economic benefits as maintenance costs decreased by 20% (ETB 658,512.22/km to ETB 526,809.78 /km), confirming the long-term cost efficiency of sustainable railway materials. The use of composite sleepers, made from recycled HDPE and glass fiber, contributed to reduced CO_2 emissions by approximately 1.2 tons/km annually, while geogrid reinforcement extended ballast renewal cycles and enhanced subgrades' resilience. These improvements

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validate the system's suitability for high-load, high-speed, and climate-challenged railway networks, offering a cost-effective and sustainable alternative to traditional track technologies.

B. Recommendations for Implementation

Based on the findings, the following recommendations are proposed for railway infrastructure development: - Adoption of composite sleepers in high-load and high-speed corridors, given their superior fatigue resistance and longer lifespan (50+ years); composite sleepers should replace traditional timber or concrete sleepers in high-speed rail (HSR) and heavy freight routes; and implementation of geogrid-reinforced subgrades in maintenance-intensive sections of tracks in soft soil regions, high-load freight corridors, and areas prone to extreme weather should prioritize geogrid reinforcement to enhance stability and extend track lifespan. The integration of Finite Element Modeling (FEM) in railway design is recommended, and future railway projects should incorporate FEM simulations to optimize track designs before implementation, reducing experimental costs and improving infrastructure resilience. Lifecycle Cost Analysis (LCCA) for infrastructure planning, rail operators should conduct a comprehensive LCCA before track upgrades to compare initial investment costs vs. long-term savings, ensuring financially viable decisions. The sustainability-oriented development policies of governments and railway authorities should incentivize the use of recycled composite materials and sustainable subgrade stabilization techniques to promote green transportation infrastructure.

C. Future Research Directions

While this study demonstrates the effectiveness of composite sleepers and geogrid-reinforced subgrades, further research is needed to evaluate long-term performance in diverse climatic conditions. Future studies should monitor material behavior under extreme heat, freeze-thaw cycles, and heavy rainfall across different geographic regions. Assessment of performance under higher axle loads (>25 Tons). Freight corridors with axle loads exceeding 25 tons should be studied to determine whether additional reinforcement is required. If developed, hybrid reinforcement strategies combining geogrids with other soil stabilization methods (e.g., chemical stabilization or geo-polymer) could further enhance track performance. Further material composition optimization can be done for cost-effectiveness. Further research should explore alternative composite sleeper formulations to reduce initial material costs without compromising durability.

Finally, this research contributes to the development of resilient, cost-effective, and environmentally sustainable railway infrastructure by demonstrating the benefits of composite sleepers and geogrid-reinforced subgrades. The results confirm that these materials enhance track performance, reduce

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maintenance needs, and support global sustainability goals. Future research and policy adoption will further accelerate the transition toward sustainable railway transportation systems.

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Kafi Noonoo to English Machine Translation using Deep Learning Approaches

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Abstract

Kafi Noonoo is one of the Ethiopian languages that is spoken by the Kaffa people in the southwestern part of Ethiopia. Additionally, it is a morphologically rich language and has an indigenous name for prestige, cultural place, and cultural dejectedness, which has no equivalent meaning in other languages. Machine translation is a technique that automatically translates text or speech's meaning from one language to another without human involvement to resolve information gaps. Various machine translation studies have been conducted for resource-rich languages like English, French, German, and others. However, the variety of linguistic patterns, the dominance of technologically developed languages, and the lack of machine translation from Kafi Noonoo to English will lead to the disappearance of Kafi Noonoo's indigenous words among native speakers. To tackle such a problem, this article designed a Kafi Noonoo to English and vice versa machine translation solution by using deep learning approaches. The bidirectional long short-term memory, bidirectional gated recurrent unit with and without attention, and transformer were applied. In order to train the model, the bilingual parallel sentences were collected from Kafi Noonoo's linguistic-related sources. Different experiments were applied to find out the optimal value of the proposed model. Based on the experiment's result, the transformer performed better with an accuracy of 89% and a BLEU score of 6.34 and 5.42 for Kafi Noonoo to English and English to Kafi Noonoo, respectively. According to our experiment results, the transformer model was suitable for morphologically rich languages like Kafi Noonoo to English and vice versa, for machine translation. For a better result, there is a necessity to generate parallel corpora in order to conduct comparable research.

Keywords: Kaffa, Kafi Noonoo, Low-resource Machine Translation, Transformer

I. Introduction

Natural language is one of the fundamental aspects of human behavior and a basic element of daily activities, and it is mainly used for exchanging thoughts, feelings, and information through spoken, written, and signed communication [1]. According to [2], distinct natural languages are spoken all over the world.

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Kafi noonoo is one component that is spoken by the Kaffa people (Kafecho) in the southwestern part of Ethiopia. Natural languages are studied in different academic disciplines such as linguistics, psycholinguistics, computational linguistics, and others. Furthermore, each discipline defines a set of problems and has methods to address the identified problems [3]. Kafi Noonoo uses the Latin script writing system, which utilizes a total of thirty-two characters made up of twenty-seven consonant characters and five vowel characters [4][5][6][7]. In morphology, it uses inflectional, derivational, compounding, reduplication, and cases to form another word from existing words and follows the subject-object-verb order to form a grammatically correct sentence structure [8][5][9].

Computational linguistics studies the formal rules of languages and how technological devices such as computers, smartphones. and robots understand and generate natural language. Moreover, it mainly focuses on the computational description of languages as a system, and is applied by natural language processing [10][11][12][13]. Natural language processing (NLP) is a practical and interdisciplinary study domain of linguistics, mathematics, and artificial intelligence (AI) studied under computer science to process natural languages on computational devices [12][14][15]. Accordingly, different natural language processing applications such as machine translation [15][16][17], grammar error detection [18], word sense disambiguation [19], fake account detection [20], sentimental analysis [21], and others were developed.

Machine translation (MT) is utilized to convert text or speech from one human language to another, maintaining the natural language context using a computer algorithm. Using MT, anyone can share his/her knowledge, culture, tradition, history, and religious and philosophical writings from one language to another, and the accessibility of documents written in one human language to another language is easily translated [1][17]. Accordingly, to design and develop a machine translation system, rule-based (involving direct, transfer, and interlingua) translations, statistical translations, example-based translations, deep neural network (DNN) translations, and hybrid approaches were formulated [22]. In the field of MT, DNN is a newly emerging approach that has proven to achieve excellent performance. Its translation is enabled by huge amounts of structured data; the translations will be processed with a much higher accuracy rate, more scalable than traditional approaches, and identify patterns at a deeper level that can capture better way [23]. Various machine translation researches were done for Amharic-Wolaytta [24], Amharic-Ge'ez [25], English to Wolaytta [26], English to French [27], English to German [28] by understanding each language's limitations and linguistic patterns [1]. Furthermore, as our world becomes increasingly connected, language translation provides a critical cultural, political, and economic bridge between people from different countries and ethnic groups.

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However, technologically developed languages' word dominance, incompatibility of existing algorithms, and the lack of computational linguistic applications like Kafi noonoo to English machine translation will lead indigenous Kafi noonoo words like prestige names (*kateemeraashoo shooderaashoo, maaceraashoo*), cultural place names (moogo, gutoo), and cultural dejectedness names (*gommo, shoosho, hichoo*) to disappear from native speakers. To overcome this problem, this article was designed for Kafi Noonoo for English machine translation (MT) by using deep learning approaches.

II. Literature Review

Mengistu and Kinfe [29] investigated the deep learning technique in bi-directional Amharic to Kistanigna machine translation. Parallel corpora from the Kistanigna dictionary to Amharic and the Holy Bible, like Saint Matiwos, Saint Marikos, and Saint Lukas, were gathered by the researcher. The researcher used a variety of deep learning algorithms, including transformer models, bidirectional long short-term memory (Bi-LSTM), long short-term memory (LSTM) with attention, and long short-term memory LSTM. Ultimately, the Transformer model produced BLEU scores of 22.4 from Kistanign to Amharic and 21.3 from Amharic to Kistanigna.

Agerie Belete [30] carried out deep learning-based bi-directional English-Awngi machine translation. According to the paper, no research was done comparing Awngi and English. The researcher compiled parallel corpora from social media documents, religious texts, and educational resources and obtained BLEU scores of 22.34 for Awngi to English and 24.94 for English to Awngi, respectively.

Amdework Asefa [25] performed a Bidirectional neural machine translation (MT) for Ge'ez and Amharic using deep learning techniques. The goal of the researcher is to demonstrate the deep learning models' proficiency in MT tasks for those morphologically complex languages. Utilizing the praise of Saint Mary, the Mass media, and other Ethiopian Orthodox Church religious texts and the Bible, the researchers created a dataset. Using a transformer, the researcher assessed the results of an experiment and obtained BLEU scores of 22.9 for Ge'ez to Amharic and 29.7 for Amharic to Ge'ez.

Abdu Wahid [31] carried out their research on the deep learning-based MT system for English to Urdu. The dataset was gathered from news articles and everyday utterances included in the English-Urdu parallel corpus. They created a new parallel corpus and experimented with various training settings for the English to Urdu MT model, which is an LSTM encoder-decoder.

Levi Corallo et al. [32] used a gated recurrent unit recurrent neural network (RNN) to perform German-English machine translation. The researchers' framework aims to construct apps, facilitate future work in

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the field, and act as a pilot method for translating strings from German news sources into English phrases. They obtain statistics from the WMT2021 and create a framework that might be helpful in creating mobile applications for rapid translation, where efficiency is essential. By classifying RNN models with various hyperparameters, they finished two tests. The final training and validation accuracy of Model I were 0.655 and 0.653, respectively, while the final validation accuracy of Model II was 0.645 and 0.649. Model I's final validation loss is 2.78, while its final training loss is 2.78 (as depicted in Fig. 2).

Elias Asefa [33] used the neural network approach in conjunction with RNN in order to create a unidirectional English-to-Dawurootsuwa MT model. He finished creating the algorithm to identify and examine patterns in data sequences and forecast the output text using the text data that was entered. Additionally, a total of 20,345 pairs of corpora that were gathered from various sources were able to acquire a BLEU score of 0.5187.

Mekdes Melese [26] worked on English-Wolaita's attention-based neural machine translation (NMT). The researcher's goal is to use attention mechanisms to create an NMT for English-Wolaita and gathered 27351 sentences from a comparable corpus. Additionally, the data was preprocessed for appropriate NMT usage. An LSTM encoder and LSTM decoder architecture with an attention mechanism has been used in the Seq-to-Seq idea to construct the English-Wolaita NMT system model. The researcher attempted to compare the model with the non-attention model and the attention mechanism in order to gauge performance by the BLEU score for measuring the effectiveness of the attention mechanism. Overall, the researcher was assessing the effectiveness of the model investigations. Finally, it was acknowledged that the attention mechanism translated more accurately, achieving a BLEU score of 5.16 and an accuracy of 88.65% for English-Wolaytta. According to literature reviews, there is no study that has been done on MT between Kafi Noonoo and English. This article designed a Kafi Noonoo to English machine translation using deep learning approaches.

III. Research Methodology

A. *Data Source*

This study requires a dataset to train and evaluate the model for translating Kafi Noonoo texts into English and vice versa. Nevertheless, there is no published dataset in bilingual content. Therefore, in order to gather the bilingual text, this study planned, identified, and gathered bilingual text from authorized Kafi Noonoo linguistics-related data sources. We have collected 36,000 sentences in two columns, one for Kafi Noonoo and one for English.

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As mentioned in Table I, the corpus we have collected is from various sources such as academic documents, the holy bible, and the existing Kafi Noonoo dictionary in order to meet the objective of creating an acceptable dataset for bilingual text from Kafi Noonoo to English.

Table I: Collected dataset

Bilingual sources	Amount
Academic document	7,000
Holy bible	10,000
Kafi Noonoo to the English dictionary	19,000
Total	36,000

B. Model Architecture

The first phase, which is carried out by the Kafi Noonoo to English translation MT architecture (as mentioned in Fig. 1), is preprocessing. Under this phase, different activities, such as data cleaning, which is used mainly to remove irrelevant symbols from the collected dataset, are done. The normalization techniques were applied to standardize all symbols in a unique form to improve dataset quality. Tokenization is the process of converting plain text into a series of tokens. Two main procedures are performed sequentially in that process. We used the tokenized words to create a word index, which is mainly focused on word identification in the dataset. The word sequence to numeric sequences conversion was also used to convert sequences of sentences into sequences of numeric values because deep learning algorithms do not understand raw text. The sequence normalization techniques were applied to normalize the sequence in matrix form. Next to this step, we designed an encoder and decoder that are mainly used to translate sentences. The encoder-decoder model has two parts. The first one accepts vectorized form source language sentences, i.e., Kafi noonoo, with a deep learning algorithm, bidirectional long short memory (BiLSTM), bidirectional gated recurrent (BiGRU) with and without attention, and transformer with fixed input sequence lengths, targeted language sequences, i.e., English, with softmax activation function. Encoder processes input sequences token by token by updating its hidden state at each time step and finally produces a model. The second decoder takes the encoder vector and generates a target sequence one at a time. The decoder performs a time step each time, as input, previous target sequences generated tokens from the decoder, as well as the previous hidden state. The hidden state is updated depending on the previous state and previous target token, and used to generate the next target token. This process continues until the decoder brings about an end-of-sequence token, indicating that the decoder has generated the entire target sequence.

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The encoding and decoding processes are trained jointly using a Seq2Seq loss function, optimizer, and learning rate epochs. During training, the input sequence is supplied to the encoder, and the decoder generates the target sequence token by token. The final encoder hidden layer context vector and target embedding sequence are accepted by the decoder model during training in order to predict the target output. Thus, the context vector is passed through to the decoder to get an output sequence.

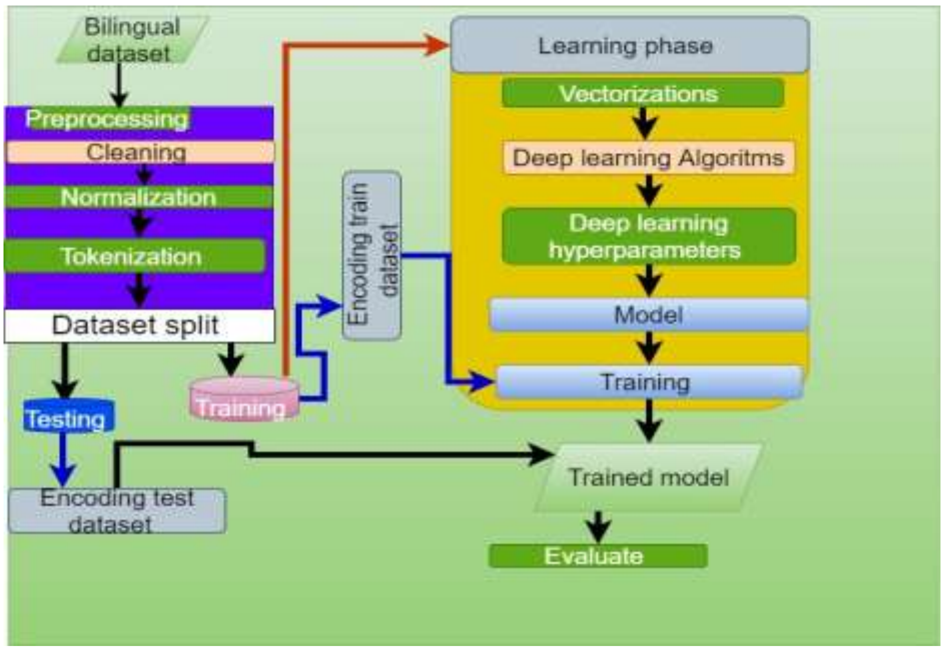

Fig. 1: Model Architecture

C. Model Performance Evaluation Metrics

1) Accuracy

The accuracy metric is used to monitor the model's performance during training. It indicates how successfully the model can categorize or predict the right output given the input data. We also used this measurement of accuracy to assess the quality of the translation in the translation process. It is computed computationally by adding the errors for each sample throughout the training set. Each batch of data is used to calculate training loss, which is then plotted as a curve [34].

2) BLEU (Bilingual Evaluation Understudy)

BLEU is a reference-based metric that measures the similarity between the system-generated translations to evaluate the quality of our translations and human-generated reference translations. It calculates common elements of n-grams, continuous sequences of matched words between the system output and the reference

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translations. The core idea behind the BLEU score is that a good translation should contain similar n-grams to the human reference translations. Performance evaluation is important after training models; there are various methods used in MT translation accuracy. BLEU computes the precision of n-grams, including unigrams, bigrams, trigrams, etc. The effectiveness of MT is determined by assessing how closely it aligns with human translation. When the machine-generated text closely resembles the human translation, it is considered to be of higher quality and more successful in achieving accurate translation [35].

IV. Results and Discussion

A. Results

The proposed deep learning-based Kafi Noonoo to English machine translation model has been aimed to translate Kafi Noonoo to English and vice versa. Finally, the artefact was designed and developed by using BiLSTM and BiGRU with attention and without attention, and transformer deep learning algorithms. In addition, different experiments were conducted by the identified deep learning algorithms to determine the effect of deep learning approaches to translate Kafi Noonoo to English and vice versa, and evaluated each experiment's results by using accuracy and BLEU (as depicted in Fig. 3). In the first experiments, we got BLEU scores of 5.18 and 4.37 from the Kafi Noonoo to English translation and English to Kafi Noonoo, respectively, by using BiGRU.

In the second trial, we added attention mechanisms to BiGRU, and the model's training time and the effectiveness of the model with the same data size and hyperparameters were improved. The training times in the analysis are compared with the BiGRU model training time, with attention to the training time without attention in the prior experiment. An attention layer has been allowed in the model for capturing the context and ignoring the ignore word. For this reason, encoder-decoders without attention mechanisms cannot handle large numbers of sentences. The other outcome of attention methods can reduce the amount of training time needed for the model to finish. The effectiveness of the BiGRU model with attention includes an accuracy of 86%, a loss of 0.11 from Kafi Noonoo to English, and the impact of attention on the metrics compared to previous experiments. We see better accuracy, loss, and training results compared to previous experiments. In this phase, the BLEU score from Kafi Noonoo to English has taken 404 seconds, and from English to Kafi Noonoo, it has taken 420 seconds, and the BLEU score has obtained 5.82 and 4.74, respectively.

Our third experiment was done using bidirectional long short-term memory. It contains double long and short-term memory (LSTM) cells on the encoder side, which take up a lot more memory than a single LSTM. Here we have used the same parameters as we did with BiGRU and BiGRU with attention. We

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obtained accuracy results of 87.89% and 88.5% and loss values of 0.39 and 0.12 from Kafi Noonoo to English and English to Kafi Noonoo. It took 365 seconds and 378 seconds to get BLEU 5.89 and 4.83 from Kafi Noonoo to English and English to Kafi Noonoo, respectively.

In the fourth trial, we conducted the Bidirectional long short-term memory with attention, and we used similar parameters to those we used in the others. In the BiLSTM with attention model, we analyzed the result of varying the number of epochs on the model and explored how increasing the number of epochs influences the model's ability to learn from the training dataset, improve its performance, and decrease the value of loss. It took 265 seconds and 300 seconds to get BLEU 5.99 and 4.93 from Kafi Noonoo to English and English to Kafi Noonoo, respectively.

Our transformer model does not have an additional attention mechanism. Here we have fed both token embedding and position embedding vectors to our transformer model. Because the transformer model accepts all inputs in parallel. We have used 6 layers in our transformer model. Like the BiGRU and BiLSTM without attention and with attention, our transformer models use only the last encoder context vector passed to the decoder directly without additional attention mechanisms, because the transformer model has its attention. The encoder-transformer model has a feed-forward network and self-multi-head attention. The decoder model has a masked multi-head focused and a feed-forward neural network (NN). And we have used the RLU feed-forward network in both the encoder and decoder models. It took 100 seconds and 120 seconds to get BLEU 6.34 and 5.42 from Kafi Noonoo to English and English to Kafi Noonoo, respectively.

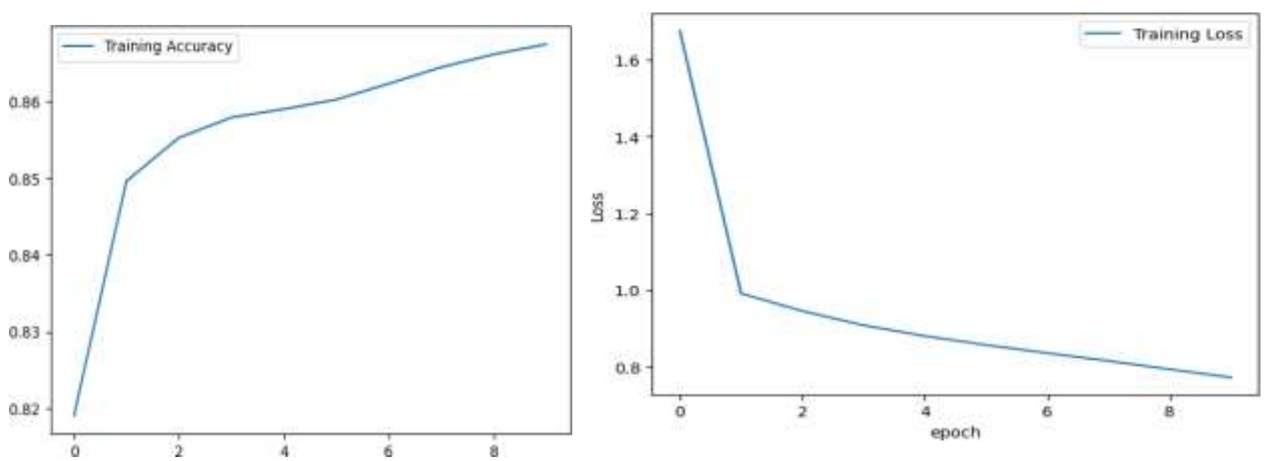

Fig. 2: Training accuracy and loss graph

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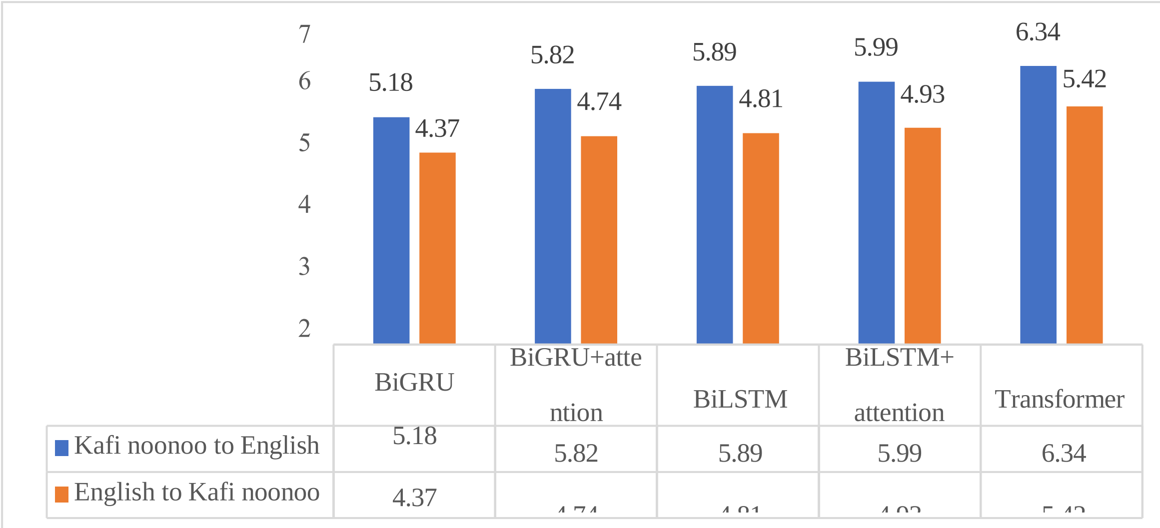

Fig. 3: Comparison of the deep learning algorithm's BLEU score

B. Discussion

To translate Kafi Noonoo to English and vice versa, different preprocessing steps were done. The encoder-decoder architecture was built with attention or without attention using BiLSTM, BiGRU, and transformers. The encoder reads all of the data into a single real-valued vector, which is then sent to the decoder, which uses the vector to produce the target translation. To identify a word by a specific index at the moment it is encountered in the data, each word in the sentences must be given a new identity number as it is visited. Different experimentation setups with different deep learning algorithm hyperparameters were designed to find out the optimal result measured by accuracy and BLEU score. We obtained different results in each experiment. Based on the result of the experiment on BiLSM and BiGRU with attention, the BLEU score shows that the attention-based approach is better than the one without attention for Kafi Noonoo-English MT models, and a better outcome is obtained when the transformer model is used instead of BiLSTM and BiGRU with and without attention.

Nevertheless, it is difficult to obtain a more effective translation model, given the short amount of data employed in this article. Even with a small dataset, the highest possible BLEU score of 6.34 and accuracy of 89% is recorded by adjusting different hyperparameters while experimenting with this small corpus. From our experimental findings, we have seen that deep learning has become a successful MT technique as a result of increased processing capacity. Sentences can be translated by a built model with remarkable accuracy using the Encoder-Decoder architecture. Finally, considering all the experiments, a better BLEU score is achieved or documented when Kafi Noonoo is used as the source language and English as the target language using transformer deep learning approaches.

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V. Conclusion

Based on the experiments' results, the transformer model outperforms Bi-LSTM and BiGRU with and without attention models in terms of accuracy, BLEU score, and training time. The transformer also demonstrates better performance than other models examined in these studies when translating more complex sentences. In both translation directions, the transformer model has a faster training time than the other models used in the experiment.

Overall, our research confirms that the transformer model provides good translation accuracy in both directions between the language pairs. Consequently, there is a need to generate parallel corpora and add different dialect corpora to conduct comparable research and include more phonetic variation in Kafi Noonoo.

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Experimental and Numerical Approaches: Performance Optimization of a Baffled Solar Cabinet Dryer for Mango Slices

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Abstract

During peak seasons, postharvest loss of mangoes remains a significant challenge for smallholder farmers in Ethiopia, driven by high production volumes, limited market access, and a lack of preservation methods. The objective of this research was to develop and enhance the performance of a solar cabinet dryer for mango slices through Computational Fluid Dynamics (CFD) simulations. A solar cabinet dryer incorporating a rectangular baffle solar collector was developed, built, and experimentally validated. The CFD simulation results showed a temperature difference of 4.35% and a relative humidity deviation of 7.8%, indicating good agreement with the experimental data. The model optimized the baffle design and inlet air velocity to maximize outlet temperature and minimize pressure drop. The optimal design was identified using Response Surface Methodology (RSM) in conjunction with ANSYS software. The best-performing configuration featured four baffles with 25% cut openings and an inlet air velocity of 1 m/s. The porous domain of mango slices was incorporated into the model to predict moisture transport with experimental effective diffusivity of (5.224×10^{-7} m²/s). Results showed that the designed dryer achieved uniform temperature and moisture distribution, with higher drying rates observed near the lower trays. The moisture content in mango slices was reduced from 45942.17 mol/m³ to 2,677 mol/m³ within two hours of drying. The CFD model showed strong predictive accuracy with only minor discrepancies observed in the simulation of temperature, relative humidity, and moisture movement. The developed dryer provides a sustainable and cost-effective solution to reduce postharvest mango losses with an efficient design that enhances food security and farmer livelihoods.

Keywords: CFD Modeling, Heat and Mass Transfer, Mango Slices, Postharvest Loss, Solar Dryer

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I. Introduction

Postharvest losses of fruits, particularly mangoes, continue to pose a serious challenge for smallholder farmers in Ethiopia. Although mangoes are highly valued for their nutritional benefits and economic importance, they often experience significant post-harvest losses due to insufficient preservation and processing techniques, particularly during peak production seasons. The Food and Agriculture Organization (FAO) estimates that in developing nations, up to 40% of perishable goods may be lost, undermining food security and reducing the earnings of agricultural producers [1].

Solar drying offers a sustainable and cost-efficient alternative to conventional drying approaches, enhancing energy efficiency and minimizing dependence on fossil fuels. Nevertheless, its performance is sometimes hindered by challenges such as uneven temperature distribution, low efficiency, considerable energy losses, and inadequate airflow—factors that adversely affect drying time and product quality [2].

Computational Fluid Dynamics (CFD) has emerged as a powerful analytical tool in both academic research and industrial applications for studying fluid flow behavior and thermal processes in drying systems. Recent progress in CFD techniques has empowered researchers to more effectively design and optimize solar dryers. This, in turn, has led to enhanced thermal performance, energy efficiency, and drying uniformity. CFD provides a detailed understanding of heat and mass transfer phenomena, enabling the prediction and enhancement of drying conditions within solar dryers. Studies have demonstrated the potential of baffled solar collectors to enhance airflow and temperature distribution, thereby improving drying efficiency [3].

This study focuses on designing and optimizing a solar cabinet dryer equipped with baffles for mango slices through CFD modeling, targeting issues of uneven drying and energy loss. The results are intended to advance solar drying technology, improve mango preservation methods, and contribute to strengthening food security in Ethiopia.

II. Materials and Methods

A. *Development, Fabrication, and Field Evaluation of the Dryer*

The study was conducted at the Bahir Dar Institute of Technology, Bahir Dar University, located in northwestern Ethiopia. The solar dryer was constructed from materials such as MDF wood, glass, sheet metal, black paint, and mesh trays. Equipment used included a digital balance, Lux meter, anemometer, data loggers, photovoltaic (PV) system, colorimeter, refractometer, and caliper. Computational Fluid Dynamics (CFD) simulations were performed using ANSYS Workbench version 18.0.

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B. CFD Simulation of the Solar Cabinet Dryer

Accurate experimental setup, validation, and optimization are essential for effective CFD modeling aimed at enhancing design and performance [4]. The study involved the design, modeling, simulation, and optimization of solar cabinet dryers by varying the number of baffles, baffle cut dimensions, and air velocity, as outlined in Table I.

Table I: Collector configurations

Flat plate collector	**Flat plate collectors with**	
without baffle	Baffle cut	Number of baffles
	25%	2,4,6
	37.5%	2,4,6
	50%	2,4,6

ANSYS CFX 18.1 was used to model fluid transport in the dryer, testing solar collectors with and without baffles. Mango slices were modeled as a 3 mm porous medium (Fig. 1).

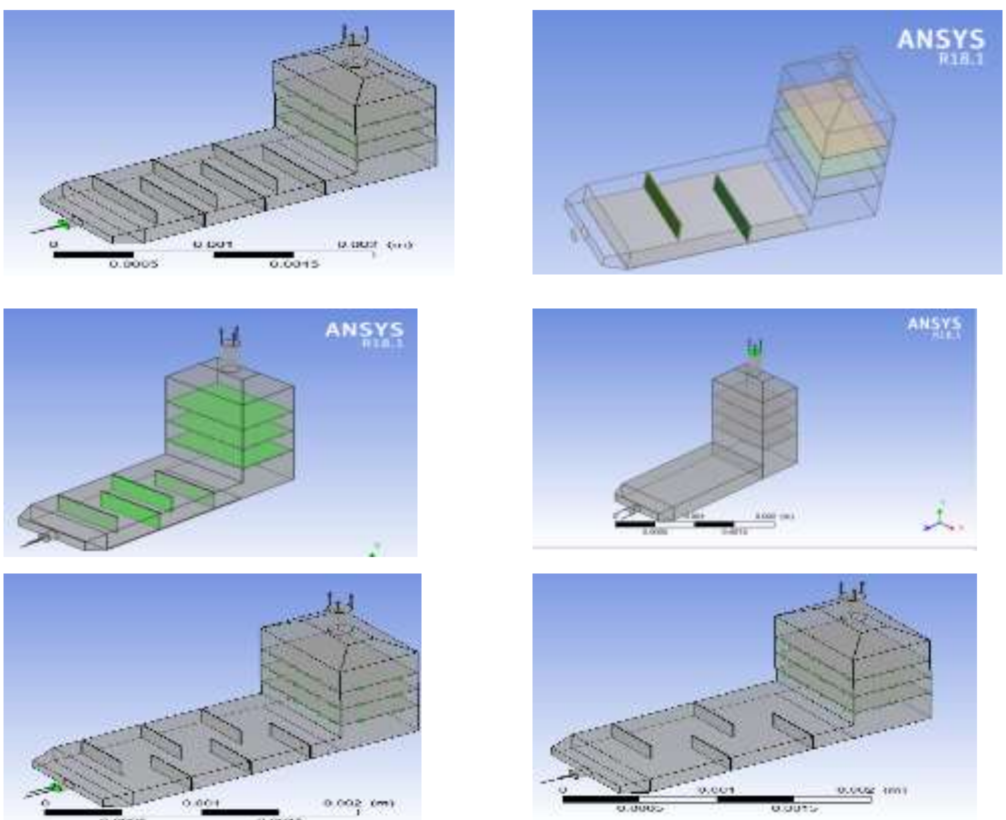

Fig. 1: Solar cabinet dryers with 0, 2, 4, and 6 baffles with baffle cut of (25%-50%)

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The turbulent airflow in the drying system was modeled by the standard Reynolds-averaged Navier-Stokes equations, complete with energy transport equations using equations 1-3.

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho\vec{v}) =0 \qquad \text{Equation 1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v})\ \nabla.\ (\rho\vec{v}\vec{v}) = -\nabla p\ \nabla.\ (\bar{\bar{\tau}})\ \rho\vec{g}\ F \qquad \text{Equation 2}$$

$$\frac{\partial}{\partial t}(\rho E)\ \nabla.\ (\vec{v}(\rho E\ p)) = \nabla.\ [-\vec{q}\sum j\ hj\vec{J}j\ (\bar{\bar{\tau}}eff.\ \vec{v})\ ] \qquad \text{Equation 3}$$

Where

$\vec{v}$= is the fluid velocity vector and

ρ□= is the density of air

$\vec{F}$ = is the source term for momentum

E = is the total energy, $\bar{\bar{\tau}}$= stress tensor

1) Geometry and Meshing Setup: The three-dimensional model shown in Fig. 2 was discretized using the finite volume approach and meshed with tetrahedral elements in ANSYS-CFX, applying mesh refinement in key regions.

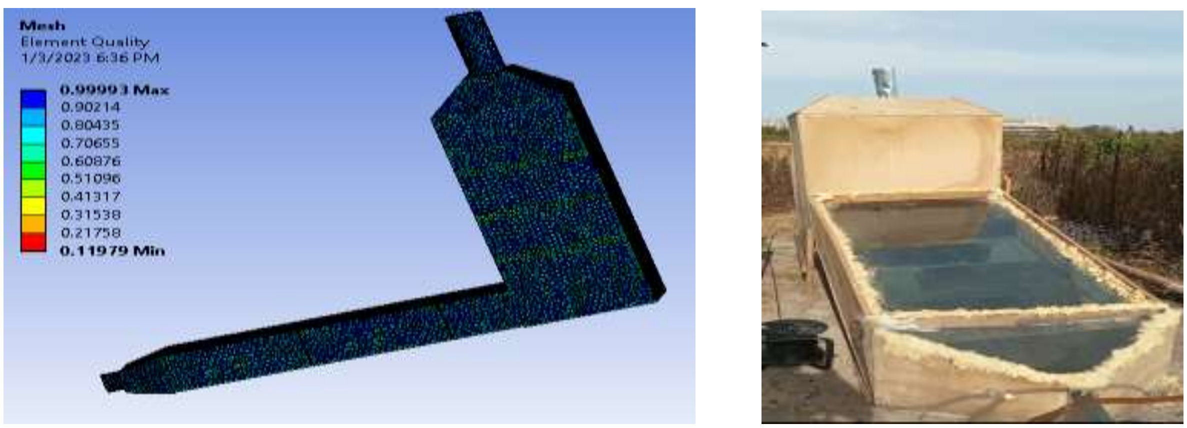

Fig. 2: Computational mesh of the solar dryer alongside the fabricated prototype.

2) Model setup and boundary conditions: In this study, the boundary conditions were defined as a function of the meteorological conditions of Bahir Dar and informed by prior experimental results, as summarized in Table II.

Table II: Model setup and boundary conditions

Parameter	Type	Value and unit
Solar radiation	Daily ambient	$-26.924t^2+279.54t+259.33, R^2=0.9827$
Inlet temperature (for transit simulation)	ambient	$4e-8*t^2+0.0012*t+19.57$
Inlet air velocity	normal	2m/s for experiment and 1-4(m/s)
Wall	wood (MDF)	0.018m

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Collector	sheet metal	0.008m
Glass	window glass	4mm, transparent
Baffle	sheet metal	0.008m
Porous(product)	Mango	3.88kj/(kg k)

3) Turbulence model: Among various turbulence models, the standard SST (Shear Stress Transport) model was selected due to its suitability for capturing swirling flow characteristics [5].

4) Sensibility Analysis: Given that the outlet temperature was a critical outcome of interest in the simulation, the mesh independence study was carried out by analyzing variations in this parameter across different mesh densities.

5) Model Validation: To validate the simulation results, the outlet temperature predicted by the CFD model was compared with the experimentally measured outlet temperature. The accuracy of the model was assessed using the Percent Bias (PBIAS) statistical metric, which quantifies the average tendency of the simulated values to deviate from the observed data. A lower PBIAS value indicates a better agreement between the model and experimental results. The PBIAS was calculated using the following equation [6] as shown in equation 4.

$$\text{PBIAS}=\frac{\sum_{i=1}^{N}(T_{expi}-T_{prei})*100}{\sum_{i=1}^{N}T_{expi}} \qquad \text{Equation 4}$$

Where:

Texpi is the experimental outlet temperature at time step i,

Tprei is the predicted outlet temperature from the model at time step i, and

N is the total number of data points.

6) Drying Temperature, Velocity, and Relative Humidity Distribution: A CFD model was developed to simulate temperature, pressure, velocity, and relative humidity by solving the RANS equations alongside turbulence models, incorporating supplementary expressions for saturation pressure (p^sat) and relative humidity as given in Equations 5 and 6 [7].

$$\ln(p_{sat}) = \text{A} - \left(\frac{B}{T+C}\right) \qquad \text{Equation 5}$$

Where A, B, and C are constants specific to water 16.3872, 3885.70, and 230.170, respectively.

$$\text{RH} = \left(\frac{P}{P_{sat}}\right) * 100 \qquad \text{Equation 6}$$

7) Optimization of the Developed Model: As shown in Table III, following the parameter studies, an optimized design, considering air velocity, baffle cut dimensions, and the number of baffles, was

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developed to maximize the outlet temperature while minimizing pressure drop. This tailored design was further refined using the Response Surface Methodology (RSM) optimization tool available within the ANSYS software.

Table III: Optimization parameters and their levels

Parameter	Units	Levels	L1	L2	L3	L4
Velocity of air	m/s	4	1	2	3	4
Baffle cut	%	3	25	37.5	50550	
No. of baffles	N	3	2	4	6	

8) Simulation of Moisture Movement: In solar dryers, water vapor is treated as a scalar property, independently solving its mass transport with a general conservation equation without affecting mass, momentum, and energy solutions for dry air.

$$\frac{\partial(\rho w)}{\partial t} = \nabla.(\rho\vec{u}w) = \nabla.(\rho D) + S_W \qquad \text{Equation 7}$$

Where w is the humidity ratio (kg water vapor/kg dry air) and D is the water vapor diffusion coefficient, which depends on temperature, the moisture transfer between mango slices and air during drying is represented by S_W determined by equation 8

$$S_W = Mw = A_{sv}h_m(C_e - C_a) \qquad \text{Equation 8}$$

The source term S_w is added corresponding to the moisture transfer between the mango slices and air during drying. The equivalent water vapor concentration of the mango slices and the water vapor concentration of the air are given by the following equations 9 (a and b).

$$C_e = \frac{M_w P_{sat} a_w}{RT} \quad (a) \qquad C_a = \frac{M_w P_{sat} RH}{RT} \quad (b) \qquad \text{Equation 9}$$

$$h_s = \frac{D_{eff}}{L_s}, \qquad \mathrm{RH} = \frac{\mathrm{Pa}}{\mathrm{Psat}} \qquad \text{Equation 10}$$

The overall mass transfer coefficient $\frac{1}{h_m} = \frac{1}{h_s}$ Where h_m= surface mass transfer coefficient(m/s) Asv is the ratio of the mango slice's surface area to volumeD_{eff} =5.224*$10^{-7}$$m^2$/s calculated from the previous experimental study [8].

The moisture source term was determined based on the rate of change of moisture content during the drying process. This rate depends on the mass transfer coefficient (km) and the difference between concentrations

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of water vapor at the outer surface of mango slices, Ce, and in the surrounding air, Ca. pa is the vapor pressure and $psat$ is the saturation vapor pressure of free water. Antoine's equation was used to calculate the saturation vapor pressure as a function of temperature.

$$p_{sat}=exp\left(A-\frac{B}{T+C-273}\right) \qquad \text{Equation 11}$$

Determination of mass transfer coefficient

The heat transfer coefficient was calculated using the Chilton–Colburn analogy for thermal and concentration boundary layers, as described in [9].

$\frac{D_{eff}}{k}$ K is the mango thermal conductivity=*0.925 W/m·°C.* Initial Moisture content (82.75%) in (mol/m^3) =MC=$\frac{MW}{Mmango}$ the initial moisture content of the product was calculated as 45942.17(mol/m^3) with a total of 6kg of mango slices.

9) Thin-Layer Drying Model: In the simulation of the mango slice drying process, the Page model was adopted to describe the thin-layer drying kinetics due to its proven accuracy in modeling the drying behavior of fruits and vegetables [10]. The model is expressed as:

MR=exp(-kt$^{n)}$

where:

MR is the moisture ratio (dimensionless),

k is the drying rate constant (1/min),

t is the drying time (min), and

n is a dimensionless empirical constant.

The parameters *k* and *n* were obtained from previous experimental studies on mango drying under similar conditions. This model was integrated into the simulation to predict the moisture removal rate from mango slices during drying, providing a more realistic representation of the drying curve. The use of the Page model enhances the accuracy of simulation outputs by aligning them closely with observed drying behavior.

III. Model Simulation Results

A. Mesh Independent Study Result

Meshing is crucial for accurate modeling, as results must remain consistent regardless of mesh size. To ensure precision, the optimal number of nodes and elements should be identified where further refinement does not affect the results.

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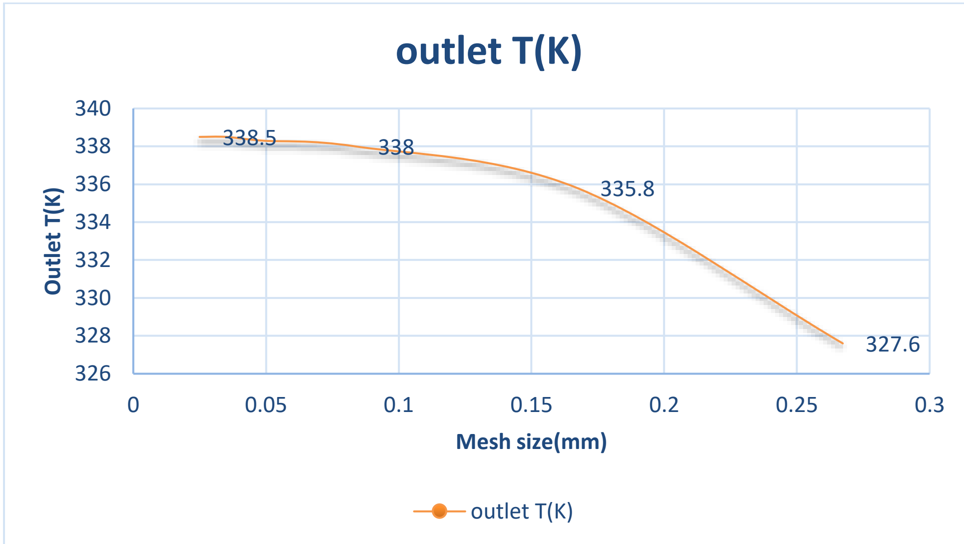

Fig. 3: Mesh independent based on mush size on the outlet temperature

From the mesh independent study (Fig. 3), the mesh size with 0.048992mm and 82,793, 18,963 numbers of elements and nodes respectively were selected for further study.

B. Model Validation

The CFD model overestimated the tray temperature by 2.176℃ (4.35%) compared to the experimental part of this research [8] due to unaccounted heat losses. The moisture distribution also underestimated the experimental value by 7.8%, as shown in Fig. 4.

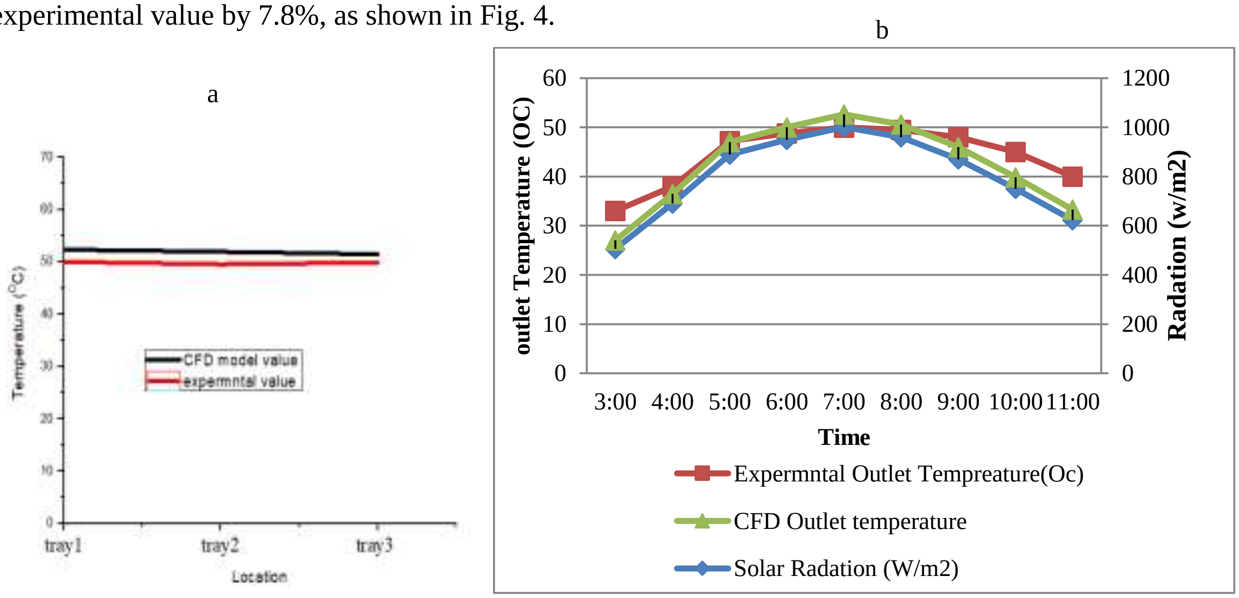

Fig. 4: Validation graph based on the location of outlet T (ºC) (a) and daily temperature variation (transit simulation) (b)

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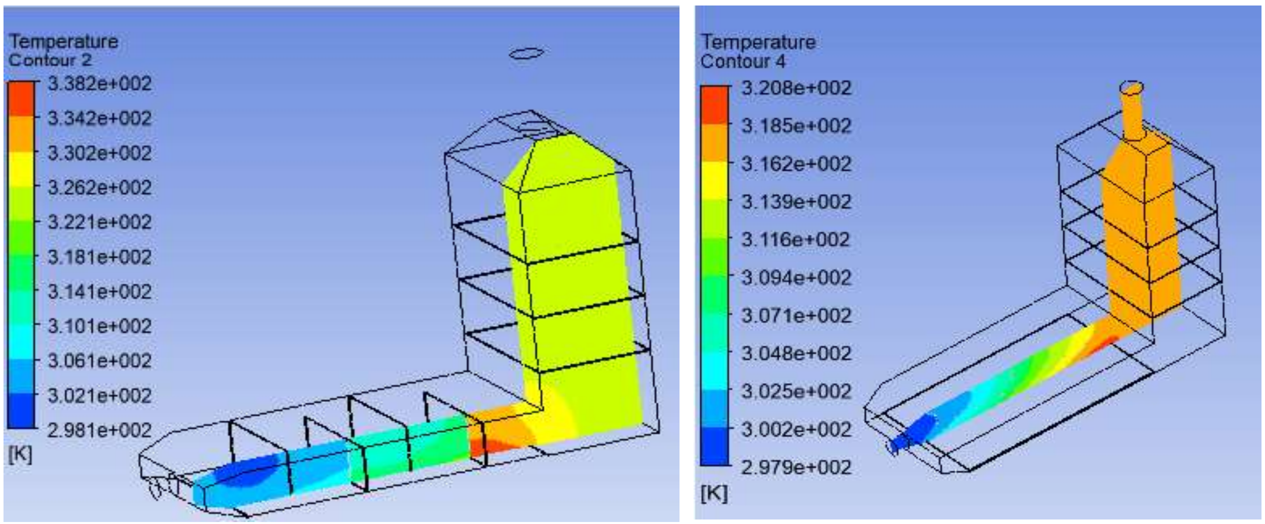
C. Pressure, Temperature, and Velocity Distribution

Efficient solar dryer operation depends on short drying time and uniform air velocity, temperature, and moisture distribution [2]. Figs. 6-7 show velocity streamlines and temperature distribution. A maximum velocity of 4 m/s and pressure of 22 Pa ensured uniform airflow in the drying chamber. High velocity and pressure at the inlet and outlet were attributed to the narrow cross-section. The absorber temperature peaked at 338.2 K, while tray 1 reached 365.2 K, indicating improved thermal performance due to the rectangular baffled solar collector Fig. 5 (a and b).



(a) (b)

Fig. 5: Temperature distribution inside the baffled collector and collector without baffle: a-collector with baffle, b-collector without baffle

As shown in the Fig. 5 simulation results, the solar cabinet dryer integrated with a rectangular baffle showed that the overall drying output temperature in the location of tray 1 was increased by 7.403℃(14%) than the non-baffled one. Solar collector with rectangular baffles improves the circulation of air within the collector, resulting in a more efficient transfer of energy from the heated metal sheet to the humid air. Based on this validation, the optimization of solar dryers was done with solar cabinet dryers integrated with rectangular baffles.

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D. Velocity and Temperature Distribution

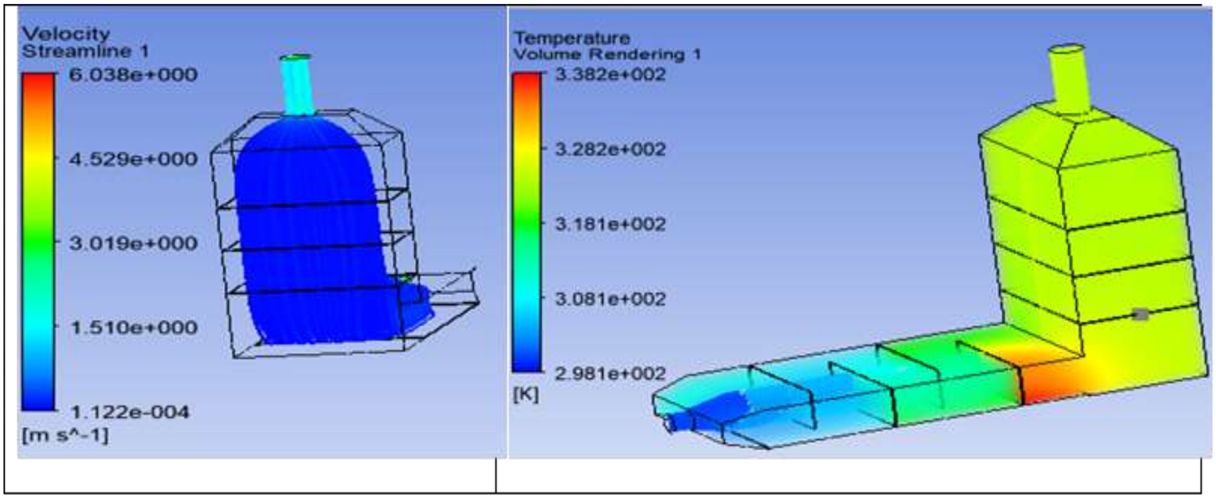

Fig. 6: Velocity and temperature distribution on the designed solar dryer

Fig. 6 shows higher temperatures at the bottom of the collector compared to near the cover, with slight temperature variation in the chamber. The CFD model indicated an even distribution of heated air (50-54℃), contributing to faster, well-dried mango slices, as noted by [2].

E. Relative Humidity Distribution

Relative humidity (RH) measures the moisture in the air relative to its maximum capacity at a given temperature. In the dryer, heated air reduces RH. The CFD model showed RH in the chamber at 17.5%, close to the experimental value of 19%, with a 7.8% error, indicating acceptable accuracy for parametric surveys.

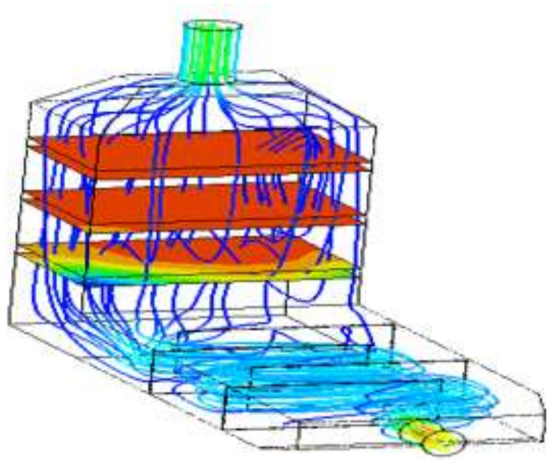

Fig. 7: Relative humidity distribution inside the dryer (counterplot with mango slices loading)

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F. Improving Dryer Efficiency Using CFD Simulations

The outlet temperature of the solar collector is key to improving product quality and reducing drying time. Maintaining an optimal pressure drop is essential for minimizing energy consumption and ensuring cost-effective operation.

1) Development of Regression Model Equation: The model equations correlating pressure drop (2FI model) and outlet temperature (quadratic model) to process variables are provided in equations 12 and 13.

$$\text{Temperature(K)} = 315.41 - 15.35 * A - 5.69 * B + 3.27 * C[1] - 1.64 * C[2] + 5.28 * AC[1] - 2.83 * AC[2] - 3.76 * BC + 18.7 * A^2 - 6.16 * B^2 \qquad \text{Equation 12}$$

$$\text{Pressure drop (pa)} = 29.45 + 17.26 * \mathrm{A} - 5.32 * \mathrm{B} - 13.01\mathrm{C1} - 3.97 * \mathrm{C2} - 12.5 * \mathrm{AC1} - 4.88 * \mathrm{AC2} + 2.09 * \mathrm{BC} \qquad \text{Equation 13}$$

The regression model estimates temperature and pressure drop based on air velocity (A), baffle cut (B), and number of baffles (C). Temperature decreases with higher air velocity and baffle cut, while it increases with more baffles and the interaction of A and C. Pressure drop increases with air velocity but decreases with higher baffle cut and fewer baffles. Coefficients indicate the strength and direction of these effects, with C1 and C2 representing binary interactions using 6 baffles as a reference.

G. Study of Desirability

The objective of this study is to find the best configuration of the baffle (baffle cut and baffle number) and velocity of air to maximize the outlet temperature while minimizing the pressure drop, as shown in Table IV.

Table IV: Constraints for optimization of the collector

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: velocity of air	is in range	1	4	1	1	3
B: Baffle cut	is in range	25	50	1	1	3
C: Number of baffles	is in range	2	6	1	1	3
Temperature	maximize	306	350.6	1	1	3
pressure drop	minimize	2.1	88.52	1	1	3

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Table V: Optimized solutions for combinations of numerical and categorical factor levels

Number	velocity of air	number of baffles	baffle cut	Temperature	pressure drop	Desirability	
1	1.000	4	25	350.929	3.0896	0.994	Selected

As depicted in Table V, based on the optimization, it can be concluded that the best response for attaining maximum outlet temperature and minimum pressure drop was obtained by setting the velocity of air at 1m/s, the number of baffles at 4, and the baffle cut at 25%. These parameters were found to be the optimal values for achieving the desired outcome of the experiment with maximum outlet temperature (77℃) at the outlet of the collector and 58℃ on tray 1.

H. Moisture Distribution within Trays

Using a detailed geometry and mesh, simulations of airflow, heat transfer, and moisture transport were conducted for the tray dryer. As shown in Fig. 8, the simulated moisture distribution within the porous mango slices after 2 hours of drying revealed a significant reduction in moisture content—from 45,942.17mol/m³ to 2,677 mol/m³, for slices with a thickness of 3 mm.

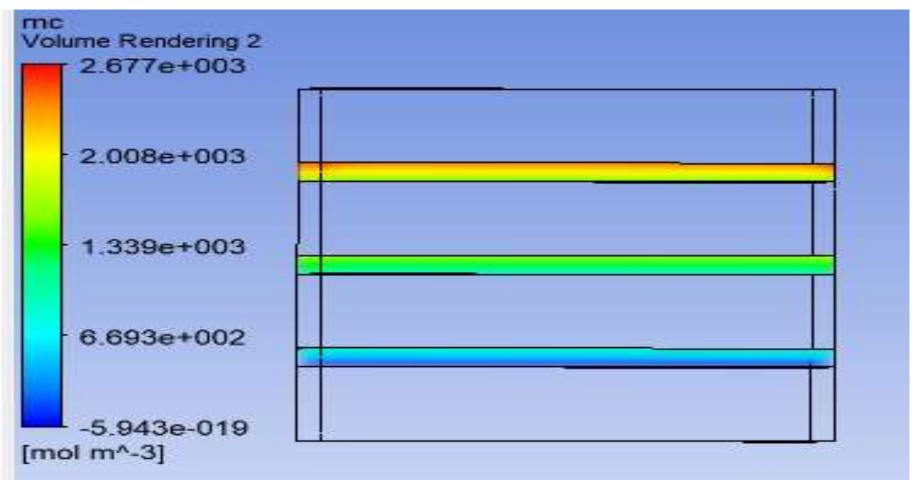

Fig. 8: Moisture content in 3 mm thick mango slices significantly decreased after 2 hours of simulation.

IV. Conclusions and Recommendations

A. Conclusion

This study successfully developed and optimized a baffled solar cabinet dryer for mango slices using Computational Fluid Dynamics (CFD) modeling. The integration of rectangular baffles significantly enhanced airflow distribution, temperature uniformity, and drying efficiency. The CFD simulations,

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validated against experimental data, demonstrated high predictive accuracy with minimal deviations, 4.35% in temperature and 7.8% in relative humidity. Optimal drying conditions were achieved with an air velocity of 1 m/s, four baffles, and a 25% baffle cut, resulting in enhanced thermal performance and minimized pressure drop. The drying system effectively reduced mango moisture content from 45,942.17 mol/m³ to 2,677 mol/m³ within two hours, confirming its potential as a sustainable and cost-effective solution to reduce postharvest losses and enhance food security. The model also established a strong foundation for further scaling and adaptation to other perishable crops. This finding is particularly significant for our community, especially in mango-producing regions like Arba Minch, as it offers a practical, low-cost solution to reduce postharvest losses, improve food preservation, and support smallholder farmers through enhanced drying technology.

B. Recommendations

Future studies should aim to boost the dryer's thermal efficiency by reducing heat losses and assessing its scalability for larger capacities. Incorporating full moisture transport modeling with high-performance computing (HPC) is also recommended to capture transient heat and mass transfer within mango slices. This approach would enhance the prediction of drying behavior and support the design of more efficient dryers for a range of perishable crops and climates.

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Impact of Shoring and Scaffolding on Construction Performance in Addis Ababa

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Abstract

The construction sector in Ethiopia contributes significantly to economic growth, but it continues to suffer from delays, cost overruns, and safety risks. This is partly due to inadequate shoring and scaffolding practices. This study investigated the impact of shoring and scaffolding systems on the performance of building construction projects in Addis Ababa. Data were collected from 167 professionals across 57 public projects using questionnaires, interviews, and case studies and were analyzed through descriptive statistics and factor analysis. Findings show that poor practices in shoring and scaffolding lead to collapses, cracks, deflections, and misalignments in concrete structures, while also contributing to up to 5% of project costs and 17.5–27.6% of project durations. Moreover, 51% of site accidents were associated with failures in these systems. Material type (metal vs. eucalyptus), quality of components, and working methodology were found to be the most influential factors. Case study comparisons confirmed that metal systems are safer, faster, and more cost-effective than timber, despite their higher initial cost. The study recommends integrating proper design, planning, and monitoring of shoring and scaffolding early in project development. For the industry, adopting standardized metal systems, enforcing safety training, and implementing quality control can substantially reduce risks, enhance productivity, and improve overall project performance.

Keywords: Cost, Project Performance, Quality, Safety, Scaffolding, Shoring, Construction in Addis Ababa

I. Introduction

Construction is a key driver of Ethiopia's socioeconomic development, yet the industry faces persistent challenges such as cost overruns, delays, poor workmanship, and safety issues. Among the factors contributing to these problems is the poor performance of temporary works, including shoring and scaffolding [1]. Since project success depends on meeting deadlines, budgets, and quality standards, the role of temporary structures in achieving these objectives is critical.

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Temporary structures are essential in facilitating permanent construction works, but past studies show they often fail due to poor design, planning, and management. Proper selection, design, and operation of temporary works directly influence a project's cost, quality, safety, and efficiency [2]. Shoring provides temporary support to structures under construction, while scaffolding enables access and supports workers and materials [3]. Historically, timber was the primary material for these systems worldwide, and in Ethiopia, eucalyptus wood is commonly used due to its availability and low cost, though steel use is gradually emerging [4].

Despite their importance, scaffolding and shoring are frequently neglected in terms of safety, cost, and timeliness. Research shows that Ethiopian projects often rely on crew experience rather than proper design standards, leading to unsafe and inefficient practices [4]. Issues such as uneven spacing of shores, lack of standardization, and poor methodology are common, while hazards, including collapse, falling, and material strikes, remain significant risks [5]. These shortcomings highlight the need for improved planning, monitoring, and control of temporary works.

In Ethiopia, reliance on eucalyptus wood for shoring and scaffolding remains common because of its low initial cost and wide availability. However, its limited durability, low reuse potential, and susceptibility to failure make it a less reliable option compared to standardized metal systems. Compounding this issue, many contractors manage temporary works informally by relying on professional experience rather than engineering design standards, which increases risks of collapse, inefficiency, and safety incidents [4]. These challenges highlight why a systematic study of shoring and scaffolding practices is particularly important for Ethiopia, where informal methods and material constraints significantly affect project quality, safety, time, and cost.

Given these challenges, this study investigates the impact of scaffolding and shoring on building construction performance in Ethiopia. By examining their influence on cost, quality, safety, and duration, the study emphasizes the crucial role of temporary works in determining overall project success. Greater attention to shoring and scaffolding practices can help reduce delays, minimize risks, and improve construction outcomes.

II. Research Methodology

A. Study Area Description

As depicted in Fig.1, this research was conducted in Addis Ababa, Ethiopia's capital city, which is the leading commercial and cultural center. It is among the fastest-growing cities in Africa, with an estimated population of about five million, constituting nearly 25% of the country's total urban population.

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Geographically, the city lies at 9°2' N latitude and 38°45' E longitude, at an average elevation of 2,400 meters above sea level, while Entoto Hill to the north reaches up to 3,200 meters [6]. The study focused on public building projects within Addis Ababa.

Fig. 1: Geographical location of Addis Ababa [6]

B. Research Design

This study employed a descriptive and explanatory research design to investigate how shoring and scaffolding systems influence building construction performance. Both qualitative and quantitative methods were applied. The quantitative approach involved collecting and analyzing numerical data to measure variables and make predictions, while the qualitative approach focused on collecting and interpreting non-numerical information. The combined findings were analyzed to assess the effects of scaffolding and shoring in construction projects in Addis Ababa in the results and discussions sections. Then, conclusions and recommendations were derived from the results and discussions that followed.

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C. Research Population and Sample Size

The study focused on active public building construction projects in Addis Ababa contracted through the Addis Ababa City Administration Construction Bureau (AACACB) and undertaken by grade one to grade five contractors. These contractors were selected because they are more experienced, employ qualified professionals, and are typically responsible for high-rise projects. Public projects were targeted since many private and commercial projects were suspended due to rising construction costs at the time of this study. It is important to note that the study's focus on public sector projects may limit the generalizability of findings to the private sector, which may operate under different contractual and financial constraints.

According to AACACB's 2014 performance report, 57 public building projects were under construction by contractors in the specified grades. All 57 projects were included as the study population because their size was manageable for data collection.

Purposive sampling was applied to select respondents based on job position, experience, availability, and willingness to participate. From each project, four professionals, such as site engineers, project managers, office engineers, safety engineers, general foremen, and consultants, were chosen. This number was based on a pilot study, which found that an average of four qualified professionals per project site could provide relevant insights into the issues under investigation.

D. Primary Data Collection Techniques

1) Primary Data Sources: Primary data were obtained through questionnaires, interviews, and site visits from contracting companies engaged in projects awarded by the Addis Ababa City Administration Construction Bureau.

a) Questionnaire: A structured questionnaire was administered to professionals and employees directly involved in scaffolding and shoring works. Both closed-ended and open-ended questions were included. The open-ended questions allowed respondents to freely express their views, supplementing the restricted options in the closed-ended questions. The questionnaire was developed based on in-person observations and targeted the major project performance indicators: cost, quality, timeliness, and safety. It consisted of three sections: general information about the project site, respondent's role, and contractor grade; the types of scaffolding and shoring systems employed; and the impacts and influencing factors of scaffolding and shoring systems on construction performance in terms of cost, quality, timeliness, and safety. Additional space was provided for respondents to include further comments or detailed explanations.

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b) Interviews: Semi-structured face-to-face interviews were conducted with selected experts to gain deeper insights into their experiences and perspectives on scaffolding and shoring practices.

c) Case Study: Two project sites were examined as case studies to assess the time and cost implications of different scaffolding and shoring systems. One site utilized eucalyptus wood, while the other employed metal systems. This comparison provided practical evidence of the effects of material choice on project performance.

2) Secondary Data: Secondary data was collected from a variety of published and unpublished sources to complement the primary data. These included journals, government reports, standards, company documents, dissertations, dictionaries, and reliable internet resources. The use of secondary data provided additional context and supported the validation of primary findings.

E. Data Collection Process

To facilitate data collection, the researcher obtained an official letter of permission outlining the purpose of the study. Following this, participants were informed about the objectives of the research, and their voluntary consent was secured. Questionnaires were distributed directly by the researcher, ensuring participants had adequate time to complete them without disruption. The study relied entirely on the willingness of respondents to participate. In addition, site observations were conducted and photographs were taken to substantiate questionnaire findings and interview responses.

F. Data Analysis

A combination of descriptive statistics, SPSS, and Microsoft Excel was employed to analyze both qualitative and quantitative data. The analysis aimed to evaluate the impact of shoring and scaffolding systems on building project performance. Results were presented using tables and graphs for clarity.

Descriptive methods provided an overview of findings. These were further interpreted and discussed in relation to cost, concrete quality, safety, and construction speed. Respondents rated potential factors influencing shoring and scaffolding performance using a five-point Likert scale. These responses were then transformed into a Relative Importance Index (RII), allowing for the ranking of factors. Finally, factor analysis was applied to identify the most significant variables affecting performance.

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III. Results and Discussions

A. Profiles of Respondents and Selected Building Projects

1) Questionnaire Response Rate: A total of 167 questionnaires were distributed to contractors and consultants. Of these, 135 were completed and found valid for analysis, representing a response rate of 80.8%. In addition, one professional from each project was interviewed to capture insights not fully addressed in the survey and to gather more in-depth qualitative information on shoring and scaffolding practices. Furthermore, two projects were selected as case studies to provide a detailed analysis and contextual understanding.

2) Grade of Contractors: The survey respondents included general contractors (GC1–4) and building contractors (BC1–3) currently engaged in public building projects in Addis Ababa. As illustrated in Fig. 2, GC-1 contractors accounted for 31.6% of respondents, followed by GC-2 with 19.3%, GC-3 with 15.8%, and GC-4 with 8.8%. Both BC-1 and BC-2 contractors represented 12.3% each. The largest share of respondents came from GC-1 and GC-2 contractors.

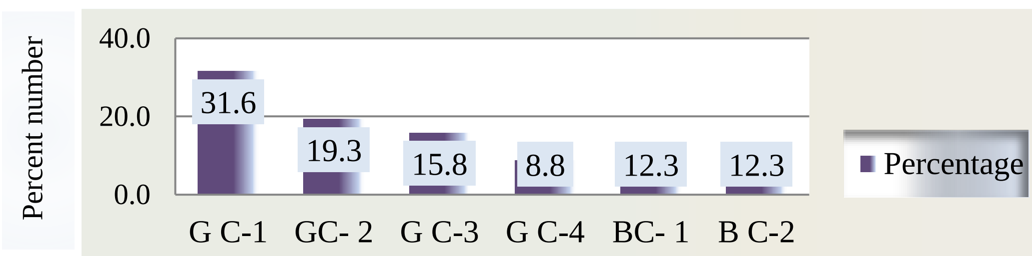

Fig. 2: Profiles of selected companies

3) Position and Experience of Respondents: As can be noted from Table I below, the professional experience of respondents varied across the selected building construction projects. About 40% had 8–12 years of experience in the industry, 27% had 4–8 years, 26% had more than 12 years, and 7% had less than 4 years of experience. This distribution indicates that the majority of respondents held senior positions on construction sites and possessed sufficient expertise to provide reliable and informed responses.

Table I: Position and experience of respondents

Position of the respondent	Percentage	The experience of the respondent ranges			
		0 to 4 years	4 to 8 years	8 to 12 years	more than 12 years
Project manager	24	-	10	14	8
Site engineer	30	6	12	12	10

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Safety engineer	9	-	5	3	4
Office engineer	26	4	6	15	10
General Forman	12	-	4	8	4
Total	100	10	37	52	36

4) The Stories of the Buildings: The level of building construction projects considered in this study is presented in Fig. 3. The findings indicate that 31.6% of the projects fall within the range of G+ (7–9) stories. This is followed by 22.8% each in the ranges of G+ (4–6) and G+ (10–12). Projects with G+ (1–3) account for 12.3%, while the smallest share, 10.5%, corresponds to buildings with more than G+12 stories.

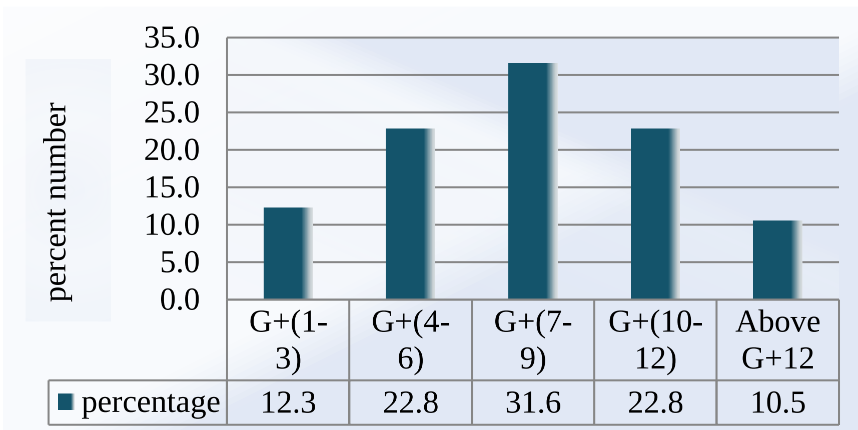

Fig. 3: The stories of the buildings

The statistical profile of respondents and projects provides important context for interpreting the study's findings. The predominance of highly experienced professionals (over two-thirds with more than eight years in the field) suggests that the responses reflect informed insights into practical challenges of shoring and scaffolding. The dominance of GC-1 and GC-2 contractors, who are typically responsible for high-rise and complex projects, indicates that the results are particularly relevant to large-scale constructions where the risks and costs of failure are higher. Similarly, the distribution of projects by building stories, with a significant proportion in the G+7 to G+12 range, underscores the growing demand for safe and efficient temporary works in vertical construction. Collectively, these statistics imply that the issues identified in this study are not isolated to small-scale projects but represent systemic challenges in Ethiopia's urban construction sector, with implications for both policy and industry practice.

B. Materials used in Shoring and Scaffolding System

In Addis Ababa's building construction projects, shoring and scaffolding systems are primarily made from eucalyptus wood, steel, or a combination of both. Despite the advantages of steel, many contractors continue

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to rely on eucalyptus wood due to its low cost and easy availability, a trend consistent with earlier findings by Biruk (2012). As shown in Fig. 4, the survey results indicate that 42% of projects use eucalyptus wood, 37% use steel, and 21% use a combination of the two materials, showing that eucalyptus wood remains the dominant choice in most construction sites.

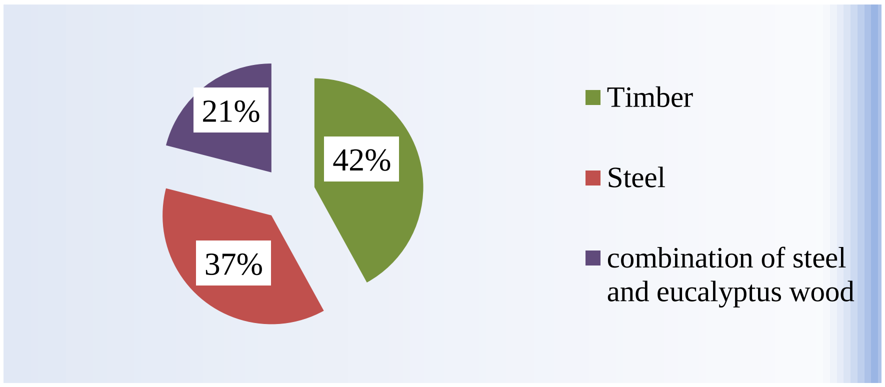

Fig. 4: Scaffolding and shoring material

C. Design of Shoring and Scaffolding

The design of shoring and scaffolding systems aims to establish proper spacing and ensure each component has sufficient strength to withstand loads and pressures. While this process should be overseen by licensed engineers, construction managers are expected to understand the fundamentals to review and request designs. However, survey results presented in Table II reveal a significant disparity: 66.7% of contractors do not prepare formal designs and instead rely on experience for material selection, erection, and stripping methods. Only 33.3% incorporate design considerations, such as load capacity and inspections, using standards like EBCS (66.7%) and ACI (33.3%). This indicates that shoring and scaffolding systems are still managed informally rather than through systematic engineering design in most projects.

Table II: Design of shoring and scaffolding

No.	Item	Response	Frequency	Percentage (%)
1.	Method of selecting and design of shoring and scaffolding material	Based on the experience of contractor professionals	90	66.7
		Using design code and standard inspection approvals	45	33.3
2.	Design codes (standards) are commonly used	EBCS	30	66.7
		ACI	15	33.3

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Field observations revealed that some projects use overly dense eucalyptus shoring systems due to contractors' fear of structural collapse stemming from the absence of proper design for prop spacing. This practice leads to excessive material use that increases project costs, while also creating congested workspaces that hinder worker movement and slow construction progress. To minimize risks and improve efficiency, contractors are advised to follow proper design standards when planning and implementing shoring and scaffolding systems.

These findings reveal a critical gap between formal engineering standards and on-site practices in Ethiopia's building construction sector. The reliance on experience rather than systematic design not only increases the risk of structural failure but also results in inefficiencies such as material overuse, congested workspaces, and reduced productivity. This informal approach reflects both the limited availability of skilled design expertise for temporary works and the industry's tendency to undervalue shoring and scaffolding compared to permanent structural elements. The broader implication is that unless design standards for temporary structures are institutionalized and enforced, projects will continue to face quality, cost, and safety setbacks. Strengthening regulatory oversight, integrating shoring and scaffolding design into contract requirements, and enhancing professional training could help bridge this gap and improve overall project performance.

D. Major Factors Affecting the Performance of Shoring and Scaffolding Systems

1) Factors Affecting Quality Performance: Based on an extensive literature review, the major factors that affect the quality of concrete structure and lead to shoring system failure in Addis Ababa building construction projects were presented in Table III.

The study identified the top ten causes of shoring system failures in Addis Ababa building construction projects based on mean scores ranging from 3.5 to 5. The most critical factor was insufficient load-carrying capacity (mean value 4.91), followed by the use of defective members (4.56), and inclined or non-rigid props (4.43). Inadequate spacing between members and excessive or concentrated loads (4.17) were also significant contributors, highlighting both structural and operational shortcomings that align with findings from previous studies.

Table III: Descriptive statistics of shoring failure factors

Cause of failure of shoring and scaffolding	Mean	Rank
Insufficient load-carrying capacity	4.91	1
Use of defective members	4.56	2

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Used inclined/none-rigid props	4.43	3
Inadequate spacing between members	4.17	4
Concentrated /excessive load due to construction material	4.17	5
Improper /premature shoring/scaffolding removal	3.82	6
Use of a defective pin/rod to hold the props at the required heights	3.80	7
Dislocation of the base plate	3.60	8
Improper mud sill installation (mudsill- a plank frame or small footing on the ground used as a base for a shore or post in shoring and scaffolding	3.52	9
Impact load during concrete pouring	3.52	10

Other major causes of failure included premature removal of shoring or scaffolding (3.82), the use of defective pins or rods (3.80), and dislocation of base plates (3.60). Additional issues of improper mud sill installation and impact loads during concrete pouring both scored a mean value of 3.52, further exacerbating the risks. These failures can result in serious consequences, including accidents, injuries, loss of life, and significant cost and time overruns, underlining the importance of systematic failure analysis and strict adherence to design and safety standards.

Beyond preventing failures, scaffolding plays a vital role in enhancing construction quality and productivity. Interviews revealed that scaffolding improves worker safety, creates a more efficient work environment, and reduces physical strain, thereby motivating employees and enabling them to focus on quality output. Unsafe conditions, by contrast, cause stress, reduce productivity, and lead to project disruptions. Thus, scaffolding not only ensures safety but also indirectly supports better project performance by fostering a secure, efficient, and high-quality construction process.

2) Factors Affecting Safety Performance: As shown in Table IV below, 26 factors that affect safety in shoring and scaffolding systems in building construction, which were categorized into four major factor sources as environmental, technical, human, and organisational factors, were considered.

Table IV: Ranking of factors affecting the safety of shoring and scaffolding systems

Factors	RII	RANK
Improper foundation	0.742	3
No guardrail and lifeline	0.735	7
Excessive load	0.818	1
Defective scaffolding material	0.742	3

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Improper use of PPE	0.738	6
Lack of protective equipment	0.701	9
Poor technical condition of the scaffolding	0.738	5
No safe work procedure	0.695	10
Lack of monitoring by the site supervisor	0.721	8
Lack of training	0.750	2

The study identified several critical factors influencing safety in building construction related to shoring and scaffolding. The leading cause is excessive load, with an RII value of 0.818, which often results in scaffold collapse when the applied load exceeds its carrying capacity. Lack of worker training follows closely with an RII of 0.750, highlighting the need for proper instruction both for those erecting scaffolds and those working on them [7]. Other significant factors include improper foundations and defective scaffolding materials (RII 0.742), which compromise stability and load distribution, as supported by Robert. Poor technical conditions of scaffolding and shoring (RII 0.738), often caused by defective design or manufacturing, also emerged as a major safety risk.

In addition, several other factors contribute to scaffolding and shoring accidents, including improper use of personal protective equipment (PPE), lack of guardrails and lifelines, inadequate site supervision, absence of protective equipment, unsafe work procedures, unskilled workers, and defective scaffolding materials. These issues, with RII values ranging from 0.735 to 0.683, reflect both technical shortcomings and human factors that increase the likelihood of accidents. Collectively, these findings emphasize the urgent need for stricter safety measures, proper training, and adherence to technical standards in order to minimize risks and improve safety performance in building construction projects.

3) Factors Affecting Time in Shoring and Scaffolding Construction: As shown in Fig.5 below, the survey results revealed that the type of shoring and scaffolding material is the most significant factor affecting construction time, with a mean score of 4.111, as steel systems are faster to install than timber systems. [4]. Delays in inspection and approval (mean 4.089) were identified as the second major factor, since work cannot proceed without the supervisor’s approval [10]. The third factor was the number and efficiency of crew members (mean 4.030), followed by poor site layout planning (mean 3.919), which can disrupt workflow and reduce productivity. Other factors influencing speed include poor site conditions, occasional overtime, project size and complexity, lack of tools and equipment, rework, and adverse weather, with mean values ranging between 3.681 and 3.519.

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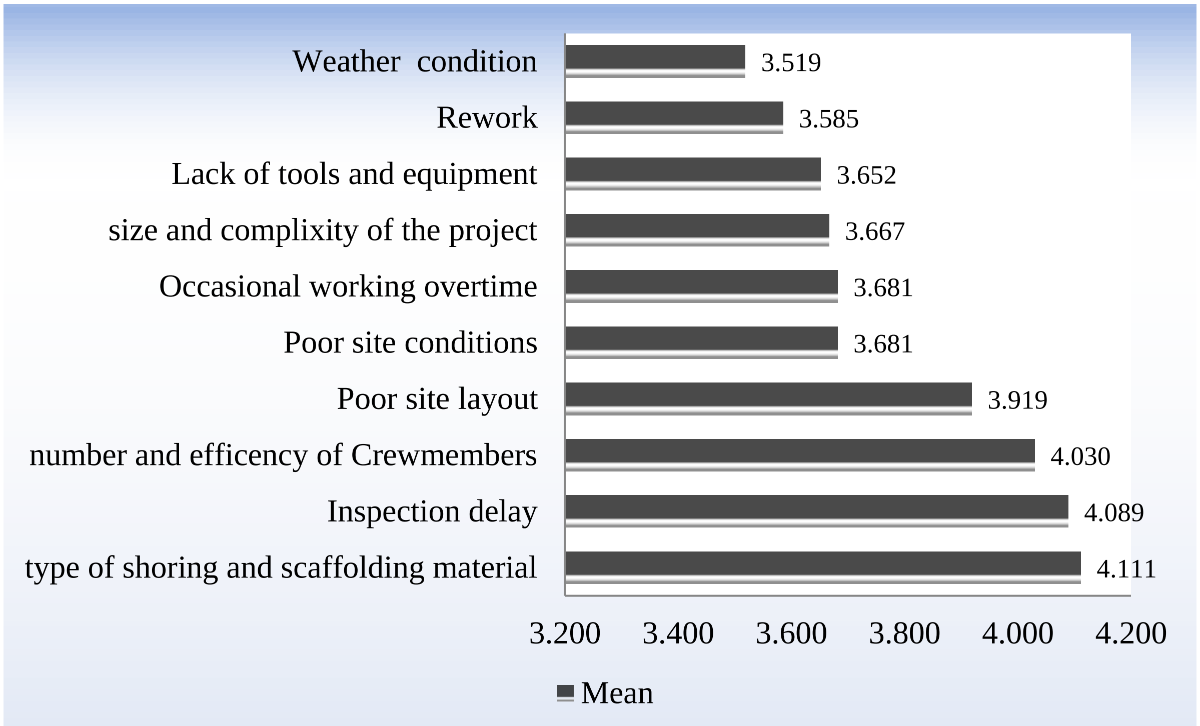

Fig. 5: Factors affecting the speed of construction

4) Factors Affecting Cost of Shoring and Scaffolding Systems: The study identified the main factors affecting the cost of shoring and scaffolding systems. The most significant factor was the type of material used (mean 4.0889), with metal scaffolding being more expensive than timber due to its higher safety and easier assembly.

The second factor was the volume and complexity of work (mean 3.7778), since complex projects require additional materials and accessories [10]. The third factor was the type of shoring and scaffolding system used (mean 3.7185), as different systems—such as double, single, or suspended scaffolding, and flying or raking shoring—require varied construction methods and components, often leading to higher rental costs. Availability of materials was identified as the fourth factor (mean 3.444), as shortages can delay work, waste labor resources, and increase overall project costs.

As depicted in Table V, additional factors influencing cost include site location, material strength, seasonal timing of rentals, price fluctuations, construction methodology, and the number of scaffolding sections used, with mean values ranging from 3.4444 to 3.0444. These findings align with earlier research and highlight that being aware of such cost drivers can help contractors and project managers reduce the economic burden of shoring and scaffolding in building construction projects.

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Table V: Factors affecting the cost of shoring and scaffolding

Factors affecting cost of shoring and scaffolding	Mean	Rank
Type of shoring and scaffolding material	4.0889	1
The number of scaffolding sections used can be factored using the length and height of the project.	3.0444	10
The time of year in which the scaffolding and shoring is being rented and the number of scaffolding and shoring rentals in the area.	3.1259	7
Volume and complexity of the work,	3.7778	2
Methodology adopted to execute the work	3.0444	9
Type of the scaffolding and shoring	3.7185	3
Strength of scaffolding and shoring	3.2444	6
Repetition of material	3.1259	7
Location of the site	3.3778	5
Fluctuation of material cost,	3.0741	8
Availability of shoring and scaffolding material,	3.4444	4

Although metal scaffolding and shoring have a higher initial cost compared to eucalyptus wood, they are more durable, reusable, and can significantly reduce overall project costs by speeding up construction, minimizing waste, and providing long-term service. In contrast, eucalyptus wood is cheaper upfront but has limited reuse potential, typically lasting for only one project, though case studies show it can sometimes be reused four to eight times. Survey results revealed that 92% of respondents view metal scaffolding as crucial for lowering costs despite its expense, yet most contractors still rely on eucalyptus wood due to budget constraints. Previous studies, including [4], confirm that H-frame metal scaffolding offers cost and time advantages over eucalyptus. Overall, the study concludes that the performance of shoring and scaffolding systems in building construction is mainly influenced by material quality, the type of system used, and the working methodology applied.

The analysis of quality, safety, time, and cost factors demonstrates that deficiencies in shoring and scaffolding performance are deeply interconnected. For example, inadequate load-carrying capacity and defective materials not only compromise concrete quality but also create safety hazards and delay progress through rework or collapse recovery. Similarly, delays in inspection and poor crew efficiency, initially categorized as time-related issues, also drive up project costs and expose workers to unsafe conditions. The findings thus suggest that addressing a single performance dimension in isolation will not be sufficient; rather, a holistic approach is required that integrates material quality control, adherence to design standards,

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workforce training, and systematic supervision. From an industry perspective, this implies that scaffolding and shoring should be managed as critical project systems with dedicated planning, budget allocation, and monitoring mechanisms, rather than as secondary or temporary works. Such a shift could significantly reduce risks while enhancing overall efficiency and reliability in Ethiopia's construction sector.

E. Effect of Shoring and Scaffolding Systems on Performance of Building Constructions

1) Effect on the Quality Performance of Building Construction: As presented in Table VI below, the RII-based survey revealed that shoring and scaffolding systems have a major impact on concrete structure quality. The most critical issue was slab bending from shoring settlement (RII = 0.849), usually due to unstable soil or poorly installed shores. Other major concerns were poor structural integrity from low-quality materials and workmanship (RII = 0.797) and cracks/deflections from premature shore removal (RII = 0.791). Additional risks include structural collapse (RII = 0.779), slab misalignment from shoring misplacement (RII = 0.759), and lateral deformation from inadequate bracing (RII = 0.753). Overall, both proper design and execution of shoring/scaffolding are essential for the safety, serviceability, and durability of concrete structures.

Table VI: Quality problem related to shoring and scaffolding

Effect of shoring on the quality of concrete structure	RII	Rank
Bending of the slab caused by the settlement of the shoring system	0.849	1
Poor structural integrity due to poor quality of shoring material and poor workmanship of shoring work.	0.797	2
Crack and deflection resulted from the premature removal of the shoring and unstable shoring system	0.791	3
Collapse or failure of the concrete and shoring structure due to a poor shoring system.	0.779	4
Misalignment of the shoring system permits the misalignment of the concrete slab	0.759	5
Lateral deformation due to poor bracing of the shoring system	0.753	6
Shoring and scaffolding systems do not affect the quality of the concrete structure	0.290	7

2) Effect on Safety Performance of Building Construction: Fig. 6 shows the survey result of injuries and accidents that occurred in their project site. Survey results show that 32% of site accidents were due to scaffolding systems and 19% due to shoring systems, meaning nearly half of construction hazards originate from these two systems. [4] further, it was found that projects using eucalyptus wood for shoring and scaffolding experienced incidents more frequently than those using metal systems.

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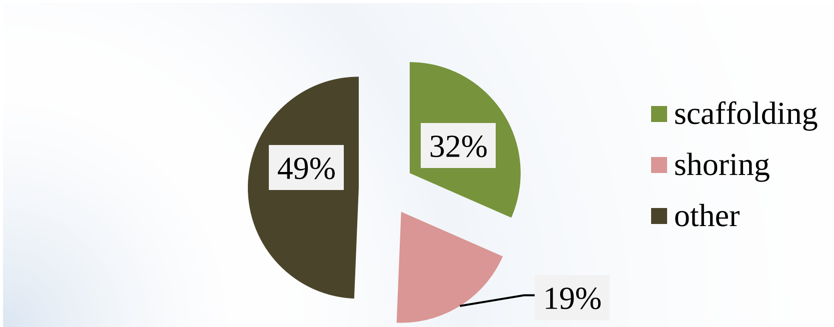

Fig. 6: Rate of accidents due to shoring and scaffolding

As shown in Fig. 7, the survey, incidents and injuries were classified as near miss, first aid, medical attention, and fatality. Results showed that 62.1% of scaffolding-related and 56.7% of shoring-related cases required only first aid. Near misses accounted for 22.9% in shoring and 17.2% in scaffolding, while about 20.8% (scaffolding) and 20.7% (shoring) needed medical attention. No fatalities were reported in the surveyed projects;

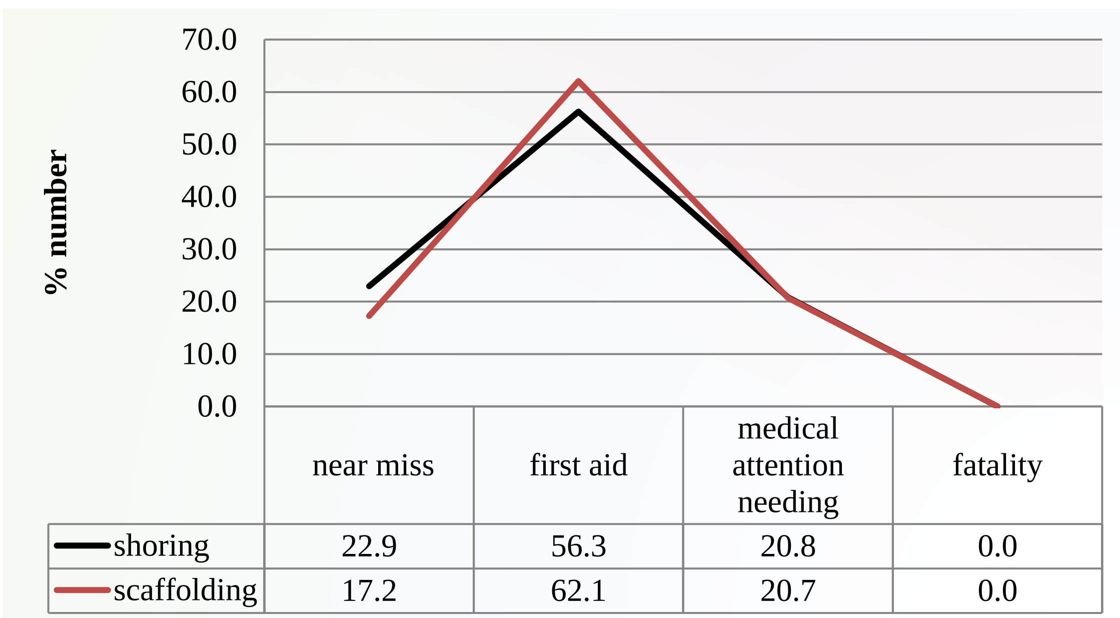

Fig. 7: Incident caused by shoring and scaffolding

[11] highlighted that scaffolding and shoring accidents increase project expenses both directly and indirectly. While health and safety systems typically cost only 0.5–3% of total project costs, the cost of accidents is much higher, often surpassing prevention costs. Contractors bear indirect expenses such as lost productivity, cleanup, replacement, delays, supervision, rescheduling, transportation, and wages for injured workers during recovery.

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3) Effect on Time Performance of Building Construction Project: This study also quantified the time share of the shoring system within a single floor cycle using data from 57 project sites. The average values, derived through interpolation of site data, were used to analyze the speed and efficiency of shoring operations.

The basic data are: -

1. The average number of crew for one floor at a time is six.
2. Average productivity by considering six crew members for each shoring material (height of the building was considered).
    - Eucalyptus wood = 4.2 m^2/hr
    - Metal = 6.8 m^2/ hr

In order to calculate the time share of shoring in the total duration of the project, this study considered two building projects as case studies. The detailed information is presented in Table VII.

Case study results show that shoring and scaffolding activities account for 17.5% of project duration when using metal systems compared to 27.6% when using eucalyptus wood. The longer time for timber systems is due to on-site measuring, cutting, fixing, and their limited reusability. Metal systems, by contrast, are faster to assemble/disassemble, reduce costs, and are more suitable for high-rise projects. Observations also revealed that eucalyptus wood systems are less safe, less environmentally friendly, and efficient. Interviews confirmed unanimous agreement among respondents that metal shoring and scaffolding systems are superior to timber systems in terms of safety, time, and cost.

4) Effect on the Cost Performance of Building Construction Projects: According to the respondents, the cost of shoring and scaffolding is the main criterion to select the type of shoring and scaffolding systems in a given project.

Table VII: Project information for the case

	Project 1	**Project 2**
Location	A.A, nifas silk lafto, woreda 12	Addis Ababa, Arada sub-city, Woreda 3
Story of building	B+ G+ 7 office Building	2G+8 mixed Building
Project duration	540 days	720 days
Total floor area	646.35 m^2 *8(No.of floor)=5171m^2	742.5 m^2*9= 6682.5

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Type of shoring and scaffolding	Metal	Eucalyptus wood,
Productivity (by 6 labourers)	6.8 m^2/hr or 54.43m^2/day	4.2 m^2/hr or 33.6 m^2/day
Total project cost	90 million birr	130 million birrs
Time share of shoring and scaffolding	5171m^2/54.43 m^2/day = 95 day 17.5% of total duration	6682.5m^2/33.6 m^2/day =199day 27.6 % of the total duration of the project

The cost of shoring and scaffolding will, of course, vary substantially depending on the project. To analyze the effect of shoring and scaffolding systems on the building construction project cost, this study calculates the cost share of shoring and scaffolding systems. The following information, as depicted in Table VIII, is used for calculating the cost of the shoring and scaffolding system.

Table VIII: Cost information of shoring and scaffolding [12]

Type of material	Unit	Price(Birr)	Reusability
Eucalyptus wood dia. 10 cm-12cm, length. 8m	Pcs	260	>4
Eucalyptus wood dia. 8cm – 10 cm, length 4m	Pcs	150	>4
H-frame 0.80m x 1.5m x3m Height	Full set	11,500	>40
H-frame (daily rental)	m^2	5.2	-
RHS 60cmx60cmx1.5cmx6m	Pcs	2500	>40
Nail	Kg	300	1.5
Black wire 2.5	Kg	200	-

$$\text{Output per crew} = \frac{\text{Productivity}}{\text{No crew x 8hr/day}}$$

$$\text{Eucalyptus wood shoring output} = \frac{106.64\text{m}^2\text{/day}}{\text{8 crew x 8hr/day}} = 1.26\text{m}^2\text{/hr.}$$

$$\text{Metal shoring output} = \frac{170\ \text{m}^2\text{/day}}{\text{8 crew x 8hr/day}} = 2.65\ \text{m}^2\text{/hr.}$$

The direct unit cost analysis was performed using the minimal reusability of each material. Four times were considered to be possible using eucalyptus wood. Owning the material or renting the material were the two options studied for metal shoring. When a material is owned, it may be reused 40 times; however, when a

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material is rented, the construction and dismantling timeframes are 10 days and 21 days, respectively. Spacing between eucalyptus wood posts is 60cm, and wastage is assumed as 10%. And the Spacing of H–frame is 0.8 m and 1.87m in longitudinal and transversal direction. Based on the above assumption, this paper calculated the cost breakdown for slab shoring. Using project information, the total share of shoring and scaffolding cost was obtained and is shown in Table IX.

Table IX: Cost share of shoring and scaffolding

	project 1	**project 2**
Total project cost	90,000,000	130,000,000
Unit price	107.2birr/m^2 for own and for rent 211.3 birr/m^2	762.1
Quantity	5217.7 m^2	6727.7 m^2
Total cost (birr)	559,337.44 Birr if material is owned and 1,102,500	5,127,180.17
Percentage	0.6 % owned and 1.2% for rent	4.50%

As shown in Table IX above, the cost share of the shoring and scaffolding system to the total project cost is 1.2% for metal shoring and scaffolding if material is rented, and 0.6% if material is owned and reused more than 40 times for project 1, and 4.5% for eucalyptus wood for project 2. Based on the result, this study concludes that the cost range of shoring and scaffolding covers up to 5% of the total project cost, depending on the type of shoring and scaffolding system.

The combined results highlight that shoring and scaffolding are not just technical site activities but critical determinants of overall project success. The evidence that these systems can account for up to 30% of project duration and 5% of total costs illustrates their disproportionate influence on resource allocation. The link between system type and accident rates further demonstrates how material and methodological choices directly translate into worker safety outcomes. Beyond the immediate project level, these findings carry broader implications for Ethiopia’s construction industry: continued reliance on eucalyptus wood and informal practices risks perpetuating inefficiencies, safety hazards, and cost overruns. By contrast, transitioning toward standardized metal systems and enforcing design-based planning could significantly improve productivity, reduce delays, and enhance structural reliability. Thus, investment in proper shoring and scaffolding should be viewed not as an ancillary expense but as a strategic priority with long-term benefits for industry competitiveness and urban development.

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IV. Conclusion

This study examined the impact of shoring and scaffolding systems on construction project performance in Addis Ababa with a focus on cost, quality, safety, and time. The findings clearly demonstrate that these temporary works play a decisive role in project outcomes and should be regarded as integral to construction planning and management.

In terms of quality, poor design and reliance on defective or informal shoring and scaffolding practices were shown to cause slab bending, cracks, misalignment, and even structural collapse, directly undermining project objectives of delivering safe and durable buildings. Regarding safety, the study revealed that over half of construction accidents are linked to failures in shoring and scaffolding, with eucalyptus wood systems posing greater risks compared to standardized metal systems. For time performance, case studies demonstrated that shoring and scaffolding account for 17.5% of project duration when using metal systems and 27.6% when using eucalyptus wood, highlighting their significant influence on schedule adherence. With respect to cost, shoring and scaffolding can represent up to 5% of total project budgets, with material type, reusability, and methodology emerging as the most critical cost drivers.

These results confirm the central argument of this study that shoring and scaffolding systems, though temporary, are fundamental determinants of construction project performance. The study recommends that contractors, consultants, and policymakers prioritize the integration of proper design, material selection, and systematic planning for these systems. By moving away from informal practices and adopting standardized approaches, particularly through the wider use of metal scaffolding and strict adherence to engineering standards, the Ethiopian construction industry can enhance structural reliability, reduce risks, improve efficiency, and ultimately achieve better project outcomes in line with its development goals.

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Combined Effect of Bamboo Fiber and Kaolin on Concrete Properties: An Experimental Study

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Abstract

Concrete is the most widely used construction material globally, but its production is energy-intensive, depletes natural resources, and contributes significantly to CO_2 emissions. This study investigates the potential of using locally sourced waste materials—calcined kaolin (CK) as a partial cement replacement and bamboo fiber (BF) as reinforcement—to develop a more sustainable concrete. An experimental program was conducted to evaluate the mechanical properties of concrete mixes with CK (4%, 8%, 12% by weight of cement) and BF (0.5%, 1%, 1.5% by volume of concrete). The compressive, splitting tensile, and flexural strengths were tested after 7, 14, and 28 days of curing. The results indicate that the combination of 8% CK and 1% BF (mix CK8BF1) yielded the optimal performance, with a 28-day compressive strength of 37.9 MPa, approximately 10.5% higher than that of the control concrete (34.3 MPa). Strength improvements were also observed in splitting tensile and flexural tests for this optimal mix. Beyond these optimum percentages, strength declined due to a reduction in cementitious content and the balling effect of fibers. This research demonstrates that the synergistic use of calcined kaolin and bamboo fiber can enhance mechanical properties while reducing the environmental footprint of concrete, offering a promising alternative for sustainable construction, particularly in regions where these materials are abundant.

Keywords: Bamboo Fibers, Calcined Kaolin, Concrete, Mechanical Properties, Metakaolin, Sustainable Construction

I. Introduction

Around the world, the building sector is increasingly playing a significant role in the expansion of national economies. It is having a significant impact on social, political, and infrastructure development. The most crucial and widely utilized building material, concrete, is in great demand. Global infrastructure development is driving up concrete usage, which is predicted to reach 18 × 109 tons by 2050 [1]. An estimated 20 billion tons of aggregate and 1.5 billion tons of cement are used each year to make concrete

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[2]. The usage of concrete is not sustainable for a number of reasons; it uses a lot of natural resources, leaving no virgin material for future generations, and its primary ingredient is cement [3], [4].

About 5% to 7% of the world's CO2 emissions are caused by the cement industry; one ton of cement generates 900 kg of carbon dioxide greenhouse gases or CO2 [4]–[8]. The other challenge is the quantity of raw materials needed to make cement; 2.5 billion tons of raw natural resources, including clay and limestone, are needed to make 1.6 billion tons of cement [5]. A recent study by [9] claims that environmental concerns are crucial to the long-term viability of the concrete and cement sectors.

The cost of the materials, their impact on the environment, and their availability and durability are the primary factors that influence the choice of building materials in the construction sector. Research have been done on replacing cement in concrete production with locally accessible materials such as wood powder [10], paper slag [11], fly ash [12], wood ash [13], termite mud, rice husk ash [14], rice straw ash [15], coal fly ash [16], and sugar cane waste [17] to lower costs and lessen environmental damage. [18] investigated if metakaolin could be used to replace some of the cement in concrete and found that after 28 days, the strength of concrete containing 20% metakaolin was greater than that of regular concrete.

Additionally, customers are worried about the price of steel in addition to cement. This can be done with locally accessible materials, like bamboo fiber, rather than steel. Bamboo is a durable fiber that has a strength-to-weight ratio comparable to steel under strain and double the compressive strength of concrete [15]. [22] concluded that adding natural fibers as reinforcement to composites (such as concrete, mortar, and/or cement paste) is an affordable method of enhancing particular qualities. Research by [23] indicates that adding bamboo fiber volume content increases the splitting tensile strength of bamboo fiber reinforced concrete while having little influence on its flexural or compressive strength. In order to assess the latest proposals by [24], a thorough investigation is necessary.

According to a study by [25], bamboo fiber reinforced concrete has a tensile strength that is on par with regular concrete. [26] assessed the efficiency of bamboo fiber as a concrete strength enhancer and proposed that bamboo fibers might be utilized as novel fibers in concrete to improve the concrete's ductility and strength. [27] determined that bamboo fiber reinforced concrete has greater strength than normal concrete after finding that the addition of fiber can boost the strength of the concrete by up to 2%. [28] found that bamboo fiber reinforced concrete outperformed regular concrete in terms of mechanical performance by 26.25%. Because bamboo and bamboo-based concrete have different strengths, more research should be done. While the individual effects of metakaolin [18-21] and bamboo fiber [23-27] on concrete properties have been studied, systematic research on their combined effect is limited. The interaction between a pozzolanic material that densifies the cement matrix and a natural fiber that provides tensile reinforcement

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could lead to synergistic improvements not observed when using either material alone. This study aims to fill this gap by comprehensively investigating the combined effect of locally sourced calcined kaolin and bamboo fiber on the mechanical properties of concrete. The originality of this work lies in the systematic optimization of both CK and BF percentages to identify an optimal mix that maximizes strength gains, providing new insights for developing eco-friendly concrete composites.

II. Materials and Methods

A. Materials Used and Preparations

1) Cement: For this research work, OPC with 42.5-grade cement readily available in the local market, which is compatible with Ethiopian Standard Cement and conforms to ASTM, was used.

2) Calcined Kaolin (Methakaolin): For this research, the material was locally sourced from Banssa around Dilla. It was burned for three hours at 700^0c °C to convert kaolin into calcined kaolin (metakaolin) and was processed in the Arba Minch University Foundry Laboratory. Finally, the final powder was ground, and the ashes that passed through a sieve size of 75 µm were used.

3) Bamboo Fiber: Natural bamboo fiber materials were gathered from Chencha and appropriately formed into fibers for this investigation. To determine the fiber lengths, the bamboos were divided along the horizontal axis. After that, the bamboo samples were submerged in water for seven days. In order to increase the specimen's strength and durability, it was then sun-dried for seven days. Various percentages of bamboo fiber, including 0.5%, 1%, and 1.5%, were employed in this experiment. The fiber is roughly 37.5 mm long.

4) Fine Aggregates (Sand): This study employed locally accessible natural (river) sand as the fine aggregate for experiments. The sand used in the experiment was gathered from the Arba Minch market, namely from supplies from the Kayle location (Konso). To assess the fine aggregate's quality and ensure that it satisfies all ASTM standards, a variety of tests were conducted.

5) Coarse Aggregates: In this investigation, well-graded crushed coarse aggregate and broken stones from nearby quarries were used. The size of the coarse aggregate utilized was 37.5 mm. It comes from Arba Minch town, which is near Bihere Mariam. Basic crushing equipment is used to break the natural rock. By following ASTM guidelines for aggregate tests of a coarse type, the coarse aggregate's physical characteristics were identified and ascertained.

6) Water: For this research, potable water was used for the experiment. Clear potable water in the construction material testing laboratory of the Faculty of Civil Engineering in Arba Minch Institute of Technology was used.

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B. Mix Proportions and Sample Preparations

For concrete with grades ranging from C to 25, the mix design used in this study was approved by ACI 211.1. Bamboo fiber was added as reinforcement in proportions of 0.5%, 1%, and 1.5% of the total volume of concrete, and OPC was partially substituted with metakaolin at weights of cement at 4%, 8%, and 12% to create the cubes. Calcined kaolin was used to partially replace the cement in each concrete mix, and bamboo fiber was added as a percentage of the concrete's overall volume. The concrete mix designation was presented in Table I below.

Table I: Concrete mix designation

Mix Code	Cement, %	Metakaolin, %	Bamboo fiber, %
CK0BF0	100	-	-
CK4BF0.5	96	4	0.50
CK4BF1	96	4	1.00
CK4BF1.5	96	4	1.50
CK8BF0.5	92	8	0.50
CK8BF1	92	8	1.00
CK8BF1.5	92	8	1.50
CK12BF0.5	88	12	0.50
CK12BF1.5	88	12	1.00
CK12BF1	88	12	1.50

C. Test Methods Used

1) Test on Hardened Concrete: Utilizing a 150 x 150 x 150 mm cubic mold, the compressive strength was evaluated. The split tensile strength was tested using a cylindrical specimen of 150 mm in diameter by 300 mm in height, and the flexural strength was tested using a beam cast measuring 500 x 10 x 10 mm. The test dates and criteria utilized for the qualities of hardened concrete are shown in Table II.

Table II: Test types, standards, and curing ages of hardened concrete

S. No.	Test Types	Test Standards	Curing Ages (Days)
1	Compressive strength	ASTM C 39	7, 14 and 28
2	Flexural strength	ASTM C 78 - 02	14 and 28

The test dates and criteria utilized for the qualities of hardened concrete are shown in Table II. For each mix proportion and test age, three identical specimens were cast and tested. The results presented are the average values of these three samples.

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III. Results and Discussions

A. Mechanical Properties of Concrete

1) Compressive Strength Test: The results for the average compressive strength after 7, 14, and 28 days have been presented and extensively discussed. As shown in Table III, the calcined kaolin at 8% replacement with OPC and bamboo fiber at 1% as reinforcement, in addition, has shown a higher compressive strength value than the control throughout the testing period, i.e., 7, 14, and 28 days. The concrete work with the calcined kaolin at 12% replacement with OPC and bamboo fiber at 1.5% as reinforcement didn't show any improvement in the compressive strength value compared to the control throughout the testing period, i.e., 7, 14, and 28 days.

Table III: Average compressive strength of 7^{th}, 14^{th} and 28^{th} days

Mix code	Fiber Content (%)	Calcined Kaolin (%)	Average Compressive Strength at 7 Days (Mpa)	Average Compressive Strength at 14 Days (Mpa)	Average Compressive Strength at 28 Days (Mpa)
CK0BF0	0		25.7	27.8	34.3
CK4BF0.5	0.5		25.7	28.5	35.3
CK4BF1	1	4	26.4	29.3	37.6
CK4B1.5	1.5		21.6	25.3	32.7
CK8BF0.5	0.5		27.8	28.6	37
CK8BF1	1	8	29.6	32.1	37.9
CK8BF1.5	1.5		28.4	30.9	35.7
CK12BF0.5	0.5		24	26.8	32.3
CK12BF1	1	12	20.9	24.9	33.1
CK12BF1.5	1.5		19.7	22.4	27.6

B. Compressive Strength at Constant Calcined Kaolin (CK) Content

Table IV: The concrete mixtures with varying percentages of bamboo fibers and 4% of constant percentages of calcined kaolin

mix code	Average compressive strength of concrete, MPa		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF0.5	25.7	28.5	35.3
CK4BF1	26.4	29.3	37.6
CK4BF1.5	21.6	25.3	32.7

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Table IV demonstrate that adding 4% calcined kaolin and 0.5%, 1%, and 1.5% of bamboo fiber to concrete increases its compressive strength. According to Table IV, as the curing age grew, so did the compressive strength of concrete prepared with kaolin and bamboo fiber.

Compressive strength increased with CK4B0.5 (4% CK + 0.5% BF) after 7 days of curing, but there was no change compared to the control concrete. With CK4B1 (4% CK + 1% BF), the concrete improved and showed a strength of 26.4 MPa, 27.24% more modified than the control concrete. Compared to untreated concrete, the concrete enhanced with CK4B1.5 (4% CK + 1.5% BF) displayed 21.6MPa, which was 15.53% lower. The strength increased significantly from 0.5% BF to 1% BF at 4% CK, but declined at 1.5% BF. This trend is consistent with findings by [23, 27], where an optimal fiber content was identified. The initial increase is attributed to the effective bridging of micro-cracks by the dispersed fibers. The subsequent decline at 1.5% BF is likely due to the balling effect of fibers, leading to poor workability and increased porosity, which outweighs the benefits of fiber reinforcement [23].

When used in excess, bamboo fiber has detrimental effects; that is, it turns into aggregates and creates a more porous structure, which eliminates the beneficial influence of the fiber on the quality of the concrete materials.

A test of ordinary concrete that had been cured for 14 days revealed a compressive strength of 27.8 MPa. But compared to the control concrete, the concrete enhanced with 4% CK + 0.5% BF measured 28.5 MPa, 2.52% higher, and the concrete modified with 4% CK + 1% BF recorded 29.3 MPa, 5.26% higher. After adding 4% CK and 1.5% BF, the concrete's strength increased to 25.3 MPa. Consequently, compared to untreated concrete, the concrete changed with 4% CK + 1.5% BF was reduced by 8.53%.

All concrete types showed a superior strength increase when the compressive strength of 14-day-cured concrete was compared to that of 7-day-cured concrete. The improvement was caused by an excess of C-S-H gels being generated during the cement hydration process. Some extra C-H was transformed into C-S-H gels as a result of the presence of CK and the improved integrity between the cement paste and the aggregates. Additionally, C3S and C2S reactions were aided to produce additional hydration products, C-S-H gel, and CH. The addition of BF enhanced the aggregation amongst the components in addition to CK.

According to test results, the typical concrete (CK0B0) that had been cured for 28 days had a compressive strength of 34.3 MPa. However, the concrete material upgraded with 4% CK + 0.5% BF exhibited 35.3 MPa, which was 9.3 MPa higher than the 7-day result and 2.97% better than regular concrete. When compared to unmodified concrete, the changed concrete's compressive strength (4% CK + 0.5% BF) was

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9.35% higher at 37.6 MPa, and it was 11.2 MPa higher after 7 days. The 32.7 MPa of the concrete that had been changed with 4% CK and 0.5% BF was 4.25% lower than that of the untreated concrete.

In contrast, the 1%BF modified concrete of 28 days cured increased by 2.3 MPa, or 6.38%, as compared to a constant 4% CK and 0.5%BF. This resulted from the bamboo fibers clumping together. A 4.26% decrease in BF-modified concrete from 1% to 1.5% resulted in a more porous structure and the loss of the beneficial effect on enhancing the concrete materials. The compressive strengths of control and modified by bamboo fiber and kaolin concrete samples of 7, 14, and 28 days cured are shown in the following key findings from the above-mentioned Table IV.

The following Table V show compressive strength at a constant 8% CK with different percentages of bamboo.

Table V: Concrete mixes with different bamboo fiber ratios and a constant 8% calcined kaolin

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK8BF0.5	27.8	28.6	37
CK8BF1	29.6	32.1	37.9
CK8BF1.5	28.4	30.9	35.7

From the point of the constant percentage of calcined kaolin, from 4%CK of replacement to 8%CK, the compressive strength of concrete increased compared with control with different percentages of bamboo fiber at all ages of curing. This is due to the calcined kaolin effect.

The reason behind this was that OPC, on the other hand, contains a smaller amount of silica by itself. The replacement of calcined kaolin in this cement has resulted in a higher compressive strength for 8% replacement. Because calcined kaolin reached the silica mineral, it reacted with the previously described cement-free C-H reaction. This is most likely due to the pozzolanic reaction of metakaolin and calcium (OH)2 from cement hydration.

The enhanced reactivity and high specific surface area resulting from the reduced particle size of the calcined kaolin critically contribute to the observed gain in compressive strength. This strength augmentation exhibited its most significant rate of increase during the initial two weeks of hydration, specifically at the 7-day and 14-day testing intervals.

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A faster pozzolanic reaction is caused by a larger surface area of calcined kaolin, which results in the early development of high strength. On the other hand, compared with modified concrete, the concrete CK8BF1 (8%CK+1.5%BF) decreased. This is the balling effect of bamboo fiber.

Table VI: The concrete mixtures with varying percentages of bamboo fibers and 12% of constant percentages of calcined kaolin

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK12BF0.5	24	26.8	32.3
CK12BF1	20.9	24.9	33.1
CK12BF1.5	19.7	22.4	27.6

Table VI illustrate the 7, 14, and 28 days compressive strength made by constant 12%CK and different percentages of bamboo fiber, i.e. 0.5%, 1%, and 1.5%BF.

The compressive strength was decreased at a constant 12%CK with different percentages of bamboo fiber through the curing ages. The probable reason for this is the high replacement of cement by calcined kaolin, thus reducing the cement content of the mixture, which in turn causes a reduction in the hydration reaction.

In addition to this, the high content of calcined kaolin resulted in a higher water requirement, making the water unavailable for the hydration of the cement. The decreasing compressive strength was a cluster effect of the materials due to the reduced workability of the concrete and the absorption of water by the bamboo fiber.

C. Compressive Strength at Constant Bamboo Fiber (BF) Content

The 7th, 14th, and 28th-day average compressive strength test results obtained from three representative samples are separately presented for 0.5%, 1%, and 1.5% BF addition as reinforcement with different CK content as cement replacement, respectively. Results of the compressive strength of concrete at constant fiber content with variable calcined kaolin percentage are shown in Table VII.

Table VII: Average compressive strength results with varying percentages of calcined kaolin and 0.5% of constant percentages of bamboo fibers

mix code	Average compressive strength (MPa)		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF0.5	25.7	28.5	35.3

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CK8BF0.5	27.8	28.6	37
CK12BF0.5	24	26.8	32.3

Table VIII: Average compressive strength results with varying percentages of calcined kaolin and 1% of constant percentages of bamboo fibers

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF1	26.4	29.3	37.6
CK8BF1	29.6	32.1	37.9
CK12BF1	20.9	24.9	33.1

Table IX: Average compressive strength results with varying percentages of calcined kaolin and 1.5% of constant percentages of bamboo fibers

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF1.5	21.6	25.3	32.7
CK8BF1.5	28.4	30.9	35.7
CK12BF1.5	19.7	22.4	27.6

Table VII demonstrates the average compressive strength of 0.5%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. Compared to conventional concrete, the compressive strength of modified concrete increased at 7^{th} and 14^{th} curing days. The calcined kaolin was replaced from 4%CK to 8%CK. The strength is not insignificant, whereas the maximum strength is achieved at 8% calcined kaolin content.

Table VIII exhibits the average compressive strength of 1%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. Results show that strength increases by increasing the CK content. Overall maximum strength was obtained at 1% fiber content. The increase in 28 days' strength is greater from 4% to 8% replacement, whereas a lesser gain in strength is observed from 8% to 12% replacement. Previous research has shown that a decrease in strength is observed after a 12% replacement level.

Table IX exhibit the average compressive strength of 1.5%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. It can be seen that the overall increase in strength is less than that obtained at 1.0% BF. The maximum strength is 4.1% greater than that of the control mix, which is obtained at 8%CK replacement.

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D. Average Maximum Compressive Strength Results Among Different Replacement Levels

Table X: Average maximum compressive strength of each replacement with different percentages of bamboo fiber.

Mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK8BF0.5	27.8	28.6	37.0
CK8BF1	29.6	32.1	37.9
CK8BF1.5	28.4	30.9	35.7

As seen in Table X, which demonstrates the maximum compressive strength from each replacement level with different fiber content at 7, 14, and 28 days. A comparison between maximum strength and each replacement level is done to find out the optimum mix for maximum strength. The graphical description shows that overall maximum strength was achieved with 8% CK replacement and 1% fiber content, but the increase in strength was not as significant from 4% to 8% replacement.

The main points noted in this experiment are the following. Results of compressive strength are shown in Table X. At 1% bamboo fiber and 8% metakaolin, the 28-day compressive strength is greatest at 1% bamboo fiber and 8% metakaolin. Hence, 1% bamboo fiber and 8% metakaolin are more suitable for improving the compressive strength of structural concrete.

E. Splitting Tensile Strength Test

The tensile strength at which failure occurs is the tensile strength of concrete. In this investigation, the test is carried out on the cylinder by splitting along its middle plane parallel to the edges by applying the compressive load to opposite edges. The 14^{th} and 28^{th} days of curing for bamboo fiber reinforced with calcined kaolin replaced cement concrete. The tensile strength of the concrete was tested at 14^{th} and 28^{th} days, and the variation of split tensile strength concerning fiber content and metakaolin is shown in Table XI.

Table XI: Average splitting tensile strength performance of concrete at 14 days

mix code	Average splitting Tensile strength (N/mm2)		
	0.5% BF	1% BF	1.5% BF
CK4	1.775	1.66	1.375
CK8	1.725	1.375	1.325
CK12	1.7	1.45	1.26

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The 28-day average splitting tensile strength of control concrete was 2.52Mpa.

Table XII: Average splitting tensile strength performance of concrete at 14 days

Mix	Average splitting Tensile strength (N/mm2)		
	0.5% BF	1% BF	1.5% BF
CK4	3.04	2.79	2.31
CK8	2.9	2.84	2.2
CK12	2.86	2.33	1.72

Tables XI and XII above show the average splitting tensile strength of concrete made with 4%, 8%, and 12% calcined kaolin and a combination of 0.5%, 1%, and 1.5% bamboo fiber after 14th and 28th days of curing, respectively.

The splitting tensile strength of 14-day cured normal concrete showed 1.49MPa. But, the concrete improved with (0.5 BF + 4 % CK) showed 1.78MPa, which was 19.46% more modified than the normal concrete. In comparison to the control concrete, the concrete that had been improved with (1 % BF + 4% CK) displayed 1.73MPa, which was 16.11% more modification. And, concrete modified with (4%CK + 1.5%) showed 1.70MPa, which was 14.09% more modified than plain concrete. The concrete modified with (8%CK + 0.5%BF) showed 1.66MPa, which was 11.47% more modified than the control concrete. Concrete modified with (8%CK + 1%) showed 1.68MPa, which was 12.75% more modified than plain concrete. And, concrete modified with (8%CK + 1.5%) showed 1.45MPa, which was 2.68% less than plain concrete. However, the splitting tensile strength was slightly reduced from 1%BF to 1.5%BF and from 4% to 12% due to collection effects. However, from 1% BF to 1.5% BF, the splitting tensile strength was somewhat decreased.

The splitting tensile strength of 28-day cured unmodified concrete showed 2.51 MPa. However, the concrete modified with (4% BF + 0.5% CK) demonstrated a 3.04MPa, which was 21.12% higher than the control concrete, and it was 1.27MPa, or 1.92% higher when compared to the 7-day test. (1%BF + 4%CK) showed 2.79MPa, which was 11.16% more modified than control concrete, and when compared with the 7-day result, it was 1.06 MPa, or 0.31% decreased. And, concrete modified with (4%CK + 1.5%) showed 2.31MPa, which was 7.97% more unmodified than plain concrete. The concrete modified with (8%CK + 0.5%BF) showed a 2.90MPa, which was 15.54% more modified than the control concrete. Concrete modified with (8%CK + 1%) showed 2.84MPa, which was 13.15% more modified than plain concrete. And, concrete modified with (8%CK + 1.5%) showed 2.20MPa, which was 12.35% less than plain concrete. However, the splitting tensile strength was slightly reduced from 1%BF to 1.5%BF and from 4% to 12% due to cluster effects.

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F. Flexural Strength Test Results

The flexural strength test gives another way of estimating the tensile strength of concrete. During pure bending, the member resisting the action is subjected to internal stresses (shear, tensile, and compressive). For a bending force applied downward to a member simply supported at its two ends, fibers above the neutral axis are generally subjected to compressive stresses, and those below the neutral axis undergo tensile stresses. The following Table XIII investigates detailed test results of flexural strength at the ages of 14th and 28th days for bamboo fiber reinforced concrete. They are presented in Appendix D3 at the end of this document.

Table XIII: 14-day flexural strength test results

Mix code	Calcined kaolin (%)	Bamboo fiber (%)	Average flexural Strength 14 days (Mpa)
CK0BF0	0	0	6.88
CK4BF0.5	4	0.5	7.15
CK4BF1	4	1	7.57
CK4BF1.5	4	1.5	7.66
CK8BF0.5	8	0.5	8.71
CK8BF1	8	1	8.20
CK8BF1.5	8	1.5	7.17
CK12BF0.5	12	0.5	7.67
CK12BF1	12	1	7.31
CK12FB1.5	12	1.5	7.50

Table XIV: 28-day flexural strength test results

Mix code	Calcined kaolin (%)	Bamboo fiber (%)	Average flexural Strength 28 days (Mpa)
CK0BF0	0	0	8.95
CK4BF0.5	4	0.5	9.09
CK4BF1	4	1	9.13
CK4BF1.5	4	1.5	9.32
CK8BF0.5	8	0.5	11.41
CK8BF1	8	1	10.35
CK8BF1.5	8	1.5	9.40
CK12BF0.5	12	0.5	9.34
CK12BF1	12	1	8.63
CK12FB1.5	12	1.5	7.99

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The above Table XIV reveal the 14 and 28-day average flexural strength test results of the concrete. It can be seen from Table XIII that the flexural strength of 14 days of cured unmodified concrete (CK0BF0) showed 6.88 MPa. However, the flexural strength of concrete modified with (0.5 % BF + 4% CK) showed 7.15 MPa, which was 23.11 % higher than unmodified concrete. The modified flexural strength concrete (1% BF + 4% CK) had a 7.57MPa, which was 51.74% higher than the unmodified concrete. The concrete modified with (1.5 % BF + 4 % CK) showed 7.66 MPa, which was 17.20 % modified. Moreover, Table XIV show that the flexural strength of concrete made by 0.5%, 1%, and 1.5% bamboo fiber in volume of concrete with 4%, 8%, and 12% of calcined kaolin of 28-day curing was 8.95. Another pertinent point is that the 28-day average flexural strength was increased by 8%CK with various percentages of BFs, and the optimum flexural strength is 11.41MPa, which was 27.45% from conventional concrete.

G. Discussion of Optimal Mix and Practical Implications

The experimental results consistently demonstrate that the mix CK8BF1 (8% CK + 1% BF) provides the optimum mechanical performance across compressive, splitting tensile, and flexural strength tests. The governing parameter for determining this optimum is the peak strength value achieved before a decline is observed due to two main factors: (1) excessive cement replacement by CK (e.g., 12%), which reduces the core cementitious content and can increase water demand, hindering complete hydration; and (2) excessive bamboo fiber content (e.g., 1.5%), which leads to fiber agglomeration (balling), creating weak zones and increasing porosity.

From a practical perspective, the CK8BF1 mix shows a 28-day compressive strength of 37.9 MPa, making it suitable for a range of applications. In non-structural applications such as paving blocks, kerbstones, and low-load-bearing walls, this mix offers a sustainable and potentially lower-cost alternative. For structural applications like secondary beams, slabs, and rural housing, the enhanced tensile and flexural properties are particularly beneficial. However, long-term durability aspects such as resistance to sulfate attack, carbonation, and the susceptibility of bamboo fiber to degradation in the alkaline concrete environment require further investigation before widespread structural implementation.

The use of these locally available materials aligns with the principles of sustainable construction by reducing the carbon footprint associated with cement production and utilizing renewable bamboo resources. This approach is especially significant for developing economies like Ethiopia, where cost reduction and local material availability are critical drivers.

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IV. Conclusion

This study experimentally investigated the combined effect of calcined kaolin (CK) as a partial cement replacement and bamboo fiber (BF) as reinforcement on the mechanical properties of concrete. Based on the results, the following conclusions are drawn:

- The incorporation of calcined kaolin and bamboo fiber significantly influences the mechanical properties of concrete. An optimal combination exists beyond which strength properties decline.
- The mix with 8% CK and 1% BF (CK8BF1) was identified as the optimum, demonstrating the highest compressive strength (37.9 MPa) that is approximately 10.5% higher than the control mix. This mix also showed superior splitting tensile and flexural strength performance.
- The improvement in strength is attributed to the synergistic effect of the pozzolanic reaction of CK, which densifies the cement matrix, and the crack-bridging action of the BF, which enhances tensile resistance.
- Replacement levels exceeding 8% CK led to a reduction in strength due to dilution of cementitious materials, while BF content above 1% caused a decline in properties due to fiber balling and increased porosity.

The findings of this research promote the use of industrial and agricultural waste products in concrete production, contributing to more sustainable and economical construction practices. The CK8BF1 mix presents a viable option for both non-structural and certain structural applications in regions where kaolin and bamboo are readily available. Future work should focus on evaluating the long-term durability, shrinkage, and workability of this modified concrete to facilitate its broader adoption in the construction industry.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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