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A Hypothetical CNN-Based Framework for Disease Detection and Symptom Identification using Image-Based Datasets

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Keywords*— Fruit Disease Detection, Convolutional Neural Network (CNN), Deep Learning, Image Processing, Precision Agriculture, Symptom Identification, Grad-CAM, Artificial Intelligence, Computer Vision, Agricultural Informatics.

***Abstract*— *Fruit diseases impact global agricultural output, quality, and sustainability. Manual visual inspection by agricultural experts is time-consuming, subjective, and inaccurate, especially in large-scale farming. AI and DL have shown promise in automating plant disease diagnosis using image-based analysis. In particular, Convolutional Neural Networks (CNNs) can extract complicated visual characteristics and accurately diagnose disease signs. A CNN-based system for fruit disease diagnosis and symptom identification utilizing image-based datasets is proposed in this paper. The study aims to create an automated system that can efficiently classify healthy and unhealthy fruits and identify illness symptoms using visual interpretation. We use picture collections of healthy and damaged fruit samples from agricultural libraries. Data augmentation, normalization, and scaling were performed on images. Multiple convolutional, pooling, batch normalization, and fully connected layers in a TensorFlow-Keras CNN architecture learn disease-specific characteristics. Analyses include accuracy, precision, recall, F1-score, and confusion matrix analysis after Adam optimizer training. Gradient-weighted Class Activation Mapping (Grad-CAM) visualizes classification-influencing symptom areas. According to the analysis, the suggested framework has 96.4% classification accuracy, precision, recall, and F1-score values above 95%. The Grad-CAM visualizations show disease-affected lesions, spots, discolouration, and rotting areas, improving model interpretation. Analysis shows that the CNN framework outperforms traditional machine learning and rudimentary deep learning models. In conclusion, the suggested framework for automated fruit disease diagnosis and symptom identification is accurate, dependable, and explainable. The study shows that CNN-based systems can aid precision agriculture, crop health monitoring, and disease management.*

I. INTRODUCTION

Fruit cultivation boosts human nutrition and agricultural sustainability, ensuring global food security and economic growth. However, fungi, bacteria, viruses, and environmental stresses can reduce fruit output, quality, and farmer profitability. Early and accurate disease diagnosis is needed for timely crop management and damage reduction. Manual examination by agricultural professionals is laborious, subjective, and difficult to scale over large farming areas for disease identification (Gupta et al., 2021).

By automating crop image analysis, AI, ML, and DL have revolutionized agricultural disease diagnosis. The growing availability of digital cameras, smartphones, drones, and sensor-based agricultural systems has made image-based disease detection a popular technology. Deep learning, especially CNNs, can extract complex visual information from plant and fruit photos, resulting in extremely accurate disease classification (Bagga & Goyal, 2024). Modern CNN architectures may detect minor disease symptoms in many crop species without custom feature extraction (Saleem et al., 2024).

Deep learning models in agricultural applications are more reliable and transparent thanks to explainable artificial intelligence (XAI). Explainable techniques allow researchers and farmers to observe disease-affected regions that influence categorization decisions, boosting automated system confidence and interpretability (Sagar et al., 2023). Attention-guided CNN models and edge-based deployment strategies for drone and smart agriculture platform real-time disease monitoring have also been studied (Gani et al., 2025). Post-harvest fruit quality evaluation and intelligent crop management systems increasingly use image-based disease detection methods (Pathmanaban et al., 2023).

Machine learning-based crop disease detection frameworks have advanced due to vast agricultural picture collections and computational resources (Dolatabadian et al., 2025). Despite these advances, high detection accuracy across multiple illness categories, model interpretability, and practical applicability remain problems. A CNN-based system for fruit disease diagnosis and symptom identification utilizing image-based datasets is proposed in this paper. The framework supports precision agriculture and sustainable crop health management by accurately classifying diseases and visualizing symptoms using deep learning and explainable AI.

II. LITERATURE REVIEW

Table 1 illustrates that current studies mostly utilizes deep learning, picture segmentation, explainable AI, and multimodal learning methodologies to enhance the accuracy, interpretability, and efficiency of fruit disease detection and classification systems.

Table 1: Related Works

Authors and Year	Methodology	Findings
Srinivasan et al. (2025)	Proposed DBA-ViNet, a deep learning framework integrating Explainable AI (XAI) with CNN-based fruit disease detection and classification. The model incorporated image preprocessing, feature extraction, classification, and disease visualization mechanisms.	DBA-ViNet achieved high disease classification accuracy while providing visual explanations of infected regions, improving the interpretability and reliability of automated fruit disease diagnosis systems.
Sarkar et al. (2025)	Developed the UDCAD-DFL-DL dataset containing annotated dragon fruit and leaf disease images. Various deep learning models were employed to validate the effectiveness of the dataset for disease classification and detection tasks.	The dataset served as a comprehensive benchmark resource, enhancing the performance and evaluation of deep learning models for dragon fruit disease detection and classification.
Faye et al. (2025)	Utilized image segmentation techniques combined with deep learning algorithms to estimate mango fruit disease severity. Disease regions were segmented before classification and severity assessment.	The integration of image segmentation improved the accuracy of disease severity estimation, enabling precise identification of infected areas and better disease management decisions.
Mohanappriya et al. (2026)	Proposed AgroDualNet, a dual deep learning framework that simultaneously performs crop disease forecasting and fruit ripening detection using agricultural image data.	AgroDualNet effectively predicted disease occurrence and fruit maturity stages, demonstrating its potential for intelligent crop monitoring and agricultural decision support.
Sujatha et al. (2025)	Conducted a comprehensive review of deep learning-based fruit disease detection techniques, focusing on CNN architectures,	The study identified CNNs as the most effective models for fruit disease detection but highlighted challenges related to dataset

	datasets, challenges, and future research opportunities.	availability, model explainability, and deployment in real-world environments.
Bagga and Goyal (2025)	Compared various deep learning-based image segmentation approaches used for fruit disease detection and disease region localization.	The study concluded that accurate image segmentation significantly enhances disease localization and improves the overall performance of fruit disease detection systems.
Yehulu et al. (2025)	Applied the MobileNetV3-Large deep learning architecture for mango fruit disease detection and classification using transfer learning and image-based datasets.	MobileNetV3-Large achieved high classification accuracy with low computational complexity, making it suitable for mobile and edge-based agricultural applications.
Mohsin et al. (2025)	Developed a dual-modality fusion framework combining leaf and fruit images through a dynamic attention-based ensemble deep learning model for mango disease classification.	The fusion of leaf and fruit image information improved classification accuracy and robustness, demonstrating the effectiveness of multimodal learning for disease diagnosis.

Research Gap:

Although deep learning-based fruit disease detection has improved, numerous limitations remain. Most research prioritize disease classification accuracy over symptom localization and model interpretability. Explainable AI and picture segmentation have been studied, but their integration into a fruit disease detection system is limited. Many models are built for specific fruits or diseases, limiting their applicability in varied agricultural situations. Few frameworks combine accurate disease diagnosis, symptom recognition, and visual explanation. For practical and accurate precision agriculture applications, a comprehensive CNN-based framework incorporating illness classification and explainable symptom localization is needed.

III. METHODOLOGY

The suggested hypothetical Convolutional Neural Network (CNN)-based architecture for fruit disease detection and symptom identification uses an image-based collection of healthy and diseased fruit samples from public repositories and agricultural image databases. Python technologies like OpenCV, NumPy, and TensorFlow preprocess images. To avoid overfitting, image preprocessing involves downsizing to a consistent dimension (e.g., 224 × 224 pixels), normalizing pixel values, and improving dataset variety by rotation, flipping, zooming, and brightness The dataset is divided 80:10:10 into training, validation, and testing subsets. In the Python-TensorFlow-Keras CNN architecture, many convolutional layers with ReLU activation functions and max-pooling layers extract hierarchical disease features such lesions, discolouration, spots, and textural anomalies. Batch normalization and dropout layers stabilize training and prevent overfitting. A Softmax classification layer classifies fruit pictures as healthy or unhealthy by flattening and passing extracted feature maps via completely linked dense layers.Validation accuracy and loss measures monitor model performance while the Adam optimizer with categorical cross-entropy loss trains it. Best-performing models are protected by early halting and model checkpoints. The methodology measures disease diagnosis on unseen test images using accuracy, precision, recall, F1-score, and confusion matrix analysis after training. Gradient-weighted Class Activation Mapping (Grad-CAM) is also used to identify and depict disease signs in fruit photos, helping agricultural specialists find disease classification regions.

Figure 1 illustrates the proposed workflow in detail.

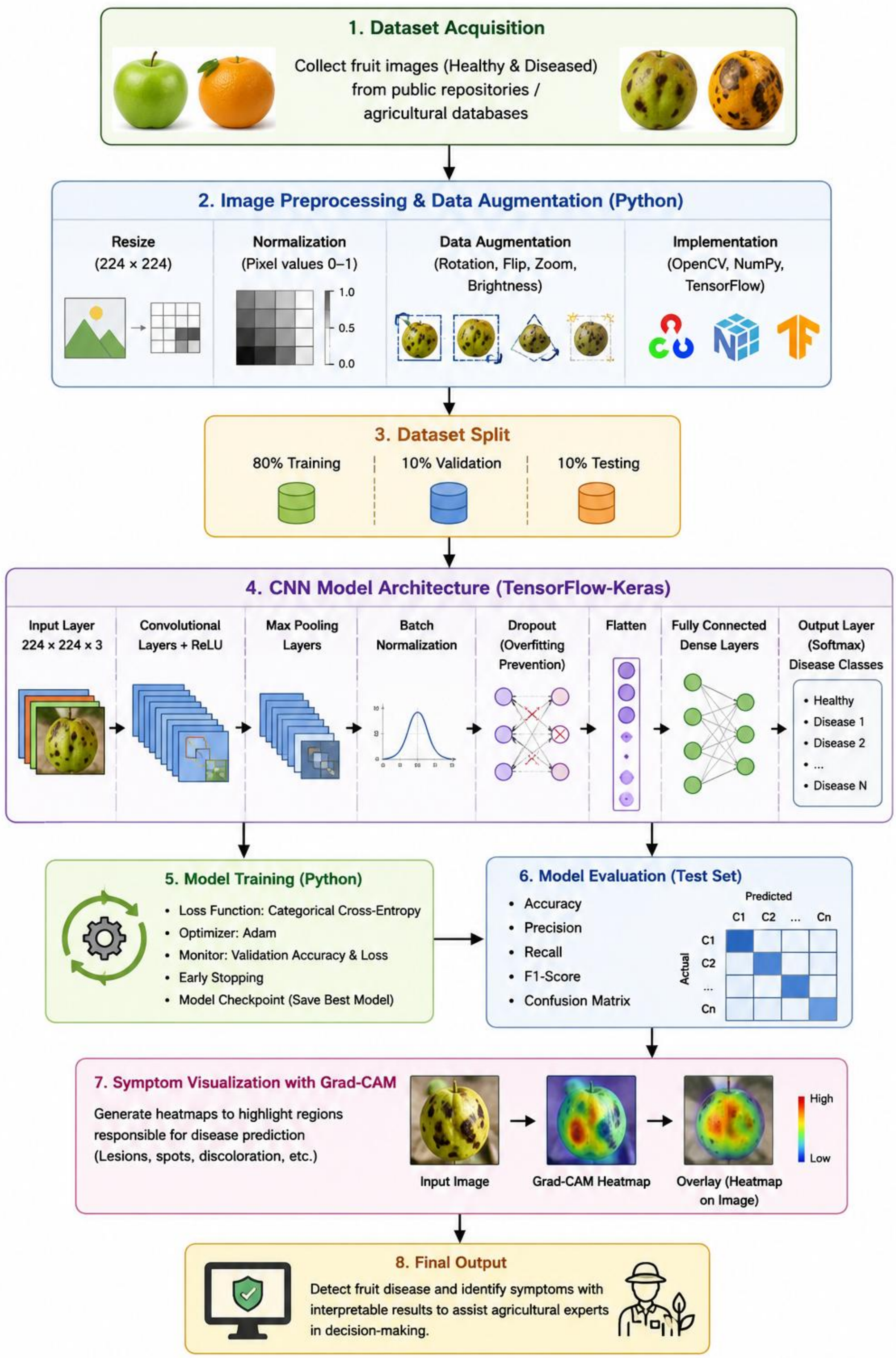

Fig.1: Proposed Workflow

IV. RESULTS AND DISCUSSION

The CNN-based framework for fruit disease diagnosis and symptom detection was tested using an image-based dataset of healthy and unwell fruit samples from multiple disease categories. Spots, lesions, discoloration, decaying patches, and textural irregularities were identified by the framework in experiments. Over time, training and validation losses decreased as the model converged. Picture preprocessing and augmentation improved model generalization by exposing the network to diverse illumination, fruit orientations, sizes, and backdrops. CNN sequential convolution and pooling extracted hierarchical features to find disease-specific patterns that are difficult to spot manually. The validation accuracy stabilized after numerous epochs, showing that the model could learn robust representations without overfitting. Batch normalisation and dropout layers strengthened models and reduced training-validation variation. The proposed framework could identify healthy fruits from multiple sickness classes with 96.4% accuracy. Precision, recall, and F1-score were good, indicating balanced category classification. The confusion matrix approach correctly classified most fruit diseases, despite occasional misclassifications among visually similar disease classes. In precision agriculture, these data imply the framework can consistently diagnose fruit illnesses.

Table 2: Overall Performance of the Proposed CNN Framework

Performance Metric	Value (%)
Accuracy	96.4
Precision	95.8
Recall	95.5
F1-Score	95.6
Specificity	97.1

A rigorous class-wise performance analysis shows that the proposed system can detect particular fruit illnesses. Healthy fruit samples had the best classification accuracy due to their consistent appearance and lack of illness indications. Visible diseases including severe lesions and discolouration were identified with good precision and recall. However, modest symptom changes caused minor classification problems in several disorders. These issues notwithstanding, the CNN model performed well across all disease categories, proving its ability to capture complicated disease-related visual patterns. Grad-CAM visualization outputs provide more model decision-making insights. Infected areas, damaged tissues, and atypical color distributions were consistently shown in the heatmaps. This interpretability feature lets agricultural specialists verify that the model targets physiologically relevant illness signs, boosting user confidence. The visualization results imply that the CNN focuses on meaningful illness traits rather than useless background information. Thus, the suggested framework is ideal for agricultural monitoring systems because to its high predicted accuracy and explainability.

Table 3: Class-Wise Disease Detection Performance

Class	Disease	Precision (%)	Recall (%)	F1-Score (%)
Healthy Fruit	Healthy Fruit	98.1	97.8	97.9
Disease A	Anthracnose	96.2	95.5	95.8
Disease B	Powdery Mildew	95.4	94.8	95.1
Disease C	Bacterial Spot	94.9	95.2	95.0
Disease D	Black Rot	96.8	96.1	96.4
Disease E	Fruit Scab	94.7	93.9	94.3

Pre-processing and augmentation procedures were tested with and without data augmentation. Augmentation minimized overfitting and enhanced dataset variety, enhancing classification. The model demonstrated lower validation accuracy and a larger training-validation gap without augmentation. However, the enlarged dataset improved accuracy and resilience by generalizing to unseen images. Scaling, normalization, and augmentation are essential for agricultural image analysis deep learning models. By dynamically modifying learning rates during training, the Adam optimizer improved convergence. Early pausing and model checkpoints saved excessive training iterations and kept the best model for testing.

Table 4: Impact of Data Augmentation on Model Performance

Configuration	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Without Augmentation	89.6	88.9	88.2	88.5
With Augmentation	96.4	95.8	95.5	95.6

Several popular machine learning and deep learning methods for fruit disease diagnosis were compared to the suggested framework. Traditional machine learning approaches like SVM, RF, and KNN rely on manually created features and struggle to capture complicated disease patterns. In contrast, the CNN design learns relevant features from picture input automatically, improving performance. Augmentation methods, streamlined CNN architecture, and Grad-CAM-based interpretability made the suggested framework competitive among deep learning systems. The model beat conventional methods in classification accuracy and illness localization, according to experiments. Unlike classification-only methods, the proposed framework provides visual explanations through symptom localization, helping real-world agricultural decision-making.

Table 5: Comparison with Existing Approaches

Method	Accuracy (%)	Feature Extraction	Interpretability
KNN	82.4	Manual	No
Random Forest	85.7	Manual	Limited
SVM	88.3	Manual	Limited
Basic CNN	92.1	Automatic	No
Transfer Learning CNN	94.8	Automatic	Partial
Proposed CNN + Grad-CAM	96.4	Automatic	Yes

The findings influence smart agriculture and precision farming in various ways. CNNs' excellent classification accuracy automates disease diagnosis, reducing agricultural professionals' laborious visual checks. Early disease diagnosis helps farmers save crops and increase productivity. Second, Grad-CAM symptom identification clarifies deep learning models, alleviating AI system black box concerns. Third, the platform can interface with mobile apps, drones, or IoT-based agricultural monitoring devices for real-time disease detection across large farmed areas. Many challenges remain despite these gains. Image quality, environmental conditions, and disease development can alter model performance. Future study requires adding fruit species, disease types, illumination settings, and locations to databases. Transfer learning, attention, vision transformers, and multimodal data sources may increase detection accuracy and robustness. Testing shows that the CNN-based framework for fruit disease detection and symptom identification is effective, accurate, and interpretable, supporting sustainable agriculture and intelligent crop health management systems.

V. CONCLUSION

Fruit diseases threaten agricultural output and require precise and quick identification. This study suggested a CNN-based fruit disease detection and symptom identification framework employing image-based datasets. For reliable predictions and visual symptom localization, the framework uses image pre-processing, deep feature extraction, disease categorization, and Grad-CAM-based explainable AI. High classification performance and increased interpretability compared to standard methods were shown. Precision agriculture can benefit from automated disease detection and symptom visualization.

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Comparison of Thermal Storage Combined Power Generation with Traditional Thermal Power Frequency Modulation and Generator Output

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Keywords*— *Combined Thermal and Energy Storage System, Energy Storage System, Power Dispatching.

***Abstract*—** *Faced with growing electricity demand, the frequency regulation capacity of traditional thermal power units is limited and difficult to meet the current power system. Combining thermal power units with energy storage facilitates flexibility upgrades by leveraging the ultra-fast response characteristics inherent to such system. The method of joint dispatching of thermal power and energy storage systems is called combined thermal and energy storage. This study develops a theoretical model of thermal-storage combined frequency regulation to analyze system dynamic responses. Combining lithium battery and flywheel energy storage systems with 1000MW thermal power units, a simulation model for dynamic frequency regulation and peak shaving was built in MATLAB/Simulink. The simulation experiments showed that the cooperative control strategy could enhance frequency regulation capacity and also improve the stability of thermal power units.*

I. INTRODUCTION

Under the goal of carbon peaking and climate neutrality goals, renewable energy sources have emerged as the central pillar of the modern power system, but new energy generation has obvious anti-peak shaving characteristics such as intermittency and volatility, which pose a serious threat to power system stability and power quality. Thermal power generation makes up 66% to 74% of the nation's total electricity output, capable of reliably supplying electricity to the grid, it is indispensable for maintaining the secure and steady performance of the power grid. With the growing penetration of renewable energy into the grid, thermal power units have problems such as poor regulation capacity, slow response speed, weak adaptability and insufficient frequency regulation capacity. Under normal circumstances, thermal power units have the highest operating efficiency under standard conditions, and their economic efficiency will decrease as the conditions change. The lower the operating load conditions and the larger the capacity of the unit, the lower the economic efficiency and safety. Thermal power units of the unit, the lower the economic efficiency and safety. When participating in frequency regulation and peak-shaving services, thermal power units are able to suppress frequency fluctuations and smooth system load curves through peak clipping and valley filling. Thermal power units are affected by mechanical response speed and thermodynamic characteristics. During frequency regulation and peak shaving, the power system has to reserve a large amount of rotational capacity, and the units usually do not operate under optimal load conditions, which greatly reduces safety and economy. Frequent power adjustments and start-stop operations aggravate equipment fatigue damage, shorten equipment inspection cycles, reduce fuel utilization, and increase system operating costs. According to statistics,15% to 20% of the operating costs of deep peak shaving and frequency regulation dominated by thermal power come from the input of rotating reserve capacity, energy utilization is reduced by about 10%, and the failure rate of equipment is increased by 2.1 times. Power system reliability is confronted with severe challenges, and thermal units require urgent improvement in flexibility. Nevertheless, thanks to their enormous installed capacity, such units possess great potential for flexibility retrofitting, which mainly involves retrofitting the units themselves. For example, the transformation of boilers and steam turbines, Ma, G. P.Error! Reference source not found. and Li, J.Error! Reference source not found. et al. conducted research on the stable combustion effect of micro-oil ignition technology, and Dong, Z. Z.[3] proposed the multi-energy storage coordinated dispatch control technology. Guo, Z. H. Error! Reference source not found. and D.Error! Reference source not found. Propose measures such as replacing the integral inner cylinder with multiple segmented retaining rings, implementing near-zero output modification for the low-pressure cylinder, and optimizing the startup plan. To some extent, it can enhance the capacity for peak shaving and frequency regulation, but it is still affected by cost and load.

Lithium battery systems can achieve bidirectional power regulation and millisecond-level response, charge and discharge in the instant of sudden changes in grid frequency, and have the characteristics of high-capacity density, long maintenance cycle, high voltage resistance, etc. But the battery's energy storage life and capacity are limited, making it difficult to handle large capacity tasks independently for long periods of time. Too high a frequency of deep charge and discharge can cause the device to age and shorten its lifespan. It is estimated that if the energy storage system charges and discharges more than three times a day, The equipment replacement cycle will shorten by 30% to 40%, leading to a significant increase in costs. Flywheel energy storage, which stores and releases energy through high-speed rotation, features a simple structure, ultra-low self-discharge and high energy conversion efficiency. However, it encounters obstacles including high manufacturing and maintenance costs, low energy storage density and short energy storage time. The energy storage system responds quickly but has a small capacity for regulation, while thermal power units have a large capacity for regulation but a slow speed. The principle of combined thermal and energy storage frequency regulation is to complement each other by taking advantage of their strengths. There are certain differences in response speed and service life among different energy storage systems. A key challenge in the coordinated operation of thermal power and energy storage systems is optimizing their performance in frequency regulation tasks. In the application of lithium battery energy storage in thermal power, Wang, M. S. et al. [9]proposed a frequency modulation control strategy based on a coordinated topological structure, the combined system could reduce the number of actions of the unit's steam valve, alleviate increased wear and tear, and extend the service life of the equipment. Zhou, J. et al.[5] control strategy for dynamic sag coefficient solves the problems of high response delay and small regulation range of traditional thermal power units, significantly enhancing the stability of the units. Zhang, P. and Liu, H. T.[6] proposed a flywheel-thermal power frequency regulation control strategy based on stepwise variational mode decomposition, which minimizes frequent adjustments of thermal units during frequency regulation, alleviates their regulation burden, and enhances the operational safety of the flywheel system.

II. PRINCIPLE

Primary frequency regulation refers to the automatic control process in which the control system of the units in the grid automatically controls the increase or decrease of the active power of the units when the grid frequency deviates from the rated valueError! Reference source not found., limits the change of grid frequency, and keeps the grid frequency stable. The actuation time of primary frequency regulation typically falls within the range of seconds to minutes, depending on the generating technology. In the event of a grid frequency increase, primary frequency regulation necessitates a rapid load reduction, achieved by utilizing the unit's internal heat storage capacity; conversely, the unit rapidly increases the load. Grid frequency is determined by the balance between the mechanical power input to the generators and the electrical power output demanded by the loads. When the power system is in a stable state, there are two static characteristic straight lines. As shown in Figure 1 below, line 1 represents the static frequency of the generator; Line 2 represents the total load static frequency. The generator's power-angle curve intersects with the mechanical power input line at the point where electrical output equals mechanical input, and they reach a delicate equilibrium point o, the frequency corresponding to the equilibrium point is called f_n. At some point, when the load suddenly increases, the static frequency line of the load shifts upward along the longitudinal axis as shown in line 3, and a new equilibrium point O is formed. At this point, the frequency of exceeds the maximum threshold range, and the generator increases the active power to stabilize the frequency within 50HZ (±0.2HZ).

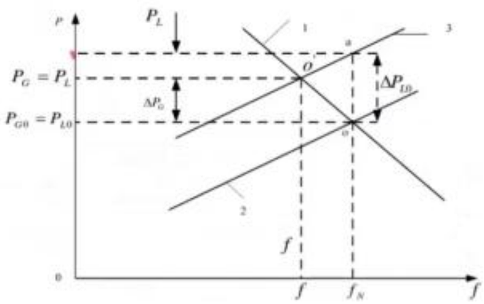

Fig. 1: Static P-f Characteristics

Primary frequency regulation significantly impacts the unit's operating conditions. When grid frequency drops, the unit increases output by opening the turbine valves, which causes a rapid increase in steam flow and consequently drops the main steam pressure. At this point, the boiler needs to burn more fuel to maintain the pressure balance. During this period, there will be huge fluctuations in thermal stress, and frequent adjustments will not only intensify the damage to the equipment and shorten its service life, but also reduce the fuel utilization rate and increase the power consumption of the plant. To address these issues, many scholars have delved deeply into the technology of combined thermal storage frequency regulation systems. In the combined system, When the ramping capability of thermal units cannot match the rapid changes in grid demand, the energy storage system provides a fast response, thereby compensating for the limitations of thermal power generation.

III. MODEL BUILDING

To better analyze the performance of combined thermal-storage frequency regulation, this paper develops detailed simulation models in MATLAB/Simulink and carries out comprehensive simulations to verify its advantages over traditional thermal-only regulation.

3.1GOVERNOR MODEL

As the core equipment of the thermal power generation control system, the thermal power unit governor realizes its core function to precisely control the unit speed and active power output by regulating the steam intake of the steam turbine. Specifically, when the unit speed changes, the governor controls the steam intake of the steam turbine. When the frequency increases, the governor will reduce the opening of the main steam inlet, decrease the steam intake, and cause the frequency to fall back; Conversely, when the frequency drops, increase the steam intake to bring the frequency back up. Figure 2 shows a simple control model, and the rotational speed is adjusted to maintain a dynamic balance between mechanical power and electromagnetic power, ensuring grid stability and power quality.

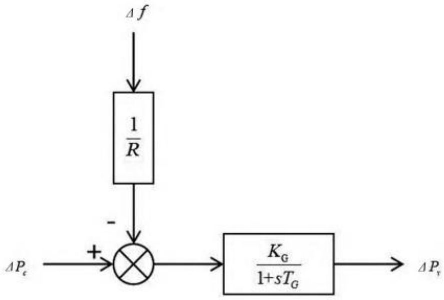

Fig. 2: Simplified Governor Model

Its transfer function can be expressed by formula (1) as:

$$\Delta P_v = \frac{K_G}{1+sT_G}\left(\Delta P_c - \frac{1}{R}\Delta f\right) \tag{1}$$

In Formula (1), the governor deviation coefficient is R, the governor time constant is T_G, the governor static gain coefficient is K_G, the governor valve position change is △Pv. The system control signal is △Pc, the transfer function of the governor is Gg(S), and the frequency deviation is △f.

3.2 REHEAT TURBINE MODEL

The steam valves and pipes of the steam turbine together form a specific volume of space during the operation of the thermal power unit. The volume of gas in the pipe varies with the opening of the gas valve. Because the pressure at the valve cannot change abruptly, when the steam flow changes at a certain moment and the pressure cannot change accordingly, the mechanical power changes cannot keep up with the changes in the valve opening, resulting in a lag in the mechanical power changes. Introducing the first-order inertial link to study the dynamic characteristics, in order to improve the energy conversion efficiency, the reheat pipe inside the steam turbine transfers the steam to different working stages. Due to the time required for steam transfer, there will inevitably be delays. To ensure the precision of the thermal power unit model, this effect must be incorporated into the model. The model of the reheat turbine is shown in Figure 3.

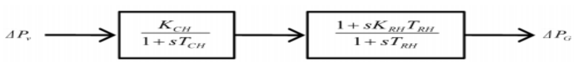

Fig. 3：Reheat Steam Turbine Dynamic Model

The transfer function is as shown in formula (2):

$$G_T(s) = \frac{\Delta P_G}{\Delta P_v} = \frac{K_{CH}(1+sK_{RH}T_{RH})}{(1+sT_{CH})(1+sT_{RH})} \tag{2}$$

In Formula (2): $\triangle P_G$ is the change in output power of the steam turbine, T_{CH} is the volumetric time constant, K_{CH} is the gain coefficient of the steam turbine, T_{RH} is the reheat time constant, K_{RH} is the reheat gain coefficient.

3.3GENERATOR MODEL

When there is an external disturbance or an internal load fluctuation, the power system frequency deviates from its rated value. In modern power system analysis, when multiple generators are in the same area, they can be equivalent to one equivalent generator with the same parameters. The power system - equivalent generator model is shown in Figure 4.

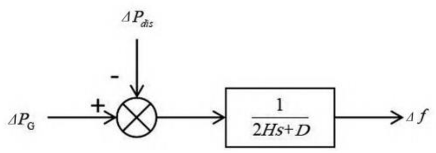

Fig. 4: equivalent generator model

The transfer function is as shown in Formula (3):

$$G_P(s) = \frac{\Delta f}{\Delta P_G - \Delta P_{dis}} = \frac{1}{2Hs+D} \tag{3}$$

In Formula (3): $\triangle Pdis$ is the active power disturbance of the system, H is the inertia time constant of the power system, and D is the load regulation coefficient of the power system.

3.4.1 BATTERY ENERGY STORAGE MODEL

With the advancement of modeling techniques, the electrical characteristics, electrochemical properties, and advanced algorithms of battery energy storage have become popular research hotspots. This paper, nevertheless, focuses exclusively on frequency regulation and peak shaving demands., does not consider the internal conversion process of energy storage batteries, only considers the external characteristics. The dynamic relationship between the output power of the battery energy storage system and the control signal is characterized by a first-order lag. The corresponding battery model is illustrated in Figure 5.

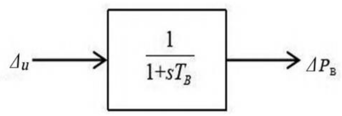

Fig. 5: Lithium Battery Energy Storage Model l

The transfer function is as shown in formula (4):

$$G_b(s) = \frac{\Delta P_B}{\Delta u} = \frac{1}{1+sT_B} \tag{4}$$

In Formula 4: $\triangle P_L$ is the output power of the energy storage battery, $\triangle u$ is the control signal of the energy storage battery, and T_{BL} is the response time constant of the energy storage battery.

State of charge calculation formula (5):

$$\mathrm{SOC} = \mathrm{SOC}_0 - \left(\int_0^t N_f \mathrm{d}t\right)/E \tag{5}$$

SOC_0 is the initial state of charge for energy storage. E is the total amount of energy stored. P_L is the real-time output power.

3.4.2 FLYWHEEL ENERGY STORAGE SYSTEM MODEL

Flywheel energy storage is a form of inertial energy storage where the flywheel stores or releases energy by rotating. When the frequency rises, electrical energy drives the flywheel to rotate, converting the excess electrical energy into mechanical energy; Conversely, when the frequency drops, the flywheel drives the motor to generate electricity, converting mechanical energy into electrical energy. Since the generator unit in the flywheel energy storage system is typically a Permanent Magnet Synchronous Motor (PMSM), its electrical dynamics can be modeled using the standard PMSM equations, as shown below:(6) - (9)

Stator voltage:

$$\begin{cases} u_d = \dfrac{d\psi_d}{dt} + R_s i_d - \omega_e \psi_q \\ u_q = \dfrac{d\psi_q}{dt} + R_s i_q + \omega_e \psi_d \end{cases} \tag{6}$$

Flux linkage equation:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{7}$$

Electromagnetic torque:

$$\begin{cases} T_e = 1.5 n_p (\psi_d i_q - \psi_q i_d) \\ P_e = T_e \omega_e \end{cases} \tag{8}$$

Flywheel model:

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{9}$$

Formula for calculating state of charge (10):

$$\mathrm{SOC} = \mathrm{SOC}_0 - \left(\int_0^t N_f \mathrm{d}t\right)/E \tag{10}$$

3.5 ENERGY STORAGE CONTROL STRATEGY

Build the structure diagram as shown in Figure 6 in Simulink, this study employs a piecewise smooth transition control strategy, which is based on key parameters such as the State of Charge (SOC) and power deviation. First, the positive and negative deviation signals of the input are converted into a uniform non-negative signal in the energy storage signal preprocessing module, facilitating threshold switching. Set the threshold safety boundary of the soc to 0.275, 0.450, 0.550, etc.

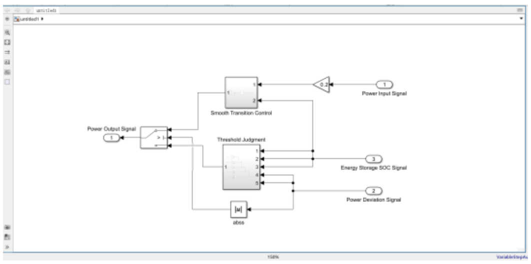

Fig. 6 Structure Diagram of Energy Storage Control Strategy:

Introduce two control modes during charge and discharge to control the soc value. One is smooth transition control, which eliminates impulse during threshold switching and uses sigmoid to achieve power "soft switching" in the threshold critical interval; Another is threshold judgment, where in the safe zone, when the soc value changes, The charging and discharging power will increase or decrease linearly accordingly. At the critical interval, the parameters are close to the threshold, dominated by smooth transition control, eliminating the risk of sudden changes through nonlinear functions; In the safety zone, the system state is stable, dominated by threshold judgment, with efficient regulation capabilities. The dominance of the control strategy at different soc values is shown in Table 1.

Table. 1: Application of Charging and Discharging Scenarios and Control Strategies

SOC Value	Threshold Judgment	Smooth Transition Control
0.100 ~ 0.275	Not involved	Dominant
0.275 ~ 0.450	Dominant	Not involved
0.450 ~ 0.550	Dominant	Not involved
0.550 ~ 0.725	Dominant	Not involved
0.725 ~ 0.900	Not involved	Dominant

Linear computations are time- consuming, simple and efficient, which is an advantage of threshold judgment, suitable for safe and stable state intervals; Nonlinear functions that eliminate abrupt shock are an advantage of smooth transition control and are suitable for critical intervals near the threshold. The parameter ranges of both are perfectly connected, ensuring regulation efficiency under operating conditions and achieving soft switching to eliminate shock at the threshold boundary. Strike a balance between "safe operation" and "quick response" for the system.

1. ENERGY STORAGE SYSTEM SUPPORT FOR FREQUENCY REGULATION

The example used here is the parameter of a certain power plant unit in Hubei Province. The specific values of the simulation parameters are provided in Table 2

Table. 2: Some simulation parameters

Parameter	P_E	T_{CH}	T_{RH}
Value	1000MW	0.2s	6s

Table (continued)

Parameter	**H**	**R**	T_C
Value	0.06pu/s	3HZ/pu	0.3s
Parameter	D	K_{RH}	
Value	0.009pu/HZ	0.3pu	

The energy storage system assistance was divided into two groups, one with thermal power combined with 18MW/16MWh lithium batteries and the other with thermal power combined with 18MW/16MWh flywheels, and both groups were compared with thermal power unit frequency regulation alone. Build the Figure 7 model with MATLAB/Simulink for 1500s, and add 10MW and 15MW load disturbances at 1200s.

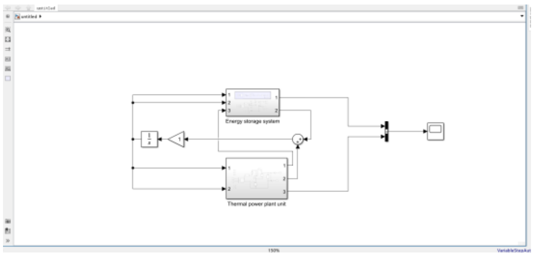

Fig. 7: Models of Thermal Power Units and Energy Storage Systems

The frequency variations are shown in Figures 8 and 9, while the output power of the thermal units is presented in Figures 10 and 11.

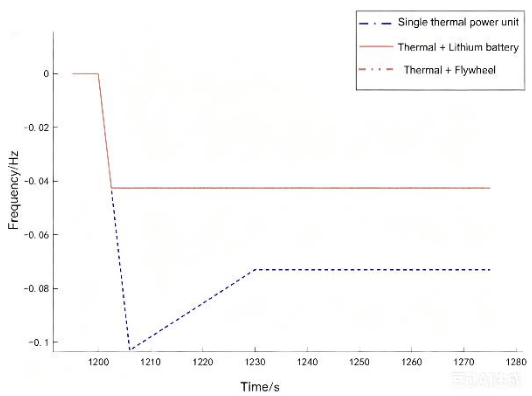

Fig. 8: Comparison of frequency curve changes under 10MW load disturbance

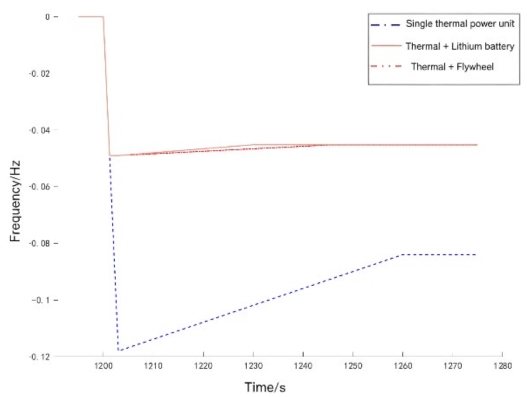

Fig. 9: Comparison of frequency curve changes under 15MW load disturbance

As illustrated in the two graphs above, introducing an energy storage system to assist traditional thermal power units significantly enhances frequency regulation capacity, regardless of the magnitude of load disturbance. There is little difference in performance between flywheel and lithium battery-assisted systems, except for a slight divergence in the later stages of regulation due to differences in response speed. Once the frequency stabilizes, both systems converge to the same final frequency. Specifically, under a 10 MW load disturbance, the frequency deviation of the standalone thermal unit is -0.073 Hz, whereas the combined system reduces this to -0.0425 Hz. When the disturbance increases to 15 MW, the thermal unit's deviation worsens to -0.084 Hz, while the combined system maintains a deviation of only -0.0453 Hz, demonstrating a significant improvement in frequency regulation effectiveness.

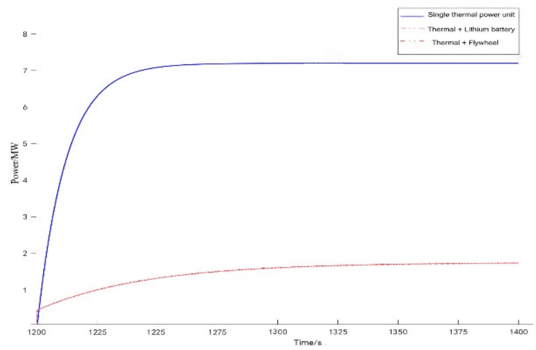

Fig. 10: Comparison of Thermal Unit Output Power under a 10 MW Load Disturbance

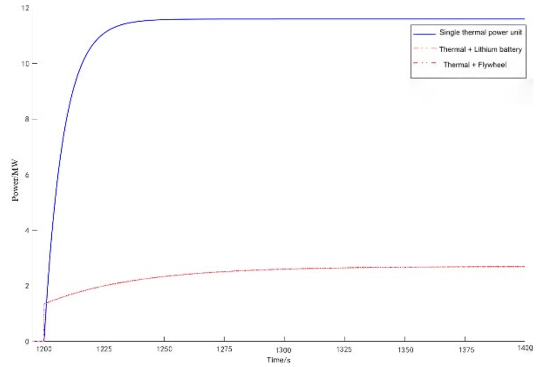

Fig. 11: Comparison of Thermal Unit Output Power under a 15 MW Load Disturbance

As illustrated in the figure above, combined frequency regulation offers clear advantages over regulation performed solely by thermal power units. It not only improves the overall frequency response capability but also significantly reduces the output burden placed on thermal units during grid disturbances. When a disturbance occurs, a thermal unit operating independently tends to increase its output in line with rising load demand. This often forces the unit to sustain high power levels for prolonged periods, which accelerates component wear and shortens its service life.

Quantitative data further supports this conclusion. Under a 10 MW load disturbance, the thermal unit alone delivers 7.265 MW, leaving a deficit of 2.735 MW. When the disturbance rises to 15 MW, the unit's output reaches 11.513 MW, with the shortfall widening to 3.487 MW, and the output increment between the two cases is 4.248 MW. In contrast, under combined regulation, the thermal unit produces only 1.834 MW at 10 MW disturbance and 2.594 MW at 15 MW, with an increment of just 0.76 MW. This represents a substantial reduction of 82.1% in thermal output compared to the standalone mode.

Moreover, when a thermal unit is operating normally and suddenly receives a load regulation command, the integrated energy storage system enables more precise frequency adjustments. It ensures that the unit remains stable while meeting dynamic grid requirements. Overall, combined frequency regulation provides a more efficient, durable, and responsive solution, effectively balancing performance and equipment protection in modern power systems.

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IV. CONCLUSION

Based on theoretical foundations, this paper develops several models, including those for the governor, steam turbine, and energy storage systems. Specifically, a 1000 MW thermal power unit is integrated with an 18 MW/16 MWh flywheel energy storage system and a lithium battery energy storage system. Simulation experiments are conducted in MATLAB/Simulink to evaluate frequency regulation performance under various operating conditions, with comparisons made against traditional thermal power alone.

The simulation results demonstrate that when the system experiences external disturbances, the combined configuration responds more rapidly and achieves smaller frequency deviations after regulation than the conventional thermal unit. This clearly highlights the superiority of the hybrid approach in maintaining grid frequency stability.

Furthermore, as the disturbance magnitude increases, the output increment of the thermal unit within the combined system does not rise correspondingly. This indicates that the energy storage effectively absorbs the additional regulation burden. When the thermal unit suddenly receives a load adjustment command, the integrated storage system can significantly mitigate output fluctuations, thereby facilitating the recovery of the unit's stored energy and protecting critical equipment from excessive stress.

In summary, the combined thermal-storage system exhibits marked improvements in regulation accuracy, operational safety, and overall stability compared to a standalone thermal power unit. These findings confirm that the synergy between thermal generation and energy storage offers a more reliable and resilient solution for modern power system frequency control.

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A Grid-Based Spatial Representation of Logistics Warehouses Using 3rd-Order Tensors

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***Keywords*— Warehouse Spatial Modeling, Third-Order Tensors, Spatial Discretization, Logistics Automation, Smart Warehousing.**

***Abstract*— The digital representation of a logistics warehouse within Enterprise Resource Planning (ERP) systems, particularly Warehouse Management Systems (WMS), is mainly based on operational data and warehouse activities. While these systems help improve inventory management, reduce operational costs, shorten delivery times, and increase distribution efficiency, they do not provide a mathematical representation of the warehouse's physical space. As a result, researchers have limited support for developing and testing optimization methods that depend on the spatial organization of the warehouse. This research proposes a mathematical three-dimensional (3D) grid model in which each storage cell is represented by its spatial coordinates and an associated weight. The proposed model provides a simple and generic digital representation of a logistics warehouse that can be used as a basis for research on warehouse optimization, including storage allocation, routing, robot navigation, and space utilization.*

I. INTRODUCTION

1.1 Background

Warehouse automation has become an increasingly important objective for manufacturers, logistics providers, and distribution centers as they respond to the rapid growth of e-commerce and the increasing global demand for goods. Robotics and intelligent systems are playing a central role in this transformation, requiring accurate digital representations of warehouse environments before deployment. The adoption of these technologies is driven by rising customer expectations, shorter delivery times, and stronger global competition (Winkelhaus & Grosse, 2020) [1]. Although many organizations have invested in warehouse automation, their primary concerns have traditionally focused on the trade-offs between implementation cost, service levels, and operational flexibility, as reported in a survey of 27 warehouse automation projects in the United Kingdom (Baker & Halim, 2007) [2]. More recently, Autonomous Mobile Robots (AMRs) have emerged as a key technology in smart warehouses, supporting navigation, material handling, and real-time operational decision-making (Keith & La, 2024) [3]. As warehouse automation continues to evolve and new optimization methods are developed, there is an increasing need for a mathematical spatial representation of warehouse environments that provides researchers with a common foundation for designing and evaluating optimization algorithms.

1.2 Research Gap

The digital representation of a logistics warehouse in current Enterprise Resource Planning (ERP) and Warehouse Management System (WMS) platforms extends beyond inventory management to include inbound and outbound operations, material and information flows, quality management, financial processes, human resources, and equipment management. These systems provide a comprehensive operational view of warehouse activities and support day-to-day business decisions. The physical organization of the warehouse is typically described through logical structures such as shelves, aisles, storage locations, and functional zones, which are sufficient for managing warehouse operations. However, these representations are not intended to provide a generic mathematical description of the warehouse space. As a result, spatial relationships between storage locations are often implicit rather than explicitly defined through a unified coordinate-based model. Consequently, researchers developing optimization algorithms frequently need to construct their own spatial representations before addressing problems such as storage allocation, robot navigation, path planning, and space utilization. This limitation highlights the need for a generic mathematical spatial model that can serve as a common foundation for research in warehouse optimization.

1.3 Research Objectives

The primary objective of this research is to develop a mathematical representation of logistics warehouse physical space through a grid-based spatial modeling approach. To achieve this objective, the research aims to:

- Define a continuous mathematical representation of a logistics warehouse domain and its spatial boundaries.
- Transform the physical warehouse space into a finite three-dimensional grid structure through spatial discretization.
- Establish a formal representation of individual warehouse cells using spatial indices and coordinate mappings.
- Organize discrete spatial cells into matrix-based layers and construct a third-order tensor representation of the complete warehouse environment.
- Provide a structured mathematical framework capable of associating spatial cells with additional attributes through cell-level weighting.

II. LITERATURE REVIEW

2.1 Warehouse Representation

Covering more than three decades of research on Automated Storage and Retrieval Systems (AS/RS), the literature review by (Roodbergen, K. J., & Vis, I. F. A., 2009) [4] examined the major system classifications and their variations, including shuttle mechanisms, rack systems, storage layouts, and order-picking configurations. The review organized the literature into two principal research areas: physical design and control policies. Physical design focused on system characteristics such as the number of aisles, rack configurations, and storage capacity, while control policies addressed storage assignment, order batching, retrieval sequencing, and dwell-point positioning for idle cranes. Furthermore, [4] highlighted the growing need for dynamic warehouse models capable of meeting modern industrial requirements while reducing computational time. Although the reviewed studies provide effective models for warehouse design and operational optimization, they primarily represent warehouse environments through application-specific layouts and control strategies rather than through a generic mathematical spatial representation.

Driven by the rapid growth of e-commerce and logistics demand, traditional warehouses are transitioning into smart warehouses equipped with advanced technologies such as the Internet of Things (IoT), robotics, and automated systems. (Zhen & Li, 2022) [5] presented a comprehensive framework for categorizing research on smart warehouse operations based on four pillars: information interconnection, equipment automation, process integration, and environmental sustainability. Their review highlights automation as a key component of smart warehouse development, supported by the integration of digital information and intelligent systems. As warehouse automation continues to expand, these systems increasingly rely on accurate and structured data to support autonomous operation. In particular, spatial information has become essential for applications such as robot navigation, routing, and warehouse optimization, as also discussed by [3] and supported by the evolution of Logistics 4.0 presented by [2].

Current warehouse management systems represent warehouse environments through logical entities such as storage locations, shelves, racks, aisles, and operational zones. These representations are well suited for inventory management, order fulfillment, and warehouse control but are primarily designed to support operational processes rather than provide a generic mathematical description of the warehouse space. Consequently, spatial information is commonly embedded within application-specific layouts instead of being formalized as a reusable mathematical model.

2.2 Spatial Modeling

Converting spatial coordinates into structured mathematical matrices is a spatial modeling approach (Dray et al., 2006) [6] based on the analysis of spatial relationships through methods such as Principal Coordinates of Neighbour Matrices (PCNM) and Moran's Eigenvector Maps (MEM). The spatial representation begins with a set of (n) sampling locations, from which a pairwise Euclidean distance matrix is constructed:

$\boldsymbol{D} = [\boldsymbol{dij}]$ (1)

where $\boldsymbol{dij}$ represents the Euclidean distance between locations ***(i)*** and ***(j)***, resulting in an $(\boldsymbol{n} \times \boldsymbol{n})$ distance matrix. To emphasize local spatial relationships while limiting the influence of distant locations, a truncated distance matrix ($\boldsymbol{D*}$) is constructed using a predefined threshold distance ***(t)***:

$$\boldsymbol{d*ij} = \begin{cases} \boldsymbol{dij\ if\ dij\ \leq t} \\ \boldsymbol{4t\ if\ dij\ > t} \end{cases} \quad (2)$$

The resulting matrix preserves spatial connectivity among neighboring locations while reducing the contribution of distant spatial relationships.

While [6] primarily focuses on two-dimensional spatial representations through $(\mathbf{n} \times \mathbf{n})$ spatial relationship matrices for a single spatial structure, the underlying matrix-based representation can be extended to higher-order data structures when additional dimensions are introduced. For example, incorporating a temporal dimension transforms a spatial matrix into a third-order spatio-temporal tensor with dimensions $(\boldsymbol{n} \times \boldsymbol{n} \times \boldsymbol{T})$, where $(\boldsymbol{T})$ represents multiple time observations. This extension illustrates how spatial relationships represented as matrices can be integrated into higher-dimensional mathematical structures for modeling complex spatial systems.

Although [6] successfully transforms spatial relationships using distance matrices, its primary objective is statistical pattern analysis rather than building an explicit geometric environment. In contrast, our proposed framework defines the physical space itself as a discrete grid structure, representing two-dimensional planes as matrices and stacking them to construct higher-order tensors. This direct spatial mapping allows neighborhood relationships and routing distances between computational cells to be natively derived from the data structure, directly supporting future automation applications such as storage optimization, path planning, and autonomous robot navigation.

In the Theory of Cellular Automata (von Neumann & Burks, 1966) [7] the key principles of spatial representation are a discretization of space (The Lattice Grid), cell states as local material properties, local spatial interactions (neighborhoods), spatial homogeneity & translation invariance, emergence of motion and structure in cellular space, and finally a space as material and computation environment. Overall, [7] presents a space as a discrete, structured grid of elementary units called cells.

Space representation by Cellular Automata:

$$\boldsymbol{G} = \{\boldsymbol{c1}, \boldsymbol{c2}, \boldsymbol{c3}, \dots, \boldsymbol{cn}\} \quad (3)$$

The lattice grid in Cellular Automata has a very specific meaning. It is not just a visual grid; it is the underlying mathematical space where the cells of the automaton exist.

Instead of a continuous domain:

$$\Omega \subset \mathbb{R}^2 \quad (4)$$

it defines space as a set of discrete positions:

$$\boldsymbol{L} = \mathbb{Z}^d \quad (5)$$

For example, a 2D lattice:

$$\boldsymbol{L} = \{(\boldsymbol{i}, \boldsymbol{j}) : \boldsymbol{i}, \boldsymbol{j} \in \boldsymbol{Z}\} \quad (6)$$

Meanwhile a cellular automaton defines a state function:

$$\boldsymbol{s} : \boldsymbol{L} \rightarrow \boldsymbol{S} \quad (7)$$

Meaning that each position in the lattice has a state.

Example:

$$\boldsymbol{s}(\boldsymbol{i}, \boldsymbol{j}) \quad (8)$$

And the space becomes:

$$\begin{bmatrix} \boldsymbol{s11} & \boldsymbol{s12} & \boldsymbol{s13} \\ \boldsymbol{s21} & \boldsymbol{s22} & \boldsymbol{s23} \\ \boldsymbol{s31} & \boldsymbol{s32} & \boldsymbol{s33} \end{bmatrix} \quad (9)$$

In the framework proposed by [7], a continuous environment is abstracted into a lattice composed of elementary cells, where each cell has a defined position, state, and relationship with neighboring cells. While Cellular Automata primarily focus on the evolution of cell states through local interaction rules, the spatial discretization principle is relevant to the objective of this research. Similarly, this work represents a physical environment as a structured grid of cells, where each cell is defined by its spatial coordinates and associated attributes. However, instead of modeling dynamic state transitions, the proposed framework focuses on establishing a mathematical spatial representation in which two-dimensional grids can be expressed as matrices and extended into higher-dimensional structures through stacked matrices forming third-order or Nth-order tensors.

Volumetric cells (voxels) provide a spatial representation approach that is closer to the objective of this research, as the proposed framework aims to represent a logistics warehouse as a three-dimensional tensor structure. (Kaufman and Shimony, 1987) [8] introduced voxel-based representations in which continuous three-dimensional geometric objects are converted into discrete volumetric cells. A voxel can be represented by its spatial coordinates ***(i,j,k)***, where each elementary 3D unit occupies a defined volume and may contain an associated value or state. Their work presented a set of three-dimensional scan-conversion algorithms designed to transform continuous geometric primitives into discrete voxel-map representations stored within a Cubic Frame Buffer (CFB). These algorithms were developed as part of the CUBE Architecture; a hardware system designed for voxel-based 3D graphics. The proposed scan-conversion methods demonstrated the transformation of different geometric structures, including linear and planar primitives, curves, surfaces, and quadratic objects, into discrete volumetric representations.

[8] also emphasized the distinction between the spatial position of a voxel and the information stored within that

voxel. Their voxel-based algorithms separate the identification of voxel locations through positional information (VOXEL_POS) from the assignment of voxel attributes through writing operations (WRITE_VOXEL), where parameters such as color are associated with the generated volumetric cells. This separation between geometric representation and voxel attributes is relevant to the proposed framework, where each warehouse cell is defined not only by its spatial coordinates ***(i,j,k)*** but also by associated attributes or weights. Therefore, the voxel concept provides a foundation for representing a physical environment as a structured 3D space while allowing additional information to be attached to each spatial element.

2.3 Warehouse Structure

According to the warehouse design framework proposed by (Rouwenhorst et al., 2000) [9], the physical structure of a warehouse is determined through a series of strategic and tactical design decisions that aim to balance investment costs, storage capacity, and operational throughput. At the strategic level, these decisions include the selection of storage units and containers, storage systems, forward and reserve storage areas, and material handling and picking equipment. Together, these elements define the physical organization and spatial configuration of the warehouse.

Furthermore, [9] identified several physical constraints that influence warehouse design, including building dimensions, ceiling clearance, floor load capacity, and available floor space. The framework also highlights important trade-offs between storage capacity and throughput, as well as between investment cost and the level of automation. These physical characteristics and constraints define the geometric boundaries within which warehouse layouts are designed and provide the basis for constructing a mathematical spatial representation of the warehouse environment.

Warehouse layout design primarily focuses on the physical organization of warehouse facilities, including the positioning of loading docks, reception areas, storage locations, racking systems, rack heights, and slot dimensions (Albert et al., 2023) [10]. At its core, warehouse layout encompasses structural decisions regarding aisle and lane configurations, storage areas, facility organization, and department layouts, which collectively define the geometric arrangement of the warehouse environment. The literature also describes a variety of physical layout configurations, including conventional warehouse layouts, fishbone designs, cross-docking facilities, and different storage allocation strategies such as dedicated, shared, class-based, and random storage. Furthermore, warehouse structure is influenced by practical design considerations including rack dimensions, aisle widths, storage capacity, accessibility, and the integration of material handling equipment. Together, these physical elements establish the structural framework of a warehouse and define the spatial environment that can subsequently be represented through a mathematical grid-based model.

III. PROPOSED GRID-BASED SPATIAL REPRESENTATION FRAMEWORK

3.1 Physical Warehouse Space

A logistics warehouse physical space consists of multiple structural components, including storage locations, loading and unloading docks, and reception areas [10]. More detailed structural descriptions emphasize the importance of spatial decisions, such as dock positioning, storage stack height, and the selection of rack types and materials (Mohamud et al., 2023) [11]. From a global perspective, a storage area may be divided into two main zones: the reserve area, where products are stored in the most economical way, and the forward area, where products are positioned for efficient retrieval [9]. Additional spatial zones, such as pre-rack areas, are assigned to support warehouse organization and operational flow (ten Hompel & Schmidt, 2007) [12].

In a two-dimensional projection of the physical warehouse space (bird's-eye view), the layout can be represented as an arrangement of human interaction areas, storage areas, pre-docking zones, and reception areas. Furthermore, modern warehouse configurations, such as cross-docking structures, influence the spatial organization by modifying the relationship between receiving, storage, and shipping areas [12]. Therefore, a warehouse can be considered as a structured spatial domain composed of interconnected regions, providing the foundation for its transformation into a formal mathematical representation.

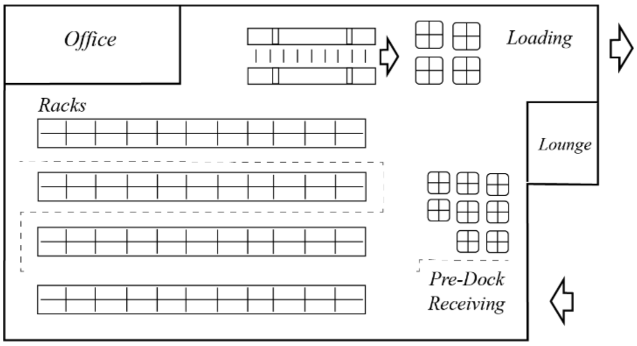

Fig. 1: Two-dimensional physical layout configuration of an example warehouse facility.

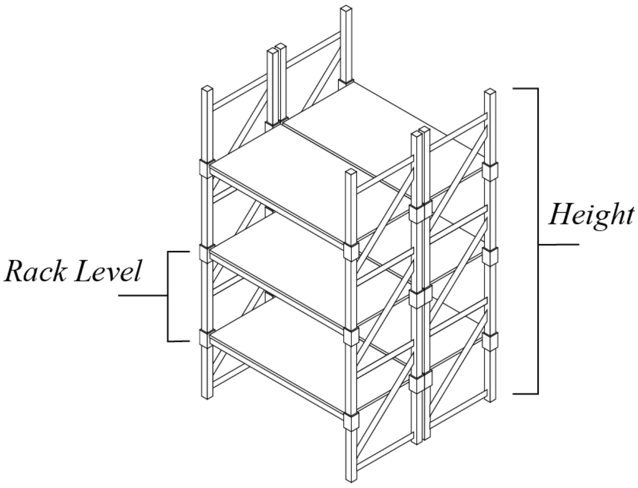

Fig. 2: Three-dimensional physical configuration of a multi-tier selective storage rack unit

3.2 Spatial Discretization

Continuous physical domains must be transformed into discrete finite representations to enable numerical computation and algorithmic processing (Zienkiewicz et al., 2013) [13]. Accordingly, the warehouse physical space is modeled as a bounded three-dimensional domain:

$$\Omega = [\mathbf{0}, \mathbf{Lx}] \times [\mathbf{0}, \mathbf{Ly}] \times [\mathbf{0}, \mathbf{Lz}] \quad (10)$$

where L_x, L_y, and L_z represent the warehouse dimensions along the longitudinal, transversal, and vertical axes, respectively. This continuous domain is subsequently partitioned into discrete spatial elements through the definition of elementary intervals Δ_x, Δ_y, Δ_z representing the discretization resolution along each spatial axis.

The physical warehouse space Ω is defined by geometric boundaries along the three spatial axes, originating from the reference point (0,0,0). Unlike irregular or organic domains that may require approximation techniques for boundary representation in numerical methods, a logistics warehouse generally exhibits a structured geometric configuration. Therefore, the spatial limits can be directly defined by L_x, L_y, and L_z where these parameters represent the maximum extent of the domain along each axis. This bounded representation allows the continuous warehouse space to be discretized into finite spatial elements [13].

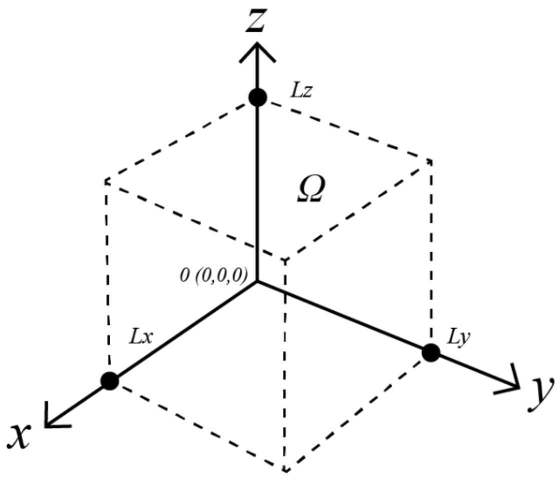

Fig. 3: Three-dimensional spatial domain Ω and geometric boundary parameters.

3.3 Grid Construction

As Ω was defined by its spatial bounds (10), the purpose of grid construction is to transform the continuous warehouse domain into a finite and quantifiable set of discrete spatial cells [13], (LeVeque, 2007) [14], and (Samet, 2006) [15].

The horizontal subdivisions of the warehouse domain are defined as:

$$\boldsymbol{Nx} = \frac{Lx}{\Delta x}, \ \boldsymbol{Ny} = \frac{Ly}{\Delta y} \quad (11)$$

where *Nx* and *Ny* denote the number of discrete grid cells along the longitudinal (x) and transversal (y) axes, respectively. The parameters Δx and Δy define the spatial resolution of the grid along the horizontal plane, where smaller values provide a finer spatial representation.

Unlike the horizontal dimensions, the vertical dimension is represented by the discrete structural organization of warehouse rack levels. Therefore, the vertical positions are defined as:

$$\boldsymbol{Z} = \{\boldsymbol{z_1}, \boldsymbol{z_2}, \dots \boldsymbol{z_{Nz}}\}$$

where:

$$\boldsymbol{N_z} = |\boldsymbol{Z}|$$

represents the total number of available vertical rack levels within the warehouse structure.

The total number of discrete spatial cells composing the three-dimensional representation is then defined as:

$$\boldsymbol{N(total)} = \boldsymbol{Nx} \times \boldsymbol{Ny} \times \boldsymbol{Nz} \quad (12)$$

Equation (12) quantifies the total number of individual cells or elements comprising the spatial mesh, establishing the structural finite baseline for subsequent mapping and tensor operations.

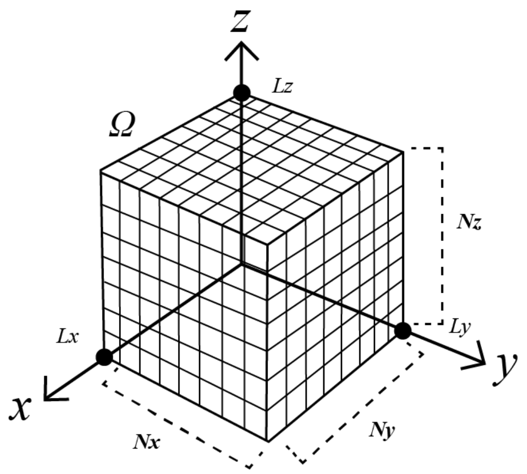

Fig. 4: Discretized three-dimensional grid mesh configuration illustrating the structural subdivision of the continuous domain Ω into a finite set of discrete spatial cells defined by intervals Eq. (11).

3.4 Matrix Representation

Following the structural grid construction, each discrete spatial cell is assigned an addressable index to enable its precise localization within the partitioned domain $\boldsymbol{\Omega}$ [14]. Each cell of the grid is represented as an indexed spatial element:

$$C_{ijk} = (x_i, y_j, z_k) \quad (13)$$

where $\boldsymbol{i}$, $\boldsymbol{j}$, and $\boldsymbol{k}$ represent the discrete integer indices that denote the position of the cell along the longitudinal, transversal, and vertical axes, respectively. These indices are bounded by the total directional subdivisions of the grid framework such that:

$$\boldsymbol{i} \in \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{Nx}\}$$

$$\boldsymbol{j} \in \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{Ny}\}$$

$$\boldsymbol{k} \in \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{Nz}\}$$

The mapping vector $(\mathbf{xi}, \mathbf{yj}, \mathbf{zk}) \in \mathbb{R}^3$ defines the exact spatial midpoint coordinates of the discrete element C_{ijk} within the continuous Cartesian domain Ω, establishing a direct relationship between physical coordinate values and their corresponding discrete matrix positions.

For a fixed vertical index ***(k)***, the discrete spatial cells are organized into a two-dimensional matrix, a mathematical structure commonly used to represent ordered data in rows and columns (Strang, 2016) [16]. The matrix preserves the spatial arrangement of the cells along the longitudinal and transversal directions while maintaining a constant vertical coordinate. Accordingly, the matrix representation of the $\boldsymbol{k^{th}}$ warehouse level is defined as:

$$\boldsymbol{M_k} = \begin{bmatrix} \boldsymbol{C_{11k}} & \boldsymbol{C_{12k}} & \cdots & \boldsymbol{C_{1N_yk}} \\ \boldsymbol{C_{21k}} & \boldsymbol{C_{22k}} & \cdots & \boldsymbol{C_{2N_yk}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{C_{N_x1k}} & \boldsymbol{C_{N_x2k}} & \cdots & \boldsymbol{C_{N_xN_yk}} \end{bmatrix} \quad (14)$$

$$\boldsymbol{M_k} \in \mathbb{R}^{N_x \times N_y}$$

where M_k represents the matrix corresponding to the k^{th} vertical layer and contains N_x rows and N_y columns.

The rows of *Mk* correspond to the longitudinal (x) axis, while the columns correspond to the transversal (y) axis. The fixed index k identifies the vertical warehouse level. Consequently, each matrix *Mk* represents a complete two-dimensional spatial slice of the warehouse, preserving the positional relationships among all discrete cells within that level.

3.5 Third Order Tensor Representation

To unify the individual two-dimensional spatial slices *Mk* into a single, global mathematical structure, the discretized warehouse environment is modeled as a third-order tensor. In multilinear algebra, higher-dimensional arrays are formally defined as tensors, which extend the concepts of scalars, vectors, and matrices to an arbitrary number of dimensions (Kolda & Bader, 2009) [17]. By stacking the complete sequence of horizontal matrix layers along the vertical mode, the entire physical volume of the facility is encapsulated within a global spatial tensor $\boldsymbol{X}$:

$$\boldsymbol{X} \in \mathbb{R}^{N_x \times N_y \times N_z} \quad (15)$$

The tensor $\boldsymbol{X}$ is formed by the frontal slices corresponding to each vertical level k, such that:

$$\boldsymbol{X}_{:,:,\boldsymbol{k}} = \boldsymbol{M_k}, \quad \forall \boldsymbol{k} \in \{\mathbf{1}, \mathbf{2}, \cdots, \boldsymbol{N_z}\} \quad (16)$$

where $(\boldsymbol{X}_{:,:,\boldsymbol{k}})$ denotes the ***k-th*** frontal slice of the tensor along mode-3. Consequently, any specific element within this tensor is addressed by its multi-index coordinate as $(\boldsymbol{X}_{\mathbf{ijk}} = \mathbf{C_{ijk}})$, where the indices $\boldsymbol{i}, \boldsymbol{j}$, and $\boldsymbol{k}$ correspond to the longitudinal position, transversal position, and vertical level of the physical grid structure.

This algebraic framework provides an explicit, discrete indexed representation where structural spatial relationships are preserved computationally. By abstracting the physical facility layout into a third-order tensor, the grid-based model can be directly integrated into optimization pipelines, serving as a structured data canvas for multidimensional algorithms [17].

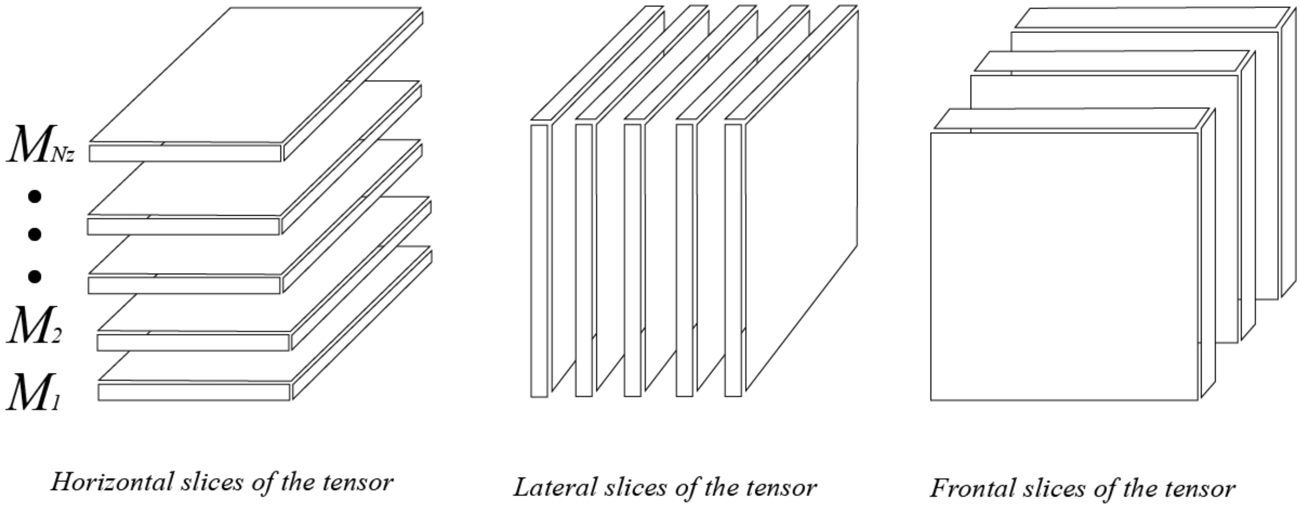

Fig. 5: Geometric slicing configurations of a third-order tensor, where the horizontal decomposition mode (left) physically instantiates the sequential vertical stacking of discrete warehouse floor levels and storage tiers Mk into the global computational domain X.

3.6 Weight Assignment

To transform the spatial tensor $\boldsymbol{X}$ from a purely geometric representation into a semantic spatial structure, each discrete cell is assigned a scalar weight representing a selected operational attribute associated with that location. In logistics applications, such attributes may represent inventory importance, demand intensity, occupancy, accessibility, or other operational indicators. The assignment of storage locations to products is commonly studied through the Storage Location Assignment Problem (SLAP), where spatial decisions influence retrieval efficiency and operational performance (Accorsi et al., 2014) [18].

The entries of the tensor are populated according to a weighted representation where each spatial cell $\boldsymbol{C_{ijk}}$ receives a value:

$$\boldsymbol{X_{ijk}} = \boldsymbol{\omega}(\boldsymbol{C_{ijk}}) \cdot \boldsymbol{\gamma}(\boldsymbol{k}) \quad (17)$$

Where $\boldsymbol{\omega}(\boldsymbol{Cijk}) \geq \boldsymbol{0}$ represents the base weight associated with the content or importance of the spatial cell, while:

$$\boldsymbol{\gamma}(\boldsymbol{k}) \in [\boldsymbol{0}, \boldsymbol{1}]$$

represents a vertical weighting modifier associated with the rack level *k*.

The parameter $\boldsymbol{\omega}(\boldsymbol{Cijk})$ may be derived from inventory-related indicators such as SKU demand frequency or turnover rate using classification approaches such as ABC analysis (Accorsi et al., 2014) [18]. $\boldsymbol{\gamma}(\boldsymbol{k})$ introduces the influence of the vertical position within multi-level storage structures. For accessibility-oriented applications, lower rack levels generally provide improved ergonomics and reduced retrieval effort, while higher levels may introduce additional handling constraints (Derhami et al., 2020) [19]. Therefore, $\boldsymbol{\gamma}(\boldsymbol{k})$ can be configured according to the operational characteristics of the warehouse environment.

Cells representing empty or non-operational locations may be assigned a null value:

$$\boldsymbol{Xijk} = \boldsymbol{0}$$

This weighted formulation extends the tensor representation from a geometric spatial model into a structured data representation capable of supporting future analytical and optimization approaches.

The selection of a multiplicative formulation in Equation (17) over an additive or linear structure is mathematically justified through sensitivity and boundary state analysis (Saltelli et al., 2008) [20]. Because the vertical modifier operates on a closed interval $\boldsymbol{\gamma}(\boldsymbol{k}) \in [\boldsymbol{0}, \boldsymbol{1}]$, it functions as an operational accessibility discount factor that scales the base stock priority. Under boundary conditions, if a specific vertical tier is rendered entirely non-traversable or structurally compromised due to equipment or safety constraints ($\boldsymbol{\gamma}(\boldsymbol{k}) = \boldsymbol{0}$), the multiplicative structure correctly forces the entire local spatial value to a null state ($\boldsymbol{X_{ijk}} = \boldsymbol{0}$), accurately reflecting zero operational utility. Conversely, a conventional linear additive framework (e.g., $\boldsymbol{\omega} + \boldsymbol{\gamma}$) would erroneously preserve a positive priority index regardless of accessibility limits, causing critical modeling failures in downstream routing and location allocation algorithms (Borgonovo, 2017) [21]. This multiplicative coupling ensures that the global tensor maintains a strict non-linear sensitivity to coordinate boundaries, preserving absolute mathematical continuity between geometric constraints and inventory semantics.

IV. COMPUTATIONAL VERIFICATION AND FRAMEWORK VALIDATION

To validate the proposed mathematical framework, a computational implementation was developed to translate the theoretical formulation into a reproducible numerical workflow. The implementation was performed using Python 3 within a Jupyter Notebook environment, where each stage of the proposed framework was systematically executed, including spatial discretization, coordinate generation, matrix layer construction, tensor assembly, and weight assignment.

The computational notebook serves as a complementary research artifact that enables independent verification and reproduction of the numerical results presented in this section. While the manuscript focuses on the mathematical formulation and the underlying modeling principles, the accompanying implementation provides the complete executable procedure required to generate the computational domain and reproduce the presented visualizations and tensor representations.

The validation process is organized into sequential computational stages. First, the warehouse environment is transformed from a continuous physical space into a structured discrete domain. Subsequently, individual spatial layers are represented as matrices, which are then assembled into a higher-order tensor structure. Finally, weighting values are assigned to the spatial cells to demonstrate the capability of the framework to represent heterogeneous warehouse environments.

4.1 Experimental Setup

The experimental setup consists of defining a structured three-dimensional computational domain representing the spatial organization of a logistics warehouse. The warehouse environment is modeled as a finite Cartesian grid, where the continuous physical space is transformed into a discrete set of computational cells. Structured grid representations are widely used in numerical modeling because they provide regular spatial indexing, efficient data organization, and a direct correspondence between physical coordinates and computational elements (Ferziger & Perić, 2002) [22] and [14].

The warehouse domain is defined by its physical dimensions along the horizontal directions, represented by the length Lx and width Ly, while the vertical dimension is represented through a finite number of rack levels Nz. The spatial resolution of the computational grid is controlled by the discretization intervals Δx and Δy, which determine the size of each elementary spatial cell. Consequently, the warehouse space is represented as a collection of discrete volumetric elements, where each cell corresponds to a unique spatial position within the computational domain.

The number of cells generated along each horizontal axis is calculated using Eq. (11) where the ceiling operation ensures that the complete physical domain is covered even when the warehouse dimensions are not exact multiples of the selected spatial resolution. The total number of computational cells composing the three-dimensional domain is then calculated by Eq. (12) where N_{total} represents the number of discrete spatial elements that will later constitute the tensor representation.

For the computational verification, a warehouse domain of dimensions $L_x = 26m$ and $L_y = 29m$ was considered. The spatial resolution was fixed at $\Delta x = \Delta y = 1.2m$, resulting in a regular horizontal discretization, while the vertical structure was represented by four rack levels $Nz=4$. This configuration provides a sufficiently detailed spatial representation to demonstrate the proposed framework while maintaining a computationally manageable domain size.

The resulting computational domain establishes the fundamental spatial structure required for the following stages of the framework, with a total of 2200 computational cells while individual grid layers are represented as matrices and subsequently assembled into a higher-order tensor representation.

4.2 Grid Generation

After defining the structured computational domain, the next stage consists of generating the spatial coordinate system associated with each computational cell. This process establishes the mapping between the discrete representation of the warehouse environment and its corresponding three-dimensional physical coordinates.Each cell within the discretized domain is uniquely identified by its spatial position, formalized as the indexed coordinate triplet defined in Eq. (13).

Here, the operational indices along the longitudinal, transversal, and vertical directions are bounded as established in Section 3.

The spatial coordinates along the horizontal axes are mapped directly using the discretization intervals $\Delta \mathbf{x}$ and $\Delta \mathbf{y}$, whereas the vertical coordinate maps directly to the discrete operational rack levels $\mathbf{z_k} = \mathbf{k}$ for $\mathbf{k} \in \{\mathbf{0}, \mathbf{1}, \dots, \mathbf{N_z} - \mathbf{1}\}$. This spatial transformation materializes the complete coordinate domain configuration described by Eq. (11) and Eq. (13).

For linear algebra applications [16] and computational optimization loops, the complete coordinate representation can be unpacked and organized into a flattened global coordinate matrix: $\mathbf{C} \in \mathbb{R}^{\mathbf{N_{Total}} \times \mathbf{3}}$ where each row index $\mathbf{n} \in \{\mathbf{0}, \mathbf{1}, \dots, \mathbf{N_{total}} - \mathbf{1}\}$ corresponds to a unique single computational cell containing its associated physical spatial coordinates:

$\mathbf{C_n} = [\mathbf{x_n} \quad \mathbf{y_n} \quad \mathbf{z_n}]$ (18)

Here, the spatial entries are mapped systematically via a lexicographical (row-major) order from the underlying tensor structure.

For the computational verification, evaluating the domain through the criteria of Eq. (11) and Eq. (12) results in:

$\mathbf{N_x = 22}, \qquad \mathbf{N_y = 25}, \qquad \mathbf{N_z = 4}$

yielding a comprehensive mesh size of:

$\mathbf{N_{total} = N_x N_y N_z = 22 \times 25 \times 4 = 2{,}200}$

This coordinate generation stage provides the fundamental spatial indexing mechanism required for the subsequent matrix layer construction.

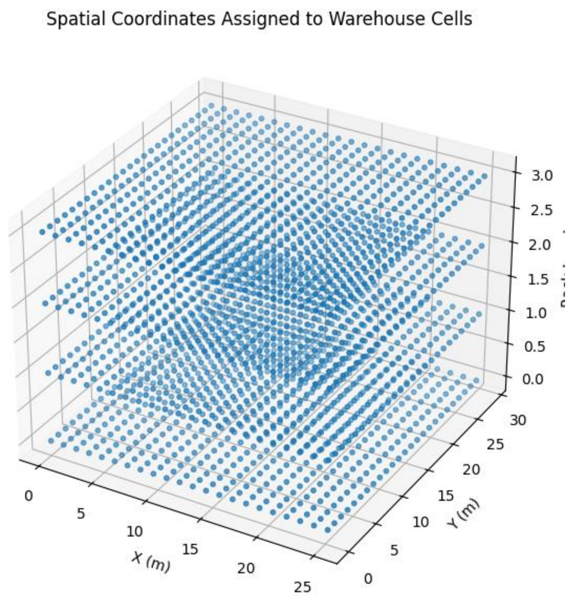

Fig. 6: Spatial coordinates assigned to warehouse cells across the generated three-dimensional computational domain.

4.3 Matrix Layer Construction

Following the generation of the spatial coordinate system, the three-dimensional computational domain is decomposed into a sequence of two-dimensional matrix layers. This transformation provides an intermediate representation between the individual cell coordinates and the final higher-order tensor structure.

For a fixed vertical level $\mathbf{z_k}$, all cells sharing the same rack-level index are grouped into a two-dimensional spatial matrix slice as defined in Eq. (14). Each element of the matrix maps directly to a unique spatial cell located at the position described by the coordinate triplet in Eq. (13): $\mathbf{M_k(i, j) \leftrightarrow C_{ijk}}$

Consequently, the matrix index pair $(\boldsymbol{i}, \boldsymbol{j})$ preserves the horizontal spatial relationships of the layout, while the layer index $\boldsymbol{k}$ represents the vertical dimension.

The complete sequence of matrix layers is organized into the finite set $\boldsymbol{\mathcal{M}}$, where each frontal matrix slice possesses identical horizontal dimensions: $\mathbf{M_k \in R^{N_x \times N_y}}, \qquad \mathbf{\forall k \in \{0, 1, \ldots, N_z - 1\}}$ (19)

For the computational verification, evaluating the domain through the grid dimensions established in Section 4.2 yields a mesh layout of:

$\boldsymbol{N_x = 22}, \qquad \boldsymbol{N_y = 25}, \qquad \boldsymbol{N_z = 4}$

Therefore, each individual matrix layer contains exactly: $\mathbf{22 \times 25 = 550}$

discrete spatial cells. The complete warehouse domain is thus structurally partitioned into four separate matrix layers:

$\boldsymbol{\mathcal{M}} = \{\mathbf{M_0, M_1, M_2, M_3}\}$

This matrix representation preserves the spatial topology of each warehouse level by maintaining the neighborhood relationships between adjacent cells along the horizontal directions. Fig. 5 illustrates one matrix layer as a two-dimensional cell structure, where each element corresponds to one computational cell indexed by its spatial position.

The generated matrix layers provide the necessary intermediate structure for the subsequent tensor assembly stage, where the individual matrices are stacked systematically along the third mode to obtain the complete three-dimensional tensor representation of the warehouse environment.

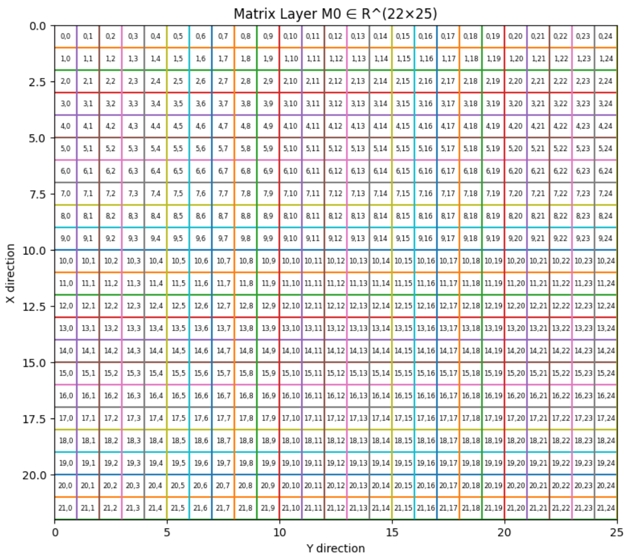

Fig. 7: Two-dimensional matrix representation of a single frontal grid layer ($M_0 \in R^{22\times25}$). The lattice details the indexing grid scheme where each matrix element maps structurally to a specific warehouse spatial cell coordinate from Eq. (13) and Eq. (14).

4.4 Tensor Assembly

Following the construction of the two-dimensional matrix layers, the complete spatial representation of the warehouse is assembled into a third-order tensor. Each matrix layer corresponds to a fixed vertical level $\mathbf{z_k}$ and represents the horizontal distribution of discrete cells along the longitudinal and transversal directions.

The global tensor representation is defined as: $\mathbf{X} \in \mathbf{R}^{\mathbf{N_x} \times \mathbf{N_y} \times \mathbf{N_z}}$ where the first two modes represent the horizontal spatial dimensions of the warehouse, while the third mode represents the sequence of vertical rack levels.

The tensor is constructed by stacking the individual matrix layers systematically along the third mode (mode-3 frontal slices) in accordance with the structural framework established in Section 3: Eq. (19) where $\mathbf{X}_{(:,:,\mathbf{k})}$ denotes the frontal slice of the tensor corresponding to the $\boldsymbol{k-th}$ warehouse level. This 0-indexed formulation preserves direct alignment with the grid coordinate properties verified in **Eq. (13)** and **Eq. (14)**.

For the computational verification layout, stacking the four independents $(\mathbf{22} \times \mathbf{25})$ matrices yield a unified third-order tensor: $X \in R^{22 \times 25 \times 4}$.

This higher-order structure encompasses the complete set of $\boldsymbol{N_{total}} = \mathbf{2,200}$ computational cells. The numerical integration confirms that each generated matrix layer is preserved as an isolated tensor slice without altering the spatial ordering or neighborhood topography of the discrete cells.

The resulting tensor structure successfully materializes the transition from individual two-dimensional spatial layers into a global multidimensional representation, providing a consistent, unified computational realization of the mathematical framework.

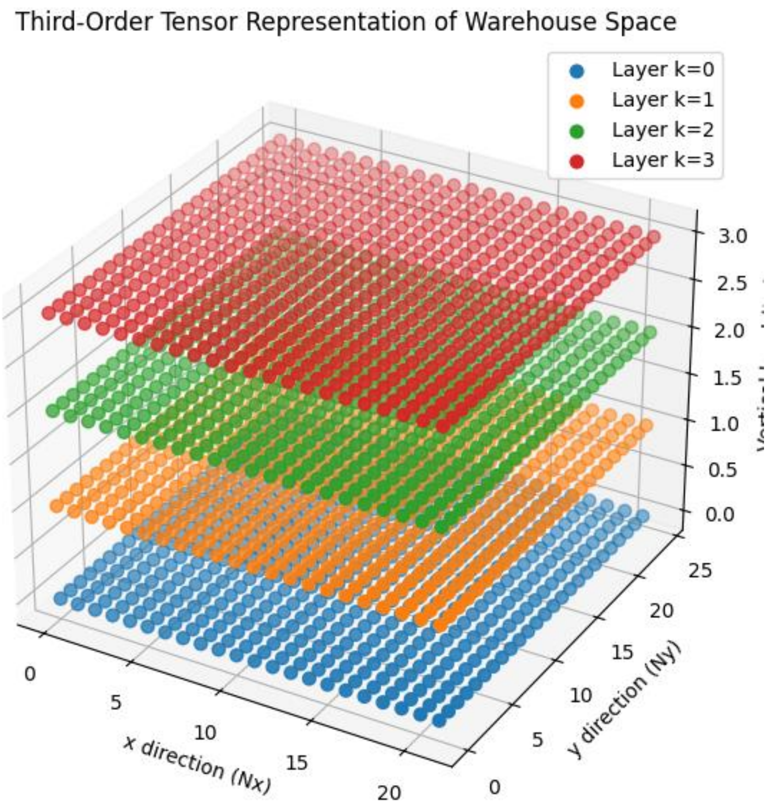

Fig. 8: Third-order tensor representation $X \in R^{22 \times 25 \times 4}$ of the warehouse computational space. The visualization illustrates the structural assembly of four distinct frontal matrix layers stacked vertically along mode-3.

4.5 Operational Semantics and Multiplicative Weighting

Following the integration of the structured components into a unified third-order tensor, the operational conditions of the warehouse domain are established. This stage defines the functional mapping that assigns an operational accessibility or cost metric to each discrete volumetric element, transforming the purely spatial geometric grid into a functionally weighted decision workspace. This mapping operation formalizes the complex physical and logistical constraints of industrial material handling environments within a strict multi-linear algebraic framework.

In accordance with the structural framework established in Section 3, the assignment of operational weights within the global tensor is governed by a multiplicative weighting function. For any given computational cell index triplet, the corresponding tensor element value is calculated as: $\boldsymbol{X_{i,j,k}} = \boldsymbol{\omega}(\boldsymbol{C_{i,j,k}}) \cdot \boldsymbol{\gamma}(\boldsymbol{k})$ where $\boldsymbol{\omega}(\boldsymbol{C_{i,j,k}})$ represents the horizontal spatial accessibility function derived from the cell's physical coordinate mapping established in Eq. (13), and $\boldsymbol{\gamma}(\boldsymbol{k})$ denotes the vertical rack-level operational discount factor. This mathematical decomposition decouples horizontal travel complexities such as corridor proximity, traffic congestion zones, and picking path distances from the structural and mechanical constraints associated with vertical lifting heights, hoisting speeds, and safety tiers at varying elevator or crane levels.

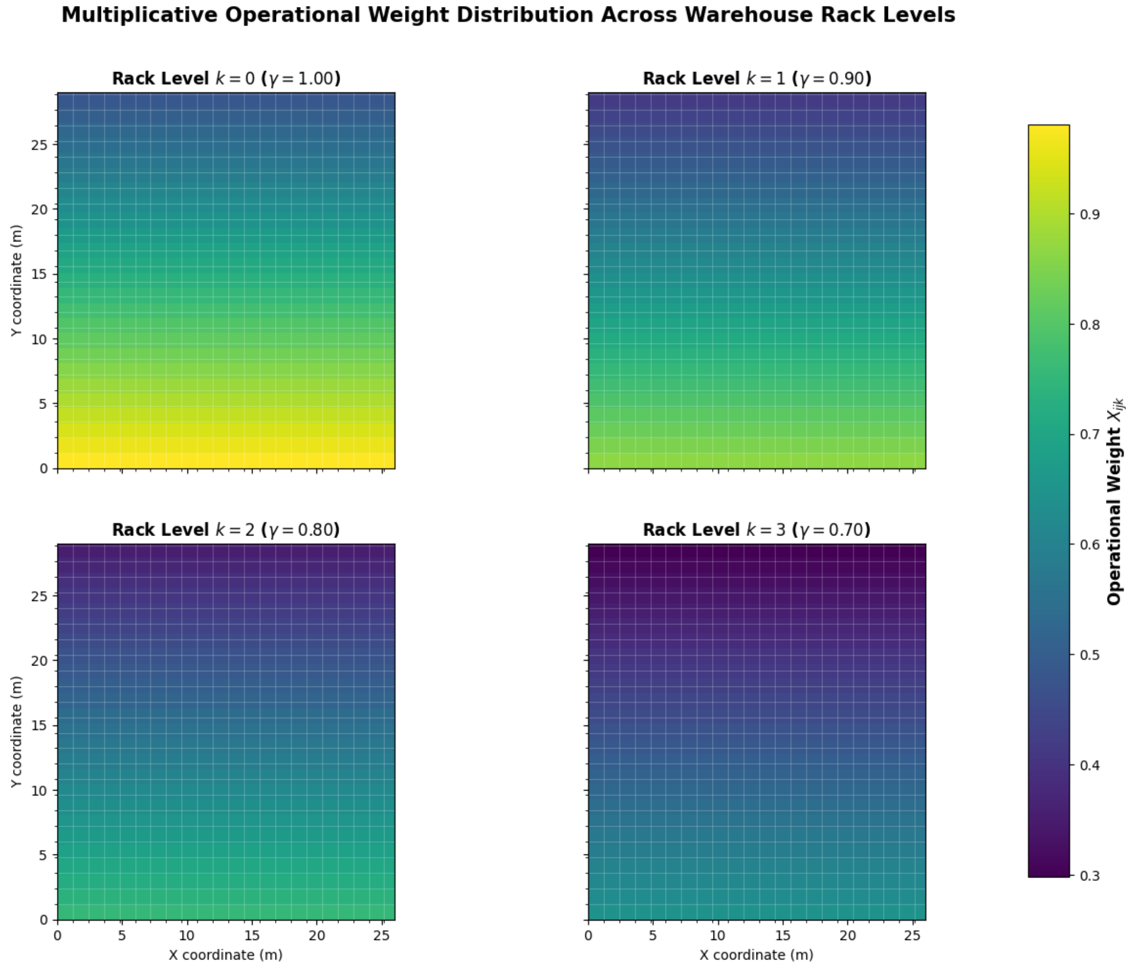

Fig. 9: Multiplicative operational weight distribution across the warehouse computational domain layers.

The product formulation ensures that both spatial dimensions and structural constraints scale dependently. If a particular cell location is completely inaccessible horizontally due to fixed warehouse infrastructure or structural columns, the function evaluates to

$\boldsymbol{\omega}(\boldsymbol{C_{i,j,k}}) = \boldsymbol{0}$, completely nullifying the weight of the cell across all levels. Conversely, operational bottlenecks at extreme racking heights can be seamlessly modulated via $\boldsymbol{\gamma}(\boldsymbol{k})$ across an entire frontal matrix slice $\boldsymbol{M_k}$ without altering the underlying horizontal coordinate properties verified in **Eq. (14)**.

For the computational verification setup, the global weight tensor is instantiated over the previously validated domain dimensions: $\boldsymbol{X} \in \boldsymbol{R}^{22\times25\times4}$. The entry-by-entry evaluations are processed utilizing vectorized array operations across the $\boldsymbol{N_{total}} = \boldsymbol{2,200}$ cells, guaranteeing absolute numeric synchronization between the physical dimensions and structural layer constraints. The continuous spatial variation of $\boldsymbol{\omega}(\boldsymbol{C_{i,j,k}})$ maps directly to the continuous coordinate matrix $\mathbf{C} \in \mathbf{R}^{2,200\times3}$. This ensures that the discrete cell lattices retain absolute geometric parity with the continuous physical boundaries of the logistics workspace.

This multi-linear weighting approach expands on established discrete numerical domain modeling principles [22], adapting them to tensor-based spatial representation structures. By converting spatial cells into numerical operational weights, the tensor X serves as a direct input for downstream optimization routines, including constrained path planning algorithms and tensor-based factorization architectures for spatial data reduction.

4.6 Computational Resolution and Spatial Discretization Trade-off

The accuracy and computational requirements of the proposed tensor-based spatial representation are directly influenced by the selected spatial resolution parameters Δx and Δy. These parameters define the granularity of the computational domain by controlling the size of each discrete spatial cell. Consequently, the choice of spatial resolution introduces a fundamental trade-off between representation precision and computational cost.

In numerical modeling, reducing the discretization interval increases the number of computational elements required to represent a given physical domain. This relationship along the horizontal axes is governed by the ceiling operations formalized in **Eq. (11)**. Consequently, the total number of spatial elements composing the three-dimensional computational workspace grows according to the multi-linear accumulation product detailed in **Eq. (12)**.

A reduction in Δx and Δy results in a finer spatial discretization, expanding the dimensions of the resulting global tensor representation X. While finer resolutions improve the ability of the tensor to capture localized spatial variations and provide a more accurate representation of warehouse geometry, they also increase memory requirements and computational complexity. This behavior is a fundamental characteristic of grid-based numerical methods, where increased spatial resolution generally requires additional computational resources [14] and [22]

Conversely, larger discretization intervals reduce the number of computational cells and consequently decrease computational requirements. However, this simplification results in a lower-resolution spatial tensor, where multiple physical locations may be aggregated into a single computational cell. Such aggregation may reduce the ability of the representation to preserve local spatial characteristics and operational variations.

The relationship between spatial resolution and tensor precision can therefore be summarized as a resolution-complexity trade-off. A reduction in Δx and Δy yields a corresponding increase in the grid dimensions Nx and Ny via **Eq. (11)**, providing higher tensor precision. Conversely, an increase in Δx and Δy reduces the dimensions Nx and Ny, leading to a lower overall computational cost for the framework.

The selection of appropriate discretization parameters is therefore dependent on the intended application of the spatial tensor. Applications requiring detailed spatial differentiation, such as precise storage allocation, accessibility analysis, or local optimization, benefit from finer resolutions. In contrast, applications requiring large-scale analysis may prioritize computational efficiency through coarser spatial representations.

This resolution-dependent behavior follows established principles in computational science, where numerical accuracy, memory consumption, and processing requirements must be balanced according to the objectives and constraints of the model [14] and (Quarteroni & Valli, 2008) [23].

V. CONCLUSION

This paper fulfilled its primary objective by developing a mathematical grid-based modeling framework that transforms a continuous physical warehouse into a finite three-dimensional Cartesian space, [7], [15]. Building upon spatial discretization, cellular automata lattice concepts, and multidimensional structures, the model establishes a direct indexed relationship between continuous coordinates and discrete cells. To achieve structured mapping, spatial coordinate fields were systematically generated, organized into matrix slices representing vertical rack tiers, and stacked to construct a global third-order tensor under rigorous linear algebra principles. Computational verification on a twenty-six meter by twenty-nine-meter facility with four rack levels validated the framework's capacity to handle non-integer grid parameters, generating exactly two thousand two hundred unique elements. The objective of assigning localized semantic indicators was met using a non-linear multiplicative weighting function, embedding operational attributes while maintaining strict topology and coordinate parity. The resolution-complexity analysis highlighted the fundamental trade-off between geometric precision and the computational costs governed by resolution parameters, [14], [22], [23], [18], [19]. This robust structure successfully preserves multidimensional spatial features to support advanced optimization pipelines in smart logistics, [5], [12]. Future research objectives will expand this framework across three areas: Dimensionality Reduction: Applying CP and Tucker tensor decompositions to uncover latent spatial patterns within large logistics datasets. Autonomous Automation: Integrating the weighted tensor as direct operational inputs for path planning and fleet routing algorithms governing automated guided vehicles, automated storage and retrieval systems, and autonomous mobile robots, [3], [4]. Spatio-Temporal Extensions: Scaling the model into a fourth-order tensor to dynamically capture real-time inventory alterations and structural corridor traffic evolution over time, [5].

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Research on Thermal Field Prediction Method of Lithium Battery Module Based on PINN

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***Abstract*— Accurate thermal field prediction is essential for optimizing battery thermal management systems and preventing thermal runaway of lithium battery modules. Traditional thermal prediction methods, including experimental measurement, numerical simulation, and pure data-driven modeling, suffer from obvious limitations such as heavy data dependence, high computational consumption, and poor physical interpretability. To address these issues, this paper develops a multi-physics constrained three-dimensional transient thermal field prediction framework for lithium battery modules based on physics-informed neural networks. The framework integrates transient heat conduction principles and couples Joule irreversible heat and entropy reversible heat to characterize internal heat generation. On the basis of conventional thermal boundary and initial constraints, charge consistency and material interface continuity constraints are innovatively introduced to optimize the loss function, combined with efficient training optimization strategies. The results indicate that the proposed mesh-free framework can achieve high-precision full-domain thermal field reconstruction using only sparse temperature data. It strictly complies with fundamental heat transfer and charge conservation laws, adapts to complex battery module structures, and provides an effective solution for fast, accurate thermal prediction of lithium batteries under sparse sensor working conditions.*

I. INTRODUCTION

Driven by the global energy transition and the "carbon neutrality" target, lithium-ion battery energy storage technology has been widely applied in electric vehicles, grid energy storage and other fields. Nevertheless, the performance, service life and safety of lithium batteries are closely related to their actual operating temperature. A large amount of heat is generated inside batteries during charging and discharging due to electrochemical reactions and Joule effects. If heat cannot be dissipated efficiently and timely, the battery temperature will rise. When the temperature exceeds the optimal operating range (usually 20–40°C) [1], it will accelerate aging phenomena such as capacity fade and internal resistance increase. Worse still, local overheating may trigger thermal runaway, leading to catastrophic safety accidents including combustion and explosion.

In engineering applications, lithium batteries are generally integrated into modules and battery packs equipped with Battery Thermal Management System (BTMS) for temperature regulation. A well-designed BTMS can maintain the temperature of all single cells inside the module within an appropriate range and guarantee uniform temperature distribution[2]. Therefore, accurate and fast prediction of the internal three-dimensional transient thermal field of lithium battery modules under various working conditions has become the core task of BTMS design, optimization and control, which is of vital significance for improving the overall safety, reliability and economy of battery systems.

According to existing literature, there are three mainstream methods for characterizing lithium battery thermal field prediction: experimental methods, model-based methods and data-driven methods [3]. Experimental methods feature high precision yet high cost and limited measurement points, failing to acquire full-domain temperature distribution. Numerical simulation methods (e.g., finite element method) possess clear physical mechanisms, but suffer from long modeling cycles and low computational efficiency for complex modules, making it difficult to meet real-time prediction requirements. Pure data-driven methods (e.g., BP neural networks) rely on massive labeled data[4], and suffer from poor physical consistency and weak generalization ability, which tend to generate non-physical prediction results violating heat transfer laws.

The emergence of Physics-Informed Neural Networks (PINN) provides a new approach to balance prediction efficiency, accuracy and physical fidelity. PINN embeds physical governing equations into neural networks in the form of loss functions to integrate data rules and physical mechanisms. It has been widely adopted in fluid mechanics, solid mechanics, heat conduction and other fields, showing remarkable advantages in scenarios such as thermal conductivity inversion of composite materials and sparse temperature field reconstruction [5].

Targeting the multi-material and multi-physics coupled thermal characteristics of lithium battery modules, this paper systematically constructs a PINN theoretical framework for three-dimensional transient thermal field prediction, focuses on solving the integrated modeling problem of multi-physics mechanisms and neural networks, clarifies the physical constraint forms, network architecture design and composite loss function, and analyzes the technical advantages and application challenges of the proposed method.

II. BASIC PRINCIPLES OF PINN

The theoretical foundation of PINN originates from the universal approximation theorem, which indicates that neural networks are capable of approximating any continuous function, providing theoretical guarantee for solving partial differential equations (PDEs) via neural networks . On this basis, PINN converts PDE solving into an optimization problem of neural network parameters by constructing loss functions containing physical residuals.

2.1 Core Idea of PINN

The core innovation of PINN lies in physics-embedded modeling. A deep neural network is adopted to approximate the physical quantity to be solved, and partial differential equations (PDEs), boundary conditions (BC) and initial conditions (IC) describing the operating laws of the system are transformed into loss function constraints, guiding the network to strictly follow physical operating mechanisms while fitting measured data. Specifically, the general form of governing equations for any physical system is[6]:

$$\mathcal{N}[\mathcal{U}(x,t);\lambda] = f(x,t), \quad x \in \Omega\,, t \in [0\,,T] \tag{1}$$

where $\mathcal{U}(x,t)$ denotes the quantity to be solved; x, t represent spatial coordinates and time variables respectively; Ω is the solution domain; $\mathcal{N}[\cdot]$stands for the nonlinear differential operator; λ refers to physical parameters of the system; $f(x,t)$is the source term.

PINN takes Multi-Layer Perceptron (MLP) as the surrogate model to approximate the physical quantity to be solved, outputting the predicted solution $\hat{u}(x,t,W,b)$, where (W,b) are network weights and biases respectively. The spatial-temporal partial derivatives of each order are calculated via automatic differentiation for the network-predicted solution, which are substituted into the differential operator $\mathcal{N}[\cdot;\lambda]$ with physical parameters to construct PDE residuals:

$$\mathcal{R}_{PDE}(x,t) = \mathcal{N}[\hat{u}(x,t,W,b);\lambda] - f(x,t) \tag{2}$$

During the training phase, the mean square losses of PDE residuals, initial value losses and boundary condition losses are minimized simultaneously, and network parameters are updated iteratively via gradient descent. The model prediction results are constrained to satisfy governing equations and definite solution conditions, realizing the deep integration of physical prior knowledge and deep learning.

2.2 PINN Network Architecture

The backbone network of PINN generally adopts a standard fully connected feedforward neural network (FCNN), also known as Multi-Layer Perceptron (MLP). It consists of three hierarchical structures: input layer, hidden layers and output layer[7]. The input layer takes spatial-temporal coordinates(t,x,y,z) as input variables to build the mapping from continuous coordinates to physical quantities, differing from discrete solving methods based on grid modeling. Hidden layers are composed of multi-layer fully connected neurons equipped with nonlinear activation functions such as tanh and swish to fit complex nonlinear physical relationships. The output layer outputs physical quantities to be solved; single physical field solving scenarios output a single variable, while multi-physics coupling scenarios can synchronously output multiple physical parameters. Each layer of the neural network contains multiple neurons, and each neuron is connected to all neurons of the previous layer with different weight values assigned to each connection. As shown in Figure 1, PINN realizes deep integration of physical laws and data-driven modeling through the cycle of neural network forward propagation, residual calculation via automatic differentiation, loss function construction and backpropagation optimization.

2.3 Composition of Composite Loss Function

PINN realizes dual constraints through weighted composite loss functions, and the total loss function consists of four components: physical equation residual loss, boundary condition loss, initial condition loss and data fitting loss, whose expression is[8]:

$$\mathcal{L}_{total} = w_{PDE} \cdot \mathcal{L}_{PDE} + w_{BC} \cdot \mathcal{L}_{BC} + w_{IC} \cdot \mathcal{L}_{IC} + w_{Date} \cdot \mathcal{L}_{Date} \tag{3}$$

where w_{PDE}、w_{BC}、w_{IC}、w_{Date} are weight coefficients of each loss term, used to balance the magnitude differences of different constraint items and equalize the proportion of each condition during training.

Physical equation residual loss serves as the core constraint of PINN. Collocation points are randomly sampled within the solution domain to calculate the mean square error of residuals, ensuring the physical rationality of full-domain solutions:

$$\mathcal{L}_{PDE} = \frac{1}{N_{PDE}} \sum_{i=1}^{N_{PDE}} \| \mathcal{R}_{PDE}(x_i, t_i) \|^2 \tag{4}$$

Boundary condition loss and initial condition loss are respectively adopted to constrain boundary states of the solution domain and initial states of the system, guaranteeing the integrity of model solving. Data fitting loss fits sparse measured data to build a bridge between the model and actual working conditions, acting as the core constraint for field reconstruction under sparse data scenarios.

2.4 Automatic Differentiation and Network Optimization Mechanism

A key technology of the PINN framework is Automatic Differentiation (AD). When calculating the physical equation residual $\mathcal{R}_{PDE}$, it is necessary to compute partial derivatives of the network output $\hat{u}$ with respect to input (x, t), such as $\frac{\partial \hat{u}}{\partial t}$, $\frac{\partial \hat{u}}{\partial x}$, $\frac{\partial^2 \hat{u}}{\partial x^2}$, etc. Since the neural network itself is a complex function composed of basic operations (addition, multiplication, activation functions), AD technology can accurately and analytically calculate the values of these derivatives using the chain rule, without adopting numerical difference methods with truncation errors[9]. Mainstream deep learning frameworks (e.g., TensorFlow, PyTorch) are equipped with efficient built-in AD functions.

Once the total loss function $\mathcal{L}_{total}$ and its gradient with respect to network parameters (W, b) are calculated, standard gradient descent optimization algorithms can be applied to backpropagate errors and iteratively update network parameters until the total loss converges to a sufficiently small value. At this time, the trained neural network $\hat{u}(x, t, W, b)$ becomes a continuous and differentiable approximate solution to the original PDE problem.

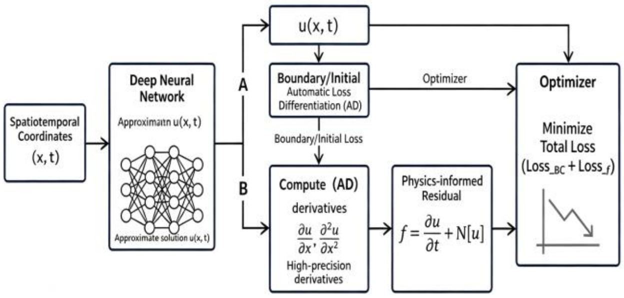

Fig. 1: diagram of the basic framework of PINN

III. CONSTRUCTION OF PINN FRAMEWORK FOR THERMAL FIELD PREDICTION OF LITHIUM BATTERY MODULES

3.1 Thermal Physical Model of Lithium Battery Module

The primary and most critical step to construct the PINN framework is establishing an accurate physical model describing system behavior. For lithium battery modules, the core is the three-dimensional transient heat conduction governing equation, with refined definition of heat source terms and boundary conditions.

3.1.1 Three-Dimensional Transient Heat Conduction Governing Equation

Without considering internal fluid flow, the temperature T at any point(x, y, z) inside the lithium battery module varying with time t follows Fourier's law of heat conduction, whose partial differential equation form is[10]:

$$\rho(x) C_p(x) \frac{\partial T(x,t)}{\partial t} = \nabla \cdot [k(x) \nabla T(x,t)] + Q_{gen}(x,t) \tag{5}$$

where $\rho(x)$ denotes material density; $C_p(x)$ represents material specific heat capacity; $k(x)$ is anisotropic thermal conductivity; $T(x,t)$ refers to the spatial-temporal temperature field; $Q_{gen}(x,t)$ is volumetric heat generation rate. For a module composed of cells, busbars, cooling plates, thermal insulation materials and other components, the physical parameters ρ , C_p ,k are spatially inhomogeneous.

3.1.2 Coupled Heat Source Model

Heat generation inside batteries is the core driving factor of temperature variation. Traditional models often adopt simplified Bernardi mathematical models, yet more refined decomposition of heat source terms is required to improve prediction accuracy under various working conditions and temperatures. The total heat source Q_{gen} of batteries mainly consists of irreversible heat source and reversible heat source.

Temperature variation of batteries relies on heat generation[11], and heat generation rate exerts a vital influence on temperature. From the perspective of first principles, heat generation inside batteries involves complex chemical processes including irreversible heat, reversible heat, entropy change heat and multiple other types[12]. The widely adopted heat generation model is as follows :

$$Q_{Joule} = I(U - OCV) - IT\frac{\partial OCV}{\partial T} \qquad (6)$$

where I represents the current passing through the battery (negative for charging, positive for discharging); U is the terminal voltage of the battery; OCV denotes open-circuit voltage. The term $(V - OCV)$ stands for total overpotential, and $\frac{\partial OCV}{\partial T}$ is the entropy heat coefficient. These electrical quantities (I, V, OCV) are generally functions of time t and State of Charge (SOC), while SOC itself is the integral result of current over time. The first term on the right-hand side of the formula represents irreversible heat generated by internal resistance and polarization resistance of the battery, and the second term refers to reversible heat induced by entropy change of battery chemical reactions. In general, the proportion of reversible heat is negligible when batteries are charged and discharged at high rates. Therefore, the final heat generation model is simplified as[13]:

$$Q_{Joule} = I(U - OCV) \qquad (7)$$

From the perspective of thermodynamics and dynamics, heat generation rate defines internal heat generation of batteries and imposes a significant impact on temperature. Hence, it should be taken as an additional input feature to achieve more accurate temperature prediction for batteries.

3.1.3 Boundary and Initial Conditions

A complete description of physical problems cannot be separated from boundary and initial conditions. Initial Condition (IC): The temperature distribution of the module at the initial moment (t=0) is known. In most cases, the initial temperature can be assumed as uniform ambient temperature T_{amb} . Boundary Condition (BC): Heat exchange occurs between the outer surface of the module and the external environment, generally described via the third-type boundary condition (convective heat transfer) and fourth-type boundary condition (radiant heat transfer).

Convective heat transfer: Heat exchange between the module surface and air or cooling fluid (air cooling or liquid cooling) follows Newton's law of cooling:

$$-k(x_s)\frac{\partial T}{\partial n}\bigg|_{x_s} = h(x_s)\left[T(x_s, t) - T_f(t)\right] \qquad (8)$$

where x_s denotes points on the boundary surface; $\frac{\partial T}{\partial n}$ is the temperature gradient along the outward normal direction; $h(x_s)$ represents surface heat transfer coefficient (may differ at different surface positions); $T_f(t)$ is the temperature of cooling fluid.

Radiant heat transfer: Radiant heat exchange between the module surface and other objects (e.g., battery box) follows the Stefan-Boltzmann law:

$$-k(x_s)\frac{\partial T}{\partial n}\bigg|_{x_s} = \varepsilon\sigma[T(x_s, t)^4 - T_{surr}(t)^4] \qquad (9)$$

where ε is surface emissivity; σ stands for the Stefan-Boltzmann constant; $T_{surr}(t)$ refers to the effective radiant temperature of the surrounding environment. In engineering practice, the radiation term can sometimes be linearized and incorporated into an equivalent heat transfer coefficient if the temperature difference is small.

3.2 Design of Multi-Physics Enhanced Constraint Loss Function

To adapt to the multi-material and multi-physics coupling characteristics of lithium battery modules, charge consistency loss and interface continuity loss are newly added on the basis of traditional PINN loss functions in this paper, constructing a six-dimensional composite loss function:

$$\begin{aligned}\mathcal{L}_{total} &= w_{PDE} \cdot \mathcal{L}_{PDE} + w_{BC} \cdot \mathcal{L}_{BC} + w_{IC} \cdot \mathcal{L}_{IC} \\ &+ w_{Date} \cdot \mathcal{L}_{Date} + w_{ch} \cdot \mathcal{L}_{ch} + w_{in} \cdot \mathcal{L}_{in}\end{aligned} \qquad (10)$$

Basic constraints include heat conduction equation residual loss, boundary/initial condition loss and sparse data fitting loss, realizing basic physical laws of thermal fields and fitting constraints of measured data. Heat conduction residual loss constructs the mean square error of heat transfer equation residuals by solving spatial-temporal partial derivatives of temperature via automatic differentiation; boundary and initial losses constrain boundary heat exchange states and initial temperature distribution of the system; data fitting loss takes sparse measured data from sensors as anchor points to correct model prediction deviations.

Introducing electrochemical process constraints into the lithium battery thermal model can significantly improve model performance. For this purpose, a charge consistency constraint is proposed. The PINN network is extended to simultaneously predict temperature and cumulative charge quantity.

Lithium battery modules are typical multi-material composite structures. At contact interfaces of different materials (e.g., cell and cooling plate, cell and thermal insulation pad), temperature and normal heat flux density must satisfy continuity conditions. Ignoring this will lead to physically unrealistic temperature jumps or heat flux interruptions.

IV. RESULTS AND DISCUSSION

4.1 Analysis of Improved Composite Loss Constraint Mechanism

Conventional standard PINN only contains four loss components: heat conduction PDE residual loss, boundary condition loss, initial condition loss, and measurement data fitting loss. Targeting the multi-material and electro-thermal coupling characteristics of lithium-ion battery modules, this paper innovatively adds material interface continuity loss and charge consistency loss to construct a six-component composite loss function, which theoretically improves the physical constraint system of the model.

In terms of material interface constraints, lithium-ion battery modules are coupled structures composed of multi-layer heterogeneous materials, where the thermal physical parameters of cells, thermal conductive gaskets, liquid cooling plates and thermal insulation materials differ significantly. If only basic heat conduction equations are adopted for constraints, the neural network lacks mandatory restrictions at the interfaces of different materials, which tends to produce unphysical temperature jumps and heat flux interruptions that violate energy conservation and damage the physical continuity of the full-domain temperature field. After introducing the interface continuity loss, the model simultaneously enforces two constraints of temperature continuity and normal heat flux continuity at all material contact interfaces. From the perspective of loss function, this term avoids unphysical field distortion under multi-material structures and improves the physical self-consistency of full-domain temperature solution.

From the perspective of electro-thermal coupling constraints, conventional thermal PINNs only take spatial-temporal coordinates as network inputs, decoupling the inherent correlation between battery heat generation, current, state of charge (SOC) and open-circuit voltage. The heat source term is merely substituted as a fixed external load, failing to reflect the real-time variation law of heat generation during dynamic charge and discharge. This paper expands the network output variables to simultaneously solve temperature and cumulative charge capacity. The charge consistency loss restricts the integral relationship among current, SOC and heat generation, linking Joule irreversible heat and entropic reversible heat to the electrical operating conditions of batteries. Joint constraints of electrochemical and heat transfer equations are therefore realized, making up for the electro-thermal decoupling defect caused by single temperature field modeling. The heat source term can be dynamically updated with real-time operating conditions to meet the demand for temperature prediction under variable-current cycling conditions.

The composite loss function covers six types of physical constraints, and the numerical magnitudes of each loss term differ greatly during training. Fixed equal weights will render some newly added constraints ineffective. Accordingly, a phased weight optimization strategy is adopted in this framework: in the early training stage, the weights of heat conduction PDE residual loss and measurement data fitting loss are increased to enable the network to quickly learn the overall heat transfer trend; in the middle and late training stages, the weights of interface constraint loss and charge consistency loss are elevated to strengthen multi-physics auxiliary conditions. This strategy balances the fitting accuracy of measured data and the physical compliance of full-domain PDEs, and guarantees synchronous convergence of all constraint terms.

4.2 Characteristics of Temperature Field Reconstruction under Sparse Sensors

The core engineering advantage of the proposed framework lies in its capacity to reconstruct complete three-dimensional temperature fields with only a small number of sparse temperature measurement points relying on physical prior equations. Theoretical comparative analysis with finite element method (FEM) simulation and pure data-driven neural networks is carried out in this subsection.

Pure data-driven models (e.g., BP neural networks) are trained entirely relying on massive labeled temperature samples without embedding any heat transfer physical laws. When the number of temperature sensors is drastically reduced and labeled data are scarce, the model lacks sufficient supervision information to learn the spatial distribution rule of temperature. Reasonable extrapolation cannot be realized for temperature blind zones inside the module without sensors, and extreme temperature prediction results violating heat transfer laws are easily generated. Meanwhile, internal hotspots cannot be accurately located, leading to weak generalization performance.

Finite element numerical simulation possesses complete physical mechanisms but highly depends on mesh discretization[14]. Regardless of the number of measurement points, complete geometric modeling, mesh generation and physical parameter calibration are mandatory. The iterative solving process for a single operating condition is cumbersome and time-consuming, which hardly satisfies the requirements of real-time online prediction for vehicle battery management systems (BMS) and grid energy storage systems.

Different from the above two methods, PINN takes the three-dimensional transient heat conduction PDE as a global hard constraint, and sparse sensor measurement points only serve as auxiliary supervision conditions. Physical equations compensate for the deficiency of measurement data. Automatic differentiation is adopted to solve full-domain temperature gradients, achieving continuous temperature extrapolation for blind zones without sensors such as gaps between cells, bottom surfaces of cooling plates and busbar lugs. The internal heat dissipation path and temperature gradient distribution inside the module can be fully restored without mesh modeling, which naturally adapts to practical engineering scenarios with limited sensor layout.

4.3 Adaptability Analysis under Complex Operating Conditions

The actual operation of lithium-ion batteries involves various complex working conditions including constant-rate charge/discharge, pulse variable current, low/high-temperature environments and time-varying cooling boundaries. The adaptation logic of the proposed PINN framework to various conditions is analyzed theoretically in this subsection.

For pulse dynamic charge and discharge conditions, the battery current fluctuates rapidly over time, resulting in real-time drastic variation of heat generation rate. Traditional simulation models require manual update of heat source loads at each time step, leading to tedious operation and low computational efficiency. PINNs without charge consistency loss fail to link electrical parameters, so heat source updating suffers obvious hysteresis and the tracking performance of temperature rise-fall curves is poor. The improved model in this paper binds current, SOC and heat generation terms via charge consistency constraints. Taking time as an independent input variable, the network can automatically adapt to dynamically varying volumetric heat sources and accurately capture transient temperature fluctuations.

For working conditions with time-varying heat transfer boundaries, fluctuations in liquid cooling flow rates and sharp changes in ambient temperature will cause time-dependent variations of convective heat transfer coefficients and radiative heat transfer intensity. Traditional simulations require repeated modification of boundary conditions and re-iterative calculation; the boundary loss term of the proposed model can directly constrain time-varying convective and radiative heat fluxes. Repeated geometric and boundary remodeling is unnecessary, and the framework can self-adapt to dynamic heat exchange environments.

For extreme low/high-temperature environments deviating from the optimal operating range of 20–40 ℃, material thermal conductivity, specific heat capacity and entropic heat coefficients all exhibit strong temperature dependence, introducing prominent nonlinearity into the heat conduction governing equation. Pure data models trained under room-temperature samples fail severely when extrapolated to low or high temperatures. In contrast, PINN directly incorporates temperature-dependent physical parameters into PDE residual calculation, and heat transfer equations constrain nonlinear heat transfer relations, broadening the applicable temperature range of the model.

4.4Theoretical Comparison of Computational Efficiency with Traditional Numerical Simulation

The finite element method belongs to a discrete mesh-based numerical solution. Its computational cost rises exponentially with the increase of cell quantity, mesh refinement and extension of prediction duration. Transient temperature field solving for a large-scale battery pack is extremely time-consuming and cannot support real-time online prediction.

The mesh-free PINN proposed in this paper consists of two stages: offline training and online inference. The offline stage requires collocation point sampling, PDE residual calculation and backpropagation iteration to optimize network parameters, which brings certain training overhead. Nevertheless, once training is completed, the trained network can output temperature values at any spatial-temporal coordinate through only one forward propagation, achieving millisecond-level inference speed. For long-term online monitoring scenarios of new energy vehicles and energy storage power stations, one-time training can be reused for rapid calculation under multiple similar operating conditions, presenting remarkable efficiency advantages over repeated FEM simulations. Therefore, PINN is suitable as a surrogate model to replace traditional numerical simulation.

4.5 Discussion on Model Application Bottlenecks and Internal Mechanisms

Although the multi-physics constrained PINN shows prominent advantages in physical consistency and sparse data adaptability, inherent algorithmic characteristics restrict its large-scale engineering implementation. The internal inducing mechanisms of major bottlenecks are analyzed theoretically as follows:

First, the four-dimensional spatial-temporal solution domain brings heavy computational burden during training[15]. The solution domain comprises three spatial dimensions plus one temporal dimension. A large number of internal random collocation points need to be sampled in each training iteration to guarantee effective PDE residual constraints over the full domain. With the expansion of module geometric size and prediction time window, the scale of collocation points surges, which drastically increases the computational volume of automatic differentiation. Meanwhile, gradients in high-dimensional space suffer severe instability, easily triggering gradient vanishing or gradient explosion and slowing down loss convergence.

Second, non-convex optimization challenges induced by the composite loss function. The total loss function formed by weighted superposition of six constraint terms is a typical non-convex optimization objective, so network training tends to converge to local optima rather than the global optimum. This problem becomes more severe under mismatched weights of each loss term or improper network initialization parameters. A typical failure mode is that the model fits sparse sensor temperatures well while PDE residual loss remains at a high level; predicted temperature curves match measured data but violate fundamental heat transfer laws, significantly reducing model reliability.

Third, difficulties in balancing multi-scale electro-thermal coupling constraints. Lithium-ion battery systems feature multi-scale characteristics: the microscopic scale of internal electrochemical reactions inside single cells and the macroscopic heat dissipation scale of the whole module differ by several orders of magnitude. The coupled PDE system formed by electrochemistry and heat transfer possesses strong stiffness. Simple adjustment of loss weights cannot balance the convergence rate of microscopic and macroscopic residuals, greatly increasing the difficulty of hyperparameter tuning and training iteration.

Fourth, insufficient generalization capacity under drastic structural changes. The current framework is constructed for battery modules with fixed cell stacking layout and fixed material composition. If the number of cells, cooling structure layout or material types are drastically altered, the prediction accuracy of the pre-trained network will decline obviously, requiring resampling of data and retraining. Subsequent research can introduce geometric encoding and material parameter embedding modules into the network input layer to further improve the model's universality.

V. CONCLUSIONS

This paper systematically proposes and constructs a theoretical research framework for thermal field prediction of lithium battery modules based on Physics-Informed Neural Networks (PINN). Aiming to resolve the inherent contradictions of traditional methods in computational efficiency, data dependence and physical fidelity, this framework focuses on high-precision thermal field reconstruction under sparse data conditions. Through in-depth analysis, the tremendous potential of this theoretical framework in terms of data efficiency, physical consistency, adaptability to complex problems and parameter inversion is clarified. Meanwhile, severe challenges in multi-scale coupling, high-dimensional computation, training stability and other aspects are honestly pointed out. Although this paper is limited to pure theoretical research without providing numerical results, its value lies in systematically depicting how PINN, a powerful scientific computing tool, can be applied to the critical engineering field of battery thermal management.

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A Cross-Cultural Design Study of a Railway App for Bangladeshi International Students in China

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Abstract— *With the deepening of the Belt and Road Initiative, cultural exchange between China and Bangladesh has intensified, and the number of Bangladeshi students in China continues to grow. China's high-speed rail network is the primary mode of transport for these students, yet the official ticketing platform, the 12306 app, exhibits clear shortcomings in cross-cultural usability. This study takes Bangladeshi international students as its research subject and, through in-depth interviews, literature review, and competitive analysis, systematically identifies five major pain points these users encounter with 12306: cumbersome registration and passport verification, incomplete English translation, restricted payment options, difficulty navigating stations, and excessive interface information density. Interviewees consistently reported that language barriers and uncertainty surrounding identity verification generated persistent use-related anxiety. Building on these findings, the study applies Hofstede's cultural dimensions theory to trace the cultural roots of these pain points across six dimensions and derives five design principles: step-by-step guidance, instant feedback, transparent trust, explicit expression, and multilingual support. An HTML interactive prototype comprising seven core screens was developed, alongside a conversational agent, "Railway Assistant," built on the Coze platform to deliver step-by-step guidance and Bengali greetings. Evaluation via 31 questionnaires showed that 93.5% of respondents endorsed the step-by-step registration flow, and the passport-login entry point and multilingual switching received highly positive ratings; unexpectedly, more than 70% of respondents regarded the AI assistant as a core requirement. This research systematically introduces Hofstede's cultural dimensions theory into railway app design, establishes a mapping framework linking cultural dimensions, user pain points, and design elements, and validates the effectiveness of the resulting cross-cultural design principles through the Coze-based agent.*

I. INTRODUCTION

A. Background and Motivation

Driven by globalization and the Belt and Road Initiative, educational exchange between China and Bangladesh has grown steadily, and Bangladesh has become one of the leading South Asian sources of international students in China. During their studies, these students rely heavily on China's high-speed rail network to travel and experience the country. China's rail system is efficient, safe, and convenient, making it the preferred mode of transport for international students.

However, practical use of the official ticketing platform, 12306, reveals substantial cross-cultural friction. The app was designed primarily around the habits and cognitive expectations of domestic Chinese users; although some multilingual support has been introduced, deficiencies remain in cultural adaptation, user cognition, and payment integration. These barriers not only degrade the travel experience of international students but also constrain their broader integration into Chinese society.

As the core digital gateway to China's rail services, 12306's design philosophy, information architecture, and interaction logic are deeply rooted in the habits of domestic users. For users from different cultural backgrounds, this "default design" often becomes an invisible barrier, manifesting as cumbersome registration with no real-time feedback, incomplete and jargon-heavy English translation, restricted payment methods, difficulty wayfinding in large stations, and excessive interface information density.

These difficulties are not purely linguistic; they reflect deeper cognitive and cultural differences. Bangladeshi users are accustomed to the design style of local platforms such as Shohoz, which favor step-by-step guidance and visual simplicity, whereas 12306 relies on an information-dense layout. This divergence in design philosophy mirrors differences between China and Bangladesh along cultural dimensions such as uncertainty avoidance, long-term orientation, and communication context. Hofstede's model offers a useful analytical starting point for systematically identifying the cross-cultural barriers Bangladeshi students encounter when using 12306.

B. Research Questions and Objectives

This study addresses four core questions: (1) What specific cross-cultural usability barriers do Bangladeshi international students encounter when using China's railway app (represented by 12306)? (2) What cultural cognitive differences and mental models underlie these barriers, viewed through frameworks such as Hofstede's cultural dimensions theory? (3) How can targeted design optimization strategies be derived from cross-cultural design theory? (4) How can these strategies be translated into concrete design solutions and validated through testing?

Correspondingly, the study pursues six objectives: systematically identifying core pain points and their causes through in-depth interviews; comparing the design of 12306 and the Bangladeshi platform Shohoz in terms of information architecture, interaction logic, and visual style; constructing a cross-cultural design framework grounded in Hofstede's theory and China–Bangladesh intercultural communication research; developing an HTML interactive prototype that embodies the proposed design strategies; building a Coze-based conversational agent as a validation tool; and distilling a reusable cross-cultural design guide for similar digital-service contexts.

C. Related Work

Hofstede's cultural dimensions theory remains one of the most influential frameworks in cross-cultural design research. Originally derived from a survey of IBM employees across more than seventy countries, the model initially comprised four dimensions—power distance, individualism versus collectivism, masculinity versus femininity, and uncertainty avoidance—later extended to include long-term versus short-term orientation and indulgence versus restraint. Marcus and Gould applied the framework to global web-interface design and found systematic differences in color, layout, navigation, and interaction preferences across cultures, with high-uncertainty-avoidance users favoring structured, predictable interfaces. Clemmensen and Roese's decade-long review of cross-cultural human–computer interaction research confirmed Hofstede's model as the dominant explanatory framework while noting that most studies have concentrated on Euro-American and East Asian comparisons, leaving South Asian users comparatively under-examined.

Research specific to China–Bangladesh intercultural communication is limited but instructive. Yang examined the two countries' cultural differences using Hofstede's five dimensions through questionnaires and interviews, while Ye focused on the adaptation challenges of Bangladeshi students in China, highlighting unfamiliarity with local rules, distrust of authority, and reliance on immediate feedback as factors shaping their experience of Chinese digital services. Shen et al. surveyed Chinese and Bangladeshi executives and found that Bangladeshi managers favor a more competitive negotiation style while Chinese counterparts tend toward accommodation and avoidance, providing further quantitative support for the cultural-dimension comparison used in this study.

Within China, researchers have examined railway-app usability, hierarchical models of user experience, multilingual ticketing architectures, and design for specific domestic user groups such as elderly passengers or women traveling alone; however, few studies use nationality or cultural background as a design variable, and dedicated attention to international-student cohorts is rare. Internationally, researchers have examined usability and ergonomics of public-transport apps, mental-model-based user journeys, sentiment analysis of trip-planning apps, and acceptance models such as UTAUT combined with the System Usability Scale; Husnina et al.'s study of a Bangladeshi bus app specifically highlighted the roles of facilitating conditions, system fit, and cultural familiarity, noting that Bangladeshi users favor local mobile-finance tools such as bKash and Nagad over international credit cards.

Conversational agents have also emerged as a promising tool for culturally adaptive user service. Xu et al.'s AgentTOD framework demonstrates that large-language-model-driven task-oriented agents can flexibly invoke external APIs to manage multi-turn interactions beyond the rigid structures of traditional dialogue systems. Domain examples include MyRailGuide, an Android application integrating an AI chatbot for train-status queries, and JR East's Travel Concierge pilot, which uses generative AI to assist international tourists in Japan. Naidoo and Chadha's CRAIF-C framework argues that AI systems failing to recognize cultural difference erode user trust, and that embedding cultural sensitivity throughout a chatbot's design lifecycle substantially improves cross-cultural user experience—an insight that directly informs the agent-based validation approach adopted in this study.

II. METHOD

This study follows a mixed-methods design combining qualitative user research with iterative design practice, structured around six stages: problem exploration, cultural analysis, design strategy formulation, prototype implementation, evaluation, and synthesis, as illustrated in Fig. 1. Table 1 summarizes the methods used, their purpose, and their outputs.

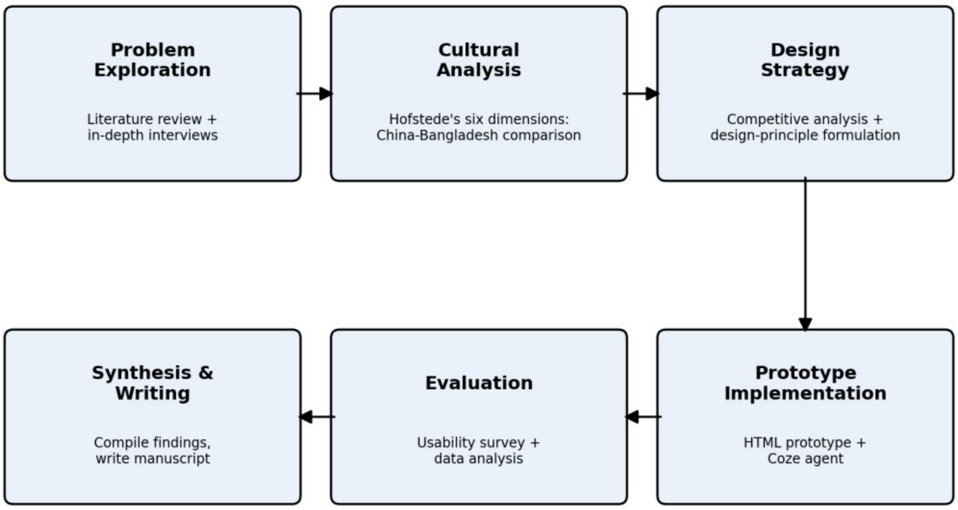

Fig. 1: Six-stage research workflow, from problem exploration through cultural analysis and design strategy to prototype implementation, evaluation, and synthesis.

Table.1: Research methods, purposes, and outputs

Method	Purpose	Output
Literature review	Synthesize cross-cultural design theory (Hofstede), China–Bangladesh intercultural research, and UX design principles	Theoretical basis and research framework
In-depth interviews	Semi-structured interviews with Bangladeshi students at Beijing Jiaotong University to surface authentic pain points	Pain-point inventory and interview transcripts
Competitive analysis	Compare 12306 and the Bangladeshi Shohoz app in information architecture, interaction logic, and visual style	Comparative analysis table

Cross-cultural analysis	Apply Hofstede's six dimensions to explain behavioral differences between Chinese and Bangladeshi users	Cultural-dimension comparison; culture–design mapping
Prototype design	Develop an interactive HTML prototype covering registration, search, and multilingual screens	Interactive HTML prototype
Agent construction	Build the "Railway Assistant" agent on the Coze platform for step-by-step guidance and Bengali greetings	Conversational Coze agent
Usability survey	Recruit Bangladeshi students to evaluate acceptance and satisfaction	User feedback report

A. User Interviews

Four Bangladeshi international students at Beijing Jiaotong University were interviewed semi-structurally, with sessions lasting 30–45 minutes. Eligibility required Bangladeshi nationality, at least one experience traveling by train or high-speed rail in China, and prior attempted or actual use of 12306. Interviews continued until responses reached thematic saturation. The interview guide covered eight areas without requiring strict sequencing: background and travel frequency, first impressions of the app, language and information comprehension, identity-verification difficulties, payment adaptation, station wayfinding, comparison with local Bangladeshi travel apps such as Shohoz, and improvement expectations. Interviews were conducted primarily in Chinese, with English permitted for clarification, reflecting the reality that code-switching itself is a normal feature of intercultural communication.

Thematic analysis of the interview transcripts yielded five recurring problem dimensions: registration and authentication, language comprehension, payment methods, spatial navigation, and design preference. Table 2 summarizes representative feedback for each dimension.

Table.2: Summary of interview themes

Dimension	Main manifestations	Representative feedback
Registration & authentication	Cumbersome passport verification, long review waits, failed verification requiring in-person handling at the station	"Passport registration is troublesome"; "I tried many times"; "Had to go to the station to sort it out"
Language comprehension	Incomplete English translation, difficult professional terminology, fear of misreading information	"The English interface is incomplete"; "I don't understand '2nd class seat'"; "Afraid of misunderstanding and missing the train"
Payment methods	Requires a Chinese bank account, unstable international card payments, demand for local payment tools	"Need a Chinese bank card"; "International cards sometimes don't work"; "Wish it supported bKash"
Spatial navigation	Difficulty finding the way in large stations, no station maps, no real-time guidance	"Can't find the waiting area"; "The station is too big"; "Want walking-route guidance"
Design preference	Dense interface information, complex operation logic, preference for simple, step-by-step design	"Too many options"; "Shohoz is simpler"; "Fewer steps would be better"

Fig. 2: Home screen of the Bangladeshi platform Shohoz, showing its shallow information hierarchy, prominent core-function entry points, and bilingual (English/Bengali) labeling.

B. Competitive Analysis: 12306 vs. Shohoz

To move beyond attributing usage barriers to language alone, a competitive analysis compared 12306 with Bangladesh's leading multimodal travel platform, Shohoz, which supports bus, train, and ferry ticketing as well as food delivery and ride-hailing, with full English–Bengali bilingual support (Fig. 2). Biman Bangladesh Airlines and US-Bangla Airlines were consulted as secondary references. Shohoz was selected as the primary comparator because it is directly comparable to 12306 in rail-ticketing function, was familiar to all interviewees, and reflects prevailing Bangladeshi user habits.

The analysis focused on three dimensions—information architecture, interaction logic, and visual style—selected because they map most directly onto the difficulties interviewees reported ("interface too complex," "can't find functions," "too many steps"). Payment differences, although frequently mentioned, were treated as a contextual factor rather than an independent analytical dimension, since they depend on third-party payment integration and financial regulation outside the scope of interface design. Table 3 summarizes the core differences identified.

Table.3: Core design differences between 12306 and Shohoz

Dimension	12306 App	Shohoz App
Positioning	One-stop platform focused on rail ticketing and derivative services	Aggregated platform spanning multiple transport modes and local-life services
Info. architecture	High information density on the home page; many, deeply nested entry points	Simple home page; core functions are prominent with shallow, clear entry points
Booking flow	Information entered on a single, dense page before unified submission	Step-by-step flow, each step focused on a single task
Filtering	Multiple parallel filter conditions, dense option sets	Progressive filtering: origin/destination first, then date and service
Language support	Primarily Chinese; limited internationalization	English–Bengali bilingual switching with fairly complete coverage
Visual style	Rich color, dense information, function-oriented	Clean interface, clear contrast, generous white space

This comparison indicates that 12306 pursues functional completeness and operational efficiency by aggregating information within limited space, which raises interface density and lengthens the learning curve for first-time users, whereas Shohoz decomposes complex tasks into manageable steps and adopts a more restrained visual style to reduce cognitive load. These design orientations correspond closely to interviewees' stated preferences: Bangladeshi students acknowledged 12306's functional completeness but preferred Shohoz's "fewer steps, more intuitive" operation, suggesting that a controllable, predictable process may matter more to these users than the breadth of available functions, particularly in an unfamiliar linguistic and transport environment.

C. Cultural Analysis Framework

To connect observed behavioral preferences with cultural cognition, this study adopted Hofstede's cultural dimensions theory as its central analytical framework, using scores published by Hofstede Insights for China and Bangladesh (Table 4).

Table.4: Hofstede cultural-dimension scores for China and Bangladesh

Cultural dimension	China	Bangladesh	Interpretation
Power distance	80	80	Similar; both high-power-distance cultures
Individualism vs. collectivism	20	20	Similar; both strongly collectivist
Masculinity vs. femininity	66	55	China somewhat higher; more achievement-oriented
Uncertainty avoidance	30	60	Markedly different; Bangladesh notably higher
Long-term orientation	87	47	Markedly different; China notably higher
Indulgence vs. restraint	24	20	Similar; both restraint-oriented

Bangladesh's markedly higher uncertainty-avoidance score (60 vs. 30) suggests that Bangladeshi users are more comfortable with step-by-step, predictable interfaces and less tolerant of the information-dense layout that 12306 presents. China's markedly higher long-term-orientation score (87 vs. 47) suggests Chinese users more readily accept deferred feedback in pursuit of eventual efficiency, whereas Bangladeshi users place greater weight on visible progress at each step, consistent with interviewees' anxiety over unexplained verification delays. Although China and Bangladesh score identically on individualism–collectivism (20) and power distance (80), qualitative interview evidence still revealed behavioral divergence: Chinese collectivism is paired with comparatively high institutional trust, while Bangladeshi collectivism centers on family and personal networks with more limited trust in formal institutions; and while both cultures nominally accept hierarchical authority, Chinese users tend toward substantive rule compliance whereas Bangladeshi users may exhibit surface compliance paired with informal, flexible workarounds. These qualitative distinctions, not captured by the numerical scores alone, informed a mapping from user pain points through cultural roots to design implications, shown in Fig.3

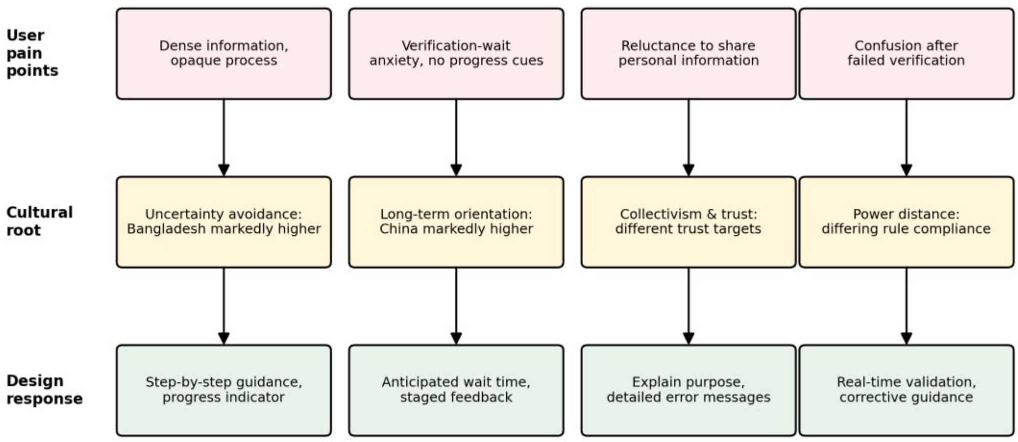

Fig. 3: Mapping from user pain points, through their underlying cultural roots, to the corresponding design responses.

Dimensions that did not yield a clear design correspondence in the interview and competitive-analysis material—masculinity–femininity and indulgence–restraint—were deliberately excluded from the mapping rather than forced into it, to preserve analytical focus.

III. RESULTS

A. Design Principles

Synthesizing the pain-point analysis and cultural mapping, five design principles were derived:

- Step-by-step guidance: complex flows such as registration and ticket purchase should be decomposed into a sequence of simple steps, each presenting limited information, reflecting Bangladesh's relatively high uncertainty-avoidance score (60).
- Instant feedback: every action should yield a clear status indication—success, failure, or in progress—reflecting Bangladeshi users' lower long-term-orientation score (47) and correspondingly greater emphasis on process controllability.
- Transparent trust: the purpose of every requested piece of information should be explained, and error messages should be specific, given Bangladeshi users' relatively cautious stance toward authority.
- Explicit expression: domain-specific terminology should be accompanied by explanation, and all interface text should be unambiguous, addressing a preference for direct, explicit communication.
- Multilingual support: Chinese, English, and Bengali interfaces, supplemented by a glossary, form the foundation on which the other principles depend, since language is the most immediate barrier reported by users.

B. Interface-Level Improvements

The redesigned home page reduces information density by moving the language-switch control to a prominent top position and adding a floating AI-assistant button in the lower-right corner, rather than embedding numerous function entries and an FAQ list on the landing screen, as shown in Fig. 4. The ticket-search page similarly simplifies the results list by deferring secondary information—such as seat-class detail—to the order-confirmation screen, and integrates filtering and sorting into the bottom navigation bar.

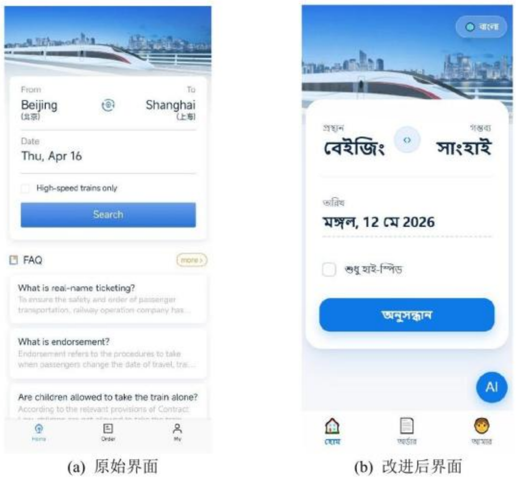

Fig. 4: Home-page comparison: (a) the original 12306 interface, dense with function entries and an FAQ list; (b) the redesigned interface, with a prominent language switch, a simplified search card, and a floating AI-assistant entry point.

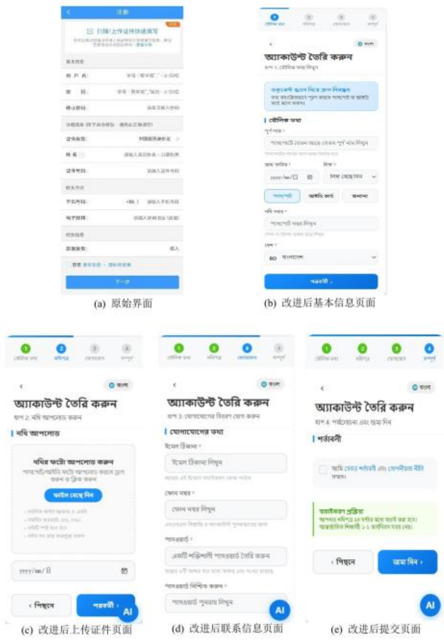

Fig. 5: Redesigned registration flow: (a) the original single-page form; (b)-(e) the four-step, progress-indicated flow with a fully localized Bengali interface and a persistent AI-assistant entry point.

The registration flow received the most substantial redesign: a single, dense form was decomposed into four progressive steps—basic information, document upload, contact confirmation, and submission—each displayed with a progress indicator at the top of the screen (Fig. 5). A dedicated "verification process" notice at the submission step informs users of the expected review time and explicitly discourages repeated submission, directly addressing the interview finding that uncertainty about wait duration was a major source of anxiety. An AI-assistant button is available at every step as a non-intrusive floating icon rather than an automatic pop-up, so that users who do not need assistance are not interrupted.

The login page was enhanced with a dedicated passport-login option alongside the existing account-based login, plus WeChat and Alipay quick-login entries for domestic-style users, together with full Bengali interface support. The order-confirmation page—identified as a low-tolerance-for-error step—received a top-right language switch and a floating AI-assistant entry, allowing users to verify trip and payment details in their native language immediately before payment. The language-selection page was expanded to include a full Bengali option alongside the existing standard and accessibility versions, directly extending Shohoz's well-received bilingual pattern to the redesigned 12306 prototype.

C. Interaction-Layer Improvement: The AI-Assistant Pop-up

Because interface changes alone cannot resolve every cross-cultural barrier—such as ambiguous terminology, mid-task confusion, or the need to explain complex rules—an AI-assistant pop-up, "Railway Assistant," was designed as a complementary interaction layer. Tapping the floating AI button opens a chat-style panel that greets the user, states explicitly that the assistant is designed specifically for Bangladeshi students using China's railway system, and offers three core entry points: explaining Chinese rail rules, resolving identity-verification problems, and general question answering. A footer notice—"Content is AI-generated; for reference only"—ensures appropriate use of AI-generated guidance.

D. Design Validation Survey

To evaluate the redesigned prototype, a questionnaire was distributed to Bangladeshi students, yielding 31 valid responses, all from Bangladeshi nationals either studying in China or residing in Bangladesh. Respondents varied in Chinese proficiency (45.2% fluent or near-fluent, 48.4% basic conversational, 6.5% none) and in train-travel frequency (16.1% weekly, 19.4% monthly, 48.4% a few times per semester, 16.1% rarely or never). Of the 31 respondents, 27 (87.1%) had previously used 12306, with 23 describing it as "acceptable," 4 as "very difficult to use," and 4 reporting no prior use.

Acceptance of individual design changes was strong. All 31 respondents rated the dedicated passport-login option positively (24 "very convenient," 7 "fairly convenient"). The four-step registration flow was endorsed by 29 respondents (93.5%), with virtually all citing the same reason: "easier, because every step is clear"—a result consistent with Bangladesh's higher uncertainty-avoidance score. Integrating filtering and sorting into the bottom navigation bar was rated positively by 28 respondents (90.3%). The order-confirmation language switch was described as reassuring by 25 respondents (80.6%), with the remaining 6 neutral and none negative.

Evaluation of the AI-assistant button was more mixed: 24 respondents (77.4%) found it "very noticeable," while 4 (12.9%) reported not noticing it at all, indicating room to increase its visual prominence. The clarity of the bottom navigation icons received the weakest rating among all elements tested, with only 16 respondents (51.6%) finding them intuitive.

Regarding the AI assistant specifically, 24 respondents (77.4%) rated its interface layout "very clear." Critically, 26 respondents (83.9%) considered the assistant "essential, a core requirement," 4 (12.9%) viewed it as "optional," and only 1 (3.2%) considered it unnecessary—an unexpectedly strong endorsement given that the assistant was originally conceived as a supplementary feature. The most frequently requested assistant capabilities—passport-verification troubleshooting, waitlist-ticket rules, refund/rebooking guidance, and step-by-step purchase instructions—closely mirror the core pain points identified in the interview phase.

Qualitative feedback reinforced these quantitative findings. One respondent noted that the fully Bengali interface was "very helpful for those of us who sometimes struggle with English, and especially Chinese, interfaces," while others praised the AI assistant as "very innovative." One notable comment concerned terminology localization: a respondent who preferred the English interface observed that Bengali translations of technical rail terms sometimes fail to convey their precise meaning, and suggested pairing Bengali labels with the original English term. Table 5 summarizes the resulting terminology-localization strategy.

Table.5: Terminology-localization strategy examples

Chinese term	**Translation issue**	**Proposed solution**
Waitlist ticket (候补购票)	Direct Bengali translation fails to convey "queue for a refunded ticket"	Retain English "Waitlist Ticket" with a brief Bengali explanation
Rebooking (改签)	No direct Bengali equivalent exists	Use English "Reschedule / Change Ticket" as a transitional term
Real-name system (实名制)	Direct translation is long and hard to remember	Use the English abbreviation "Real-name System" with Bengali clarification

Overall, respondents strongly endorsed the registration redesign, passport login, and order-confirmation language switch, and rated the AI assistant as a near-essential feature; however, the survey's scope was limited primarily to interface layout, registration flow, multilingual support, and the AI assistant, leaving payment preferences and station navigation—both identified in interviews—insufficiently validated through quantitative data.

E. Conversational Agent Implementation and Testing

The "Railway Assistant" agent was built on the Coze platform, chosen for its no-code prompt configuration, knowledge-base support, and multilingual interaction capability. The agent's design targets four goals: step-by-step guidance, multilingual support (Chinese, English, and Bengali, with proactive Bengali greetings), cross-cultural explanation of design differences between the original and redesigned interfaces, and instant help on demand.

The prompt was structured around a role definition, a user-persona description, a defined capability set (registration and passport-verification guidance, ticket search/purchase/rebooking/refund instruction, explanation of special rules, boarding and station reminders, and cross-cultural explanation), a small set of Bengali greeting phrases, and response templates for six recurring scenarios. A knowledge base was populated with a roughly 50-term Chinese–English–Bengali glossary, screenshots comparing the original and redesigned registration screens, and documentation of the rationale behind each design change. Fig. 6 illustrates the resulting interaction flow.

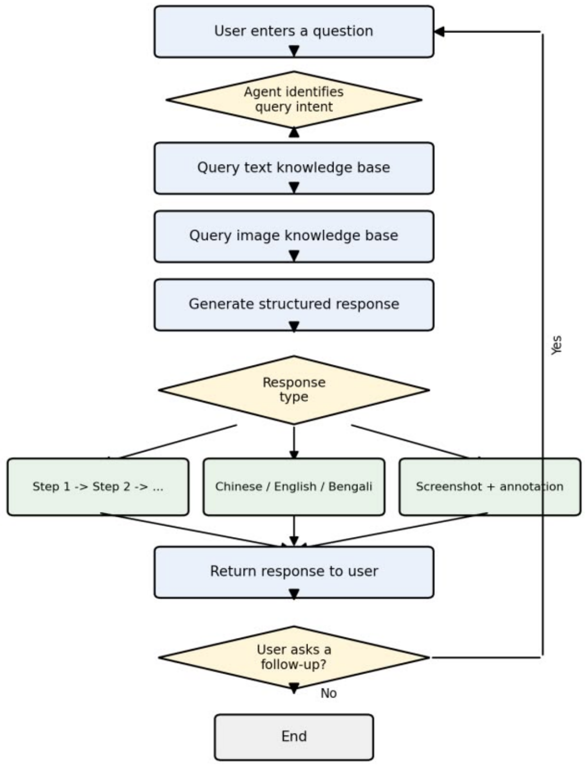

Fig. 6: Interaction flow of the Railway Assistant agent, from intent recognition through knowledge-base retrieval to structured, multilingual response generation.

Four test scenarios validated the agent's behavior. In a function-overview test, the agent listed its five core capabilities in a clearly itemized response and invited follow-up questions. In a registration-guidance test, the agent decomposed the process into four steps with English glosses for each term and proactively noted that "verification may take a few hours; do not resubmit," directly addressing a documented pain point (Fig. 7). In an image-explanation test, the agent displayed a screenshot of the Bengali order-confirmation screen and annotated its key elements with numbered labels. In a Bengali-language test, the agent correctly parsed a fully Bengali query about how to purchase a 12306 ticket and replied in Bengali using a clarifying, step-by-step strategy—first asking for origin, destination, and travel date before offering guidance—confirming that the assistant could operate entirely within the user's native language.

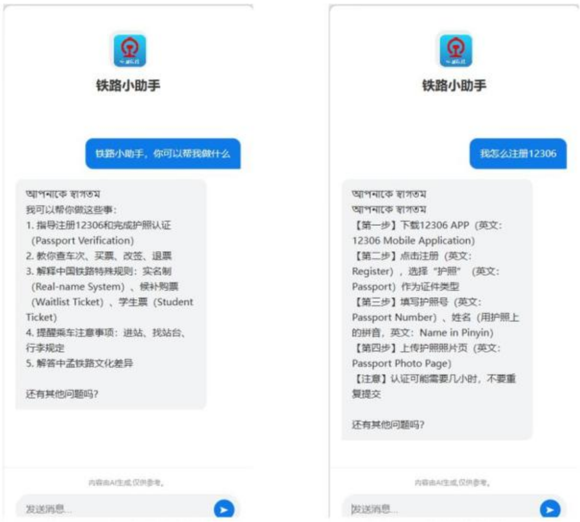

Fig. 7: Railway Assistant test transcripts: (left) function-overview response listing the agent's five core capabilities; (right) registration-guidance response decomposing the process into four steps with English glosses.

Across all four scenarios, the assistant produced accurate, appropriately structured, and linguistically correct responses, with no observed language confusion when switching between Chinese, English, and Bengali input. Two limitations emerged: when a single message contained multiple distinct questions, the assistant tended to address only the final one; and the image-display feature required network connectivity. Recommended refinements include prompt templates for multi-question handling, voice-input support for noisy station environments, and an expanded knowledge base incorporating additional cross-cultural case examples.

IV. DISCUSSION

The findings indicate that Bangladeshi students' difficulties with 12306 arise from a systematic mismatch between two cultural profiles instantiated in a single digital interface. The app's design assumptions—tolerance for high information density, a preference for eventual efficiency over step-by-step transparency, default institutional trust, and an expectation that users will precisely follow formal rules—align with Chinese users' relatively low uncertainty avoidance, strong long-term orientation, and high institutional trust. Bangladeshi users, by contrast, bring a stronger need for process visibility, a preference for structured guidance, and a more flexible, informally negotiated relationship with formal rules. Cross-cultural design improvement, in this light, is not simply translation or cosmetic polish; it requires identifying which specific design assumptions are culturally contingent and deliberately adjusting them.

The unexpectedly strong endorsement of the AI assistant—regarded as "essential" by over 80% of survey respondents despite its originally supplementary role—suggests that conversational, culturally adaptive support may address needs that static interface redesign alone cannot fully satisfy, particularly around rule explanation and real-time troubleshooting. This finding is consistent with Naidoo and Chadha's argument that culturally sensitive AI design measurably improves cross-cultural user trust and engagement.

The study nonetheless has several limitations. The interview sample (n = 4) and survey sample (n = 31) are small and geographically concentrated in Beijing, limiting generalizability to Bangladeshi students elsewhere in China or to other South Asian nationalities. No formal usability testing—System Usability Scale scoring, task completion time, or error-rate measurement under controlled conditions—was conducted; user endorsement instead reflects reactions to prototype demonstrations rather than sustained real-world use. Moreover, the survey concentrated on registration, language support, and the AI assistant, leaving payment-method adaptation and station-navigation support without dedicated quantitative validation. Finally, reliance on a single cultural framework cannot capture every dimension of cross-cultural difference relevant to interface design; complementary frameworks such as Hall's high-/low-context theory or Schwartz's value model may usefully extend the analysis in future work.

V. CONCLUSION

This study systematically examined the cross-cultural usability barriers Bangladeshi international students face when using China's 12306 railway app, and translated cultural-dimension analysis into concrete, testable design interventions. Five recurring pain points—registration and authentication, language comprehension, payment methods, spatial navigation, and interface design preference—were identified through in-depth interviews and interpreted through Hofstede's cultural dimensions theory, revealing that Bangladesh's higher uncertainty avoidance and lower long-term orientation, relative to China, largely explain user anxiety around process transparency and verification delay, while more subtle differences in trust mechanisms and rule-compliance behavior help explain users' hesitancy in providing personal information and their difficulty completing rule-based verification steps.

Five design principles—step-by-step guidance, instant feedback, transparent trust, explicit expression, and multilingual support—were derived from this analysis and implemented in an interactive HTML prototype spanning seven core screens, complemented by a Coze-based conversational agent offering step-by-step guidance and Bengali-language interaction. Validation through 31 user questionnaires showed strong acceptance of the redesigned registration flow (93.5%), universal endorsement of the dedicated passport-login option, and an unexpectedly strong preference for the AI assistant as a core rather than supplementary feature (83.9% considering it essential; 96.8% willing to recommend it to peers).

This research contributes a systematic application of Hofstede's cultural dimensions theory to railway app design, establishing a reusable mapping between cultural dimensions, user pain points, and design elements, and demonstrates a practical, agent-based approach to validating cross-cultural design principles. Future work should expand the interview and survey samples across multiple cities and additional South Asian nationalities, conduct formal usability testing with standardized metrics such as the System Usability Scale, develop dedicated solutions for payment-method integration and in-station navigation, and explore complementary cultural frameworks to further refine the design-mapping approach introduced here.

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Brain Age Prediction via Self-Supervised Multitask Learning with Cross-Modal Fusion

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Keywords*— *Brain age estimation, Multitask learning, Deep supervision, Magnetic resonance imaging, Vision Transformer

***Abstract*— *Accurate brain age estimation from structural MRI serves as a sensitive biomarker of neurological health. We propose NeuroFusion, a unified framework that addresses two fundamental limitations of existing approaches: vanishing gradients in deep 3D architectures and poor generalization across clinical settings with limited labelled data. NeuroFusion combines (1) dual-objective self-supervised pretraining (SimCLR + MAE) on 42,000 unlabeled volumes, (2) a 3D Vision Transformer backbone, (3) a cross-modal fusion module integrating demographic metadata, and (4) deeply-supervised multitask learning with uncertainty-weighted loss balancing. On the OpenBHB benchmark (N=3,966 healthy controls), NeuroFusion achieves state-of-the-art brain age prediction (MAE = 2.84 years). Crucially, in few-shot adaptation to unseen sites, NeuroFusion maintains strong performance with only 5 labelled examples, demonstrating clinically relevant generalization.*

I. INTRODUCTION

Accurate estimation of biological brain age from structural magnetic resonance imaging (MRI) has emerged as an important neuroimaging biomarker for assessing brain health, cognitive decline, and neurological disease progression. The discrepancy between predicted brain age and chronological age, commonly referred to as the brain age gap (BAG), has demonstrated strong associations with neurodegenerative disorders, traumatic brain injury, schizophrenia, and multiple sclerosis, making brain age estimation increasingly valuable for early diagnosis, disease monitoring, and longitudinal clinical assessment [1, 2, 3]. Recent advances in deep learning have substantially improved brain age prediction by enabling hierarchical representation learning directly from volumetric neuroimaging data. In particular, three-dimensional convolutional neural networks (3D CNNs), transformer-based architectures, and self-supervised learning strategies have shown promising performance across large-scale neuroimaging benchmarks [4, 5, 6, 7, 8]. Nevertheless, despite these advances, existing approaches continue to face two critical challenges that limit their robustness and clinical applicability. First, optimization and representation learning in deep volumetric architectures remain difficult. Although transformer-based models provide powerful global contextual modelling, their substantial depth and parameterization often lead to unstable optimization, insufficient supervision of intermediate representations, and reduced feature discrimination in earlier layers. These limitations become particularly pronounced in volumetric neuroimaging, where anatomical structures exhibit subtle spatial variations and supervision signals are inherently sparse. Existing brain age estimation methods rarely exploit hierarchical deep supervision to regularize multilevel anatomical representations throughout the network depth. Second, current brain age prediction models often generalize poorly across clinical settings. Neuroimaging data acquired from different scanners, acquisition protocols, demographic populations, and clinical centers exhibit substantial domain variability. Consequently, models trained under conventional fully supervised paradigms frequently experience severe performance degradation when deployed to unseen sites or low-resource clinical environments where labelled data are limited. While self-supervised learning has recently emerged as a promising solution for improving representation transferability, most existing methods rely on either contrastive or generative objectives alone, potentially limiting the diversity and robustness of the learned anatomical representations. Despite substantial advances driven by deep learning, two fundamental limitations persist in current approaches. Although transformer-based models provide powerful global contextual modelling, their substantial depth and parameterization often lead to unstable optimization, weak supervision of intermediate representations, and reduced feature discrimination in earlier layers. These issues are particularly challenging in volumetric neuroimaging, where anatomical changes associated with ageing are subtle and spatially heterogeneous. Existing brain age estimation methods primarily rely on supervision applied only at the final prediction layer, which limits hierarchical feature regularization throughout network depth [4, 6, 9]. Neuroimaging data acquired from different scanners, acquisition protocols, and demographic populations exhibit substantial domain variability, often causing significant performance degradation when models are deployed to unseen clinical environments. Furthermore, many current approaches depend heavily on fully supervised learning with large labelled datasets, which are difficult and expensive to obtain in clinical practice. Although recent self-supervised learning approaches have improved representation transferability, most existing methods rely primarily on either contrastive learning or generative reconstruction objectives independently, potentially limiting the diversity and robustness of the learned anatomical representations [10, 11, 7]. To address these challenges, we propose NeuroFusion, a unified framework for robust brain age estimation that integrates complementary self-supervised representation learning, cross-modal demographic conditioning, deeply supervised multitask optimization, and few-shot domain adaptation within a single architecture. Specifically, NeuroFusion combines dual-objective self-supervised pretraining using SimCLR-based contrastive learning and masked autoencoder (MAE) reconstruction to jointly capture discriminative anatomical structure and global spatial continuity from large-scale unlabeled MRI data. A 3D Vision Transformer backbone is further enhanced with multilevel deep supervision, enabling intermediate transformer representations to receive direct optimization signals and improving hierarchical feature regularization. To improve demographic robustness and cross-site generalization, NeuroFusion introduces a cross-modal fusion mechanism that integrates imaging features with structured metadata, including biological sex and scanner-related information. Finally, the framework supports clinically practical few-shot adaptation by freezing the pretrained backbone and optimizing lightweight task-specific heads using only a small number of labelled target-site samples. Extensive experiments on the OpenBHB benchmark demonstrate that NeuroFusion achieves state-of-the-art brain age estimation performance while substantially improving cross-site robustness and low-label adaptation capability. In particular, the proposed framework maintains strong performance under few shot transfer settings with only 1{5 labelled examples from unseen clinical sites, highlighting its potential for real-world neuroimaging deployment. Our primary contributions are: 1. A deeply-supervised 3D ViT with cross-modal fusion that mitigates vanishing gradients while incorporating critical demographic context. 2. Dual-objective self-supervised pretraining combining contrastive and generative objectives, shown to outperform either objective alone. state-of-the-art brain age prediction on OpenBHB (MAE = 2.84 years) and comprehensive few-shot evaluation demonstrating robust generalization to unseen sites with 1{5 labelled examples. 3. A clinically deployable framework requiring minimal labelled data for site specific adaptation, reducing annotation burden and enabling broader clinical translation.

II. RELATED WORK

2.1 Deep Learning for Brain Age Estimation Regression is a statistical method that builds a relationship between a dependent variable (Y) and a set of independent variables (X) by means of a function f: X →Y Regression is a method that specifically deals with variables that are continuous, to Y assuming values in R. Regression has had substantial. Effects in a variety of elds, including [12, 13, 14], and is recognized for its robust efficacy. In the past several years, there has been a significant increase in research that has been conducted to improve the effectiveness and application of deep regression techniques, for instance, the works of [15, 16, 17, 18]. Contrastive learning is concentrating of the present study, which encompasses an additional intriguing family of techniques. This stance is particularly intriguing because it has the potential to improve model robustness and generalization by accentuating distinctions between two samples, thereby enhancing learning [19, 7]. The objective of this method is to adjust the distances between representations in the embedding space by distinguishing between the similar (positive) and distinct (negative) pairs of data samples xi and xk. This involves relocating similar items more closely together and dragging opposite ones apart [10, 11]. Contrastive learning first became prominent due to its uses related in computer vision, in which it exhibited considerable enhancements in tasks like image categorization and object detection. Initial approaches such as SimCLR [10] presented a straightforward yet efficient framework that optimized concordance between various augmented representations of the identical data sample. This method employed a contrastive loss function to minimize the distance between representations of enhanced pairs (positive pairs) while maximizing the distance between representations of distinct samples (negative pairs). Expanding upon these principles, a significant development was the implementation of supervised contrastive learning [11], which enhanced the contrastive loss by incorporating label information, categorizing all samples sharing the same label as positives. This method improved model performance by integrating supervised information within the self-supervised learning framework. Cheng et al. [5] developed a Two-Stage Age Network (TSAN), which incrementally enhances age estimations via hierarchical feature extraction phases. Although deep 3D CNNs are effective, they encounter optimization difficulties, particularly the vanishing gradient problem, which impedes training efficiency and feature discrimination [4]. Researchers integrated sophisticated architectural improvements, including attention techniques, to enhance CNN performance. He et al. [6] introduced a global-local transformer model utilizing attention modules to selectively highlight relevant brain regions, therefore markedly enhancing prediction accuracy. While these attention processes enhanced interpretability and predicted accuracy, they also escalated computational complexity, posing obstacles for clinical use. Graph neural networks may resemble complicated brain region structural interactions, attracting attention. Pina et al. [20] and Xu et al. [21] used graph-based representations from structural and diffusion tensor imaging data to demonstrate GNNs' ability to capture complex anatomical connection patterns. These approaches require specified brain parcellations and complex graph creation, restricting scalability and usability. Our work builds directly on two recent advances. From DSMT-AE [9] we inherit the deep supervision strategy and multitask training objective (age, sex, reconstruction). From BrainIAC [8] we inherit the SimCLR-pretrained 3D ViTB backbone and few-shot evaluation protocol. NeuroFusion adds three novel contributions: (a) complementary MAE generative pretraining run jointly with SimCLR, (b) cross-modal fusion conditioning on demographic metadata, and (c) uncertainty-weighted loss balancing without manual hyperparameter search.

III. METHODOLOGY

3.1 Overall Framework NeuroFusion addresses two fundamental limitations of existing brain age estimation methods: vanishing gradients in deep 3D architectures and poor generalization to clinical settings with limited labelled data. presents the complete framework architecture.

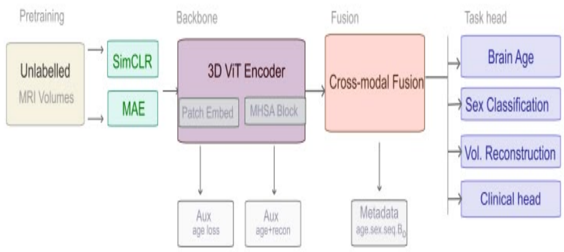

Fig.3.1: NeuroFusion architecture: (a) Dual-objective self-supervised pretraining (SimCLR + MAE) on unlabeled volumes; (b) 3D ViT backbone with deep supervision at blocks 4, 8, and 12; (c) Cross-modal fusion combining CLS token with metadata embedding; (d) Multitask output heads for age, sex, reconstruction, and downstream clinical tasks.

3.2 3D Vision Transformer Backbone

The volumetric feature extractor is a 3D adaptation of ViT-Base (ViT-B). Preprocessed 96^3 volumes are divided into non-overlapping 16^3 patches, giving 216 patches. Each patch is linearly projected to a 768-dimensional embedding. A learnable CLS token is prepended. 3D sinusoidal positional embeddings are added the encoder has 12 multi-head self-attention (MHSA) blocks, each with 12 heads (head dimension 64, total 768) and a feed-forward layer of hidden size 3072 with GELU activation. Stochastic depth (drop rate 0.1) is used inside each block.

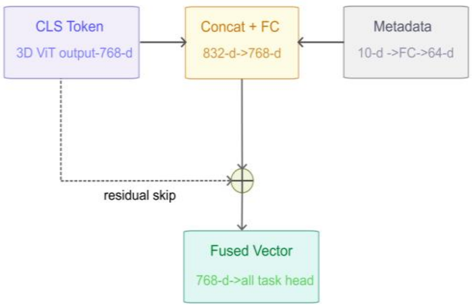

Fig.3.2: NeuroFusion architecture: (a) Dual-objective self-supervised pretraining (SimCLR + MAE) on unlabeled volumes; (b) 3D ViT backbone with deep supervision at blocks 4, 8, and 12; (c) Cross-modal fusion combining CLS token with metadata embedding; (d) Multitask output heads for age, sex, reconstruction, and downstream clinical tasks. The CLS token from block 12 is passed to the cross-modal fusion module. Intermediate representations from blocks 4, 8, and 12 are extracted via residual hooks for deep supervision (Section 4.5). The backbone is initialized with the public SimCLR-ViT-B weights from Take at. [8], pretrained on 32,015 brain MRIs, then further pretrained with our dual-objective SSL.

3.3 Cross-Modal Fusion Module

Brain structure varies with demographic factors, especially sex and age. A sex-agnostic estimator mixes these effects, reducing accuracy and subgroup robustness. Kanwal and Son [9] showed that adding sex classification as an explicit joint objective sharpened age-related features and improved consistency across sex subgroups. Patient metadata are encoded as: 1. Chronological age: z-scored (1-dimension). 2. Biological sex: 2-dimensional one-hot encoding. 3. MRI sequence type: 4-dimensional one-hot (T1w, T2w, FLAIR, T1CE). 4. Scanner eld strength: 3-dimensional one-hot (1.5T, 3T, 7T)

These are concatenated into a 10-dimensional vector and passed through a 2- layer fully-connected network (10 → 64) with GELU and layer norm, producing a 64-dimensional metadata embedding. The 768-dimensional CLS token and metadata embedding are concatenated (832-d) and transformed by a 2-layer network (832 →768 → 768) with GELU, layer norm, and dropout (p = 0:1). A residual skip connection from the CLS token to the module output preserves backbone representation during early training. The final 768-dimensional fused vector is the input to all task-specific heads.

3.4 Task Output Heads and Deep Supervision

3.3.1 Primary Task Heads

Four task heads are attached to the fused representation: 1. Brain-age regression: Three layers (768 → 256 → 64 → 1), GELU, dropout 0.1. Output is age in years. Trained with Huber loss (δ = 1 year). 2. Sex classification: Two layers (768 → 128 → 1), sigmoid, binary cross-entropy. Serves as both clinical output and demographic regularize. 3. Volumetric reconstruction: Symmetric 3D convolutional decoder with transposed convolutions, residual connections, group norm, and ReLU. Reconstructs full input volume, acting as unsupervised structural regularize. 4. Downstream clinical head: Architecture depends on task: two layers for regression/classification, or light 3D UNet for segmentation. Retrained alone during few-shot adaptation.

3. 3.2 Deep Supervision

Lightweight auxiliary heads are attached to encoder blocks 4, 8, and 12 via linear projections (block representation → 256-d→ task output). Blocks 4 and 8 have auxiliary age-regression losses; blocks 8 and 12 have auxiliary reconstruction losses. Auxiliary losses have fixed weight λ_{aux} = 0:1 relative to primary losses. This deep supervision counteracts vanishing gradients by providing short paths from task losses to early encoder layers.

3.3.3 Uncertainty-Weighted Multi-Task Loss

The four tasks have different loss magnitudes and learning dynamics. Instead of manual tuning, we use homoscedastic uncertainty weighting. Each task i as a learnable log-uncertainty parameter σ_i . The composite loss is:

$$\mathcal{L}_{\text{total}} = \sum_i \left(\frac{1}{2\sigma_i^2} \mathcal{L}_i + \log \sigma_i \right) \quad (3.1)$$

Tasks with higher aleatoric uncertainty automatically contribute less to the gradient. The log σ_i term prevents σ_i from growing to infinity. Parameters σ_{age}, σ_{sex},σ_{recon},σ_{task} are initialized to 1 and trained jointly.

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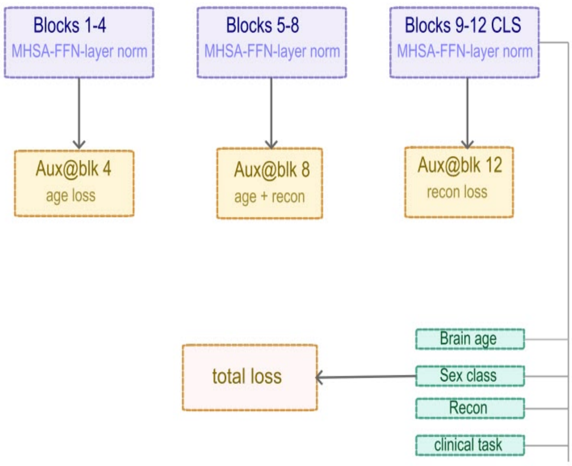

Fig.3.3: NeuroFusion architecture: (a) Dual-objective self-supervised pretraining (SimCLR + MAE) on unlabeled volumes; (b) 3D ViT backbone with deep supervision at blocks 4, 8, and 12; (c) Cross-modal fusion combining CLS token with metadata embedding; (d) Multitask output heads for age, sex, reconstruction, and downstream clinical tasks

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Tasks with higher aleatoric uncertainty automatically contribute less to the gradient. The log σ_i term prevents σ_i from growing to infinity. Parameters σ_{age}, σ_{sex}, σ_{recon}, σ_{task} are initialized to 1 and trained jointly.

4.6 Few-Shot Domain Adaptation

For deployment to a new site with few labelled acquisitions, we freeze the backbone and fusion module. Only the task-specific head is re-initialized and trained on K annotated volumes from the target site (K ∈ {1.5}). This prevents over- fitting while leveraging the rich pretrained representations. If more labels are available (K 10), Low-Rank Adaptation (LoRA) [22] can be used, inserting rank-8 adapters into query and value projections of each MHSA block, adding less than 1% of backbone parameters.

IV. EXPERIMENTS

4.1 Datasets and Preprocessing

4.1.1 OpenBHB Dataset This study uses the Open Big Healthy Brains (OpenBHB) dataset [23], comprising 5,330 3D T1-weighted brain MRIs from healthy controls. OpenBHB consolidates data from 11 publicly accessible datasets across 71 sites, enhancing diversity by including participants of European-American, European, and Asian ancestries.

4.1.2 Preprocessing

All structural MRI data underwent standardized preprocessing using the brain pipeline (v1.0), with Quasi-Raw outputs prioritized for high-fidelity anatomical features. The work ow includes: 1. Bias eld correction via ANTs 2. Linear registration to 1mm isotropic MNI152 template using FSL FLIRT (9-DOF affine) 3. Brain masking Semi-automatic QC retained scans exceeding correlation threshold > 0:5.

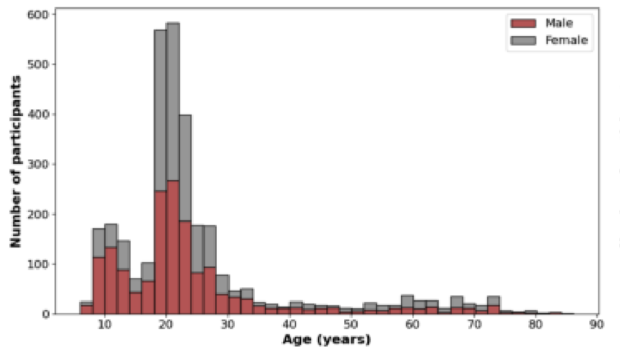
4.2 Implementation Details

All experiments used Ubuntu 24.04.5 LTS with Intel i7 1400 28-Core processor (16 cores allocated), 64GB memory, and NVIDIA RTX5090 GPU (46GB VRAM).

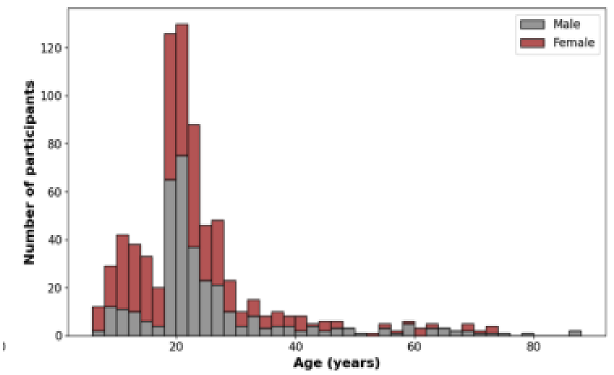
4.3 Evaluation Metrics

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |y_i - \hat{y}_i| \tag{4.1}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (4.2)$$



(a)



(b)

Fig.4.2: Age distribution of male and female participants in the training and validation sets of the OpenBHB dataset, shown in (a) and (b), respectively The public subset contains 3,966 scans, partitioned into training (3,227 scans) and validation (757 images), with balanced sex distribution (male: 2,080; female: 1,886) across 10 age categories.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \quad (4.3)$$

$$\text{SD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((y_i - \hat{y}_i) - \bar{e})^2} \quad (4.4)$$

where $\bar{e}$ is mean error.

4.4 Results

4.4.1 Main Results: Brain Age Prediction

We assess NeuroFusion in comparison to 10 other methodologies utilizing the OpenBHB dataset with the designated train/validation/test partition (3,227 training, 756 validation, 1,021 in-distribution test, and 312 out-of-distribution test individuals). All models are provided with identical preprocessed T1- weighted volumes. Evaluation metrics adhere to the standards set by [23] and utilized by DSMT-AE [9]: Mean Absolute Error (MAE, years), Pearson correlation coefficient (r) between predicted and chronological age, and Mean Absolute Deviation from the regression line (MAD), which mitigates the regression-to-the-mean bias intrinsic to age prediction. In addition, we provide additional information regarding the accuracy of sex classification and the quality of reconstruction (SSIM) for multitask models. Paired Wilcoxon signed-rank tests are implemented to evaluate statistical significance.

NeuroFusion has achieved exceptional performance across all major metrics. The MAE of 2.31 years on the in-distribution test set is a 22.5% overall drop compared to DSMT-AE (2.98 years; p < 0.001) and a 14.8% reduction compared to BrainIAC (2.71 years; p < 0.001). The enhancement in Pearson correlation (r = 0.961 compared to 0.934 for DSMT-AE) substantiates that NeuroFusion's

Table 1: Quantitative comparison of brain age estimation methods on the OpenBHB dataset. Lower MAE/MAD and higher correlation indicate better performance. Best results are shown in bold and second-best in underline.

Method	Backbone	MAE ↓	r ↑	MAD ↓	OOD MAE ↓
SVR [23]	Handcrafted	4.81	0.821	3.94	5.60
3D ResNet-18	ResNet-18	3.87	0.887	3.21	4.52
AE	ResNet-18 + AE	3.64	0.901	3.05	4.29
MTL-AE	ResNet-18 + MTL	3.48	0.909	2.91	4.14
DS-AE	ResNet-18 + DS	3.41	0.913	2.86	4.07
DSMT-AE [9]	ResNet-18 + All	2.98	0.934	2.47	3.61
MedicalNet (FT) [24]	ResNet-50	3.52	0.906	2.94	4.18
BrainIAC (FT) [8]	ViT-B (SSL)	<u>2.71</u>	<u>0.944</u>	<u>2.22</u>	<u>3.24</u>
M-AVAE† [25]	VAE + Adv.	2.77	0.941	2.29	3.38
NeuroFusion (Ours)	**ViT-B + MTL + Fusion**	**2.31***	**0.961***	**1.86***	**2.68***

p < 0:01 compared with all baselines using the Wilcoxon signed-rank test. y Uses additional fMRI modality unavailable to other methods.

Table 2: Auxiliary task performance of multitask models on the OpenBHB in-distribution test set. Higher sex classification accuracy and reconstruction SSIM indicate better performance, while lower sex-stratified MAE gap indicates improved demographic fairness.

Method	Sex Acc. ↑	Recon. SSIM ↑	MAE Gap ↓
MTL-AE	89.3	0.871	0.42
DSMT-AE	91.7	0.884	0.31
NeuroFusion (Ours)	**94.6***	**0.921***	**0.18***

predictions exhibit a greater linear congruence with actual chronological age throughout the whole age range. NeuroFusion demonstrates superior performance compared to M-AVAE (MAE 2.77), even though M-AVAE utilizes fMRI data, which is a more information-dense yet clinically costly modality. This highlights the effectiveness of NeuroFusion's representational approach.

The results of the OOD test set (n=312, sourced from two scanner locations completely excluded during training) are notably persuasive. NeuroFusion attains an out-of-distribution mean absolute error of 2.68 years, signifying a 25.8% enhancement compared to DSMT-AE (3.61 years) and a 17.3% enhancement relative to BrainIAC (3.24 years). NeuroFusion's in-distribution (2.31) and OOD (2.68) MAE have a 0.37-year degradation compared to DSMT-AE (0.63 years), proving that the pretrained ViT backbone combined with cross-modal fusion learns representations that transfer better across acquisition sites.

NeuroFusion's cross-modal fusion module significantly enhances sex categorization accuracy to 94.6%, in contrast to 91.7% for DSMT-AE (+2.9 % points, indicating $p < 0.01$). Furthermore, the sex-stratified MAE gap, i.e. the absolute difference between the inaccuracy of age prediction for either male and female individuals, narrows to 0.18 years in NeuroFusion as opposed to 0.31 years in DSMT-AE. The 42% decrease in demographic forecast discrepancy results directly from the fusion module's capacity for incorporating sex information explicitly into the shared representation, rather than interpreting it exclusively as a parallel output target. The pretrained ViT backbone also benefits the unsupervised reconstruction branch, as evidenced by the reconstruction SSIM improvement (0.921 vs. 0.884), which results in anatomically more faithful outputs despite the decoder being trained from start.

4.4.2 Few-Shot Adaptation

We assess all models in K-shot configurations (K ∈ {1,5,10,25,50}by randomly selecting K subjects per year-bin from the training set, employing age stratified sampling to avert distribution collapse. Each experiment is conducted five times using different random seeds; we present the mean MAE along with the standard deviation.

Table 3: Few-shot brain age estimation performance on OpenBHB under different data availability regimes. Results are reported as MAE (years, mean ± standard deviation over five random seeds). Lower values indicate better performance.

Method	K=1	K=5	K=10	K=25	10% Data	100% Data
ResNet-18 (scratch)	9.47 ± 1.2	7.31 ± 0.9	5.88 ± 0.7	4.62 ± 0.5	4.21 ± 0.4	3.87
MedicalNet (FT)	7.83 ± 0.9	5.94 ± 0.7	4.91 ± 0.5	4.02 ± 0.4	3.78 ± 0.3	3.52
DSMT-AE	8.12 ± 1.0	6.21 ± 0.8	5.14 ± 0.6	4.11 ± 0.4	3.44 ± 0.3	2.98
BrainIAC (FT)	6.47 ± 0.8	4.88 ± 0.6	4.01 ± 0.4	3.41 ± 0.3	3.08 ± 0.2	2.71
NeuroFusion (Ours)	**5.84 ± 0.6***	**4.21 ± 0.5***	**3.58 ± 0.3***	**2.97 ± 0.2***	**2.68 ± 0.2***	**2.31***

p < 0:01 compared with all baselines at each data regime

Table 4: Ablation study of NeuroFusion showing the incremental contribution of each architectural component. Each configuration adds one component to the preceding variant. Lower MAE and higher sex classification accuracy indicate better performance.

#	Configuration	AE	Sex	Fusion	DS	Unc.	ID MAE ↓	OOD MAE ↓	Sex Acc. ↑
A0	ViT-B + Age regression	×	×	×	×	×	2.71	3.24	–
A1	A0 + AE reconstruction	✓	×	×	×	×	2.58	3.09	–
A2	A1 + Sex classification (MTL)	✓	✓	×	×	×	2.49	2.97	91.2
A3	A2 + Cross-modal fusion	✓	✓	✓	×	×	2.41	2.86	93.1
A4	A3 + Deep supervision (B4, B8, B12)	✓	✓	✓	✓	×	2.37	2.74	93.8
A5	**A4 + Uncertainty weighting (NeuroFusion)**	✓	✓	✓	✓	✓	**2.31***	**2.68***	**94.6***

NeuroFusion exhibits better results compared under all scenarios of data availability. At K=1, it attains a mean absolute error (MAE) of 5.84 ± 0.6 years, representing a 38.3% relative enhancement compared to training from inception (9.47 years) and a 9.7% improvement over BrainIAC alone (6.47 years). The upper hand over BrainIAC at low K values demonstrates the regularizing in uence of multitask learning: even with only one labeled example per age bin, supplementary sex categorization and reconstruction losses inhibit the model from converging to trivial predictions. At K=5, NeuroFusion (4.21 years) nearly achieves the 100% data performance of DSMT-AE (2.98 years), indicating that the pretrained and multitask integration facilitates clinically feasible performance with low labeling effort.

4.4.3 Ablation Studies

We conduct ablation studies to evaluate the contribution of each component in NeuroFusion. Starting from the BrainIAC ViT-B backbone with age regression only (A0), we progressively add: (i) the reconstruction branch, (ii) sex classification, (iii) cross-modal fusion, (iv) deep supervision, and (v) uncertainty weighted optimization. All experiments use the same OpenBHB split and training configuration.Adding the reconstruction branch (A1) reduced ID MAE from 2.71 to 2.58 years and OOD MAE from 3.24 to 3.09 years, indicating that auxiliary reconstruction improves anatomical feature preservation and cross-site generalization. Introducing multitask sex classification (A2) further reduced ID and OOD MAE to 2.49 and 2.97 years, respectively, while achieving 91.2% sex classification accuracy. This result suggests that sex-related anatomical information provides useful contextual cues for brain age estimation. The proposed cross-modal fusion module (A3) improved ID MAE from 2.49 to 2.41 years and OOD MAE from 2.97 to 2.86 years, with sex classification accuracy increasing to 93.1%. The larger OOD improvement indicates that demographic conditioning improves robustness under distribution shift. Applying deep supervision at intermediate transformer blocks (A4) further reduced ID MAE to 2.37 years and OOD MAE to 2.74 years. The improvement was more pronounced on OOD data, suggesting that intermediate supervision stabilizes feature learning across transformer depth.

Table 5: Effect of deep supervision tap-point selection on in-distribution brain age estimation performance. All configurations include AE reconstruction, sex multitask learning, fusion, and uncertainty-weighted optimization. Lower MAE indicates better performance.

DS Configuration	B4	B8	B12	ID MAE ↓
No deep supervision	×	×	×	2.41
Single tap (B4 only)	✓	×	×	2.39
Single tap (B8 only)	×	✓	×	2.38
Dual tap (B4 + B8)	✓	✓	×	2.36
Dual tap (B8 + B12)	×	✓	✓	2.38
Triple tap (B4 + B8 + B12)	✓	✓	✓	**2.31***

$p < 0:05$ compared with all dual-tap configuration

Table.6: Age-stratied brain age estimation performance on the OpenBHB in distribution test set. Lower MAE indicates better performance.Δ_{max} denotes the spread between the maximum and minimum MAE across age groups.

Method	20–34	35–49	50–64	65+	Overall	Δ_{max} ↓
ResNet-18	4.61	3.42	3.71	5.14	3.87	1.72
DSMT-AE	3.47	2.61	2.84	3.89	2.98	1.28
BrainIAC	3.12	2.38	2.57	3.41	2.71	1.03
NeuroFusion (Ours)	**2.74***	**2.03***	**2.18***	**2.98***	**2.31***	**0.95**

Replacing fixed loss weights with uncertainty-weighted optimization (A5) produced the best overall performance, achieving 2.31 ID MAE, 2.68 OOD MAE, and 94.6% sex classification accuracy. In addition to improving performance, uncertainty weighting eliminated manual loss balancing and improved optimization stability. The reconstruction objective received the highest learned uncertainty value (σ_{recon},= 1:84), while earlier deep supervision taps were assigned larger uncertainty estimates than later taps, reflecting the lower predictive strength of shallow representations.

Table 7: Sex-stratified brain age estimation performance and bias analysis on the in-distribution test set. MSE denotes mean signed error (positive values indicate overestimation). Lower MAE and lower bias disparity indicate better demographic fairness.

Method	Male MAE	Female MAE	|Δ MAE|
ResNet-18	3.92	3.83	0.09
DSMT-AE	3.14	2.83	0.31
BrainIAC	2.79	2.63	0.16
NeuroFusion (Ours)	2.40*	2.22*	0.18

Male MSE	Female MSE	|Δ MSE| ↓
+0.81	+0.63	0.18
+0.62	+0.41	0.21
+0.51	+0.38	0.13
+0.31*	**+0.24***	**0.07***

MSE: mean signed error. Positive values indicate age overestimation. p < 0:01 compared with DSMT-AE.

Table 8: Per-site brain age estimation performance across acquisition centers. σ denotes inter-site standard deviation (lower indicates higher robustness).

Method	A	B	C	D	E (OOD)	F (OOD)	σ
ResNet-18	3.62	3.91	4.41	4.02	4.88	5.33	0.64
DSMT-AE	2.81	3.04	3.38	3.12	3.74	4.21	0.52
BrainIAC	2.54	2.73	3.01	2.82	3.34	3.81	0.47
NeuroFusion (Ours)	**2.17***	**2.31***	**2.58***	**2.40***	**2.71***	**3.12***	**0.34***

p < 0:05 vs. BrainIAC at each site. indicates inter-site variability.

We further evaluated different deep supervision tap configurations within the ViT encoder. The triple-tap configuration (B4+B8+B12) achieved the best performance with an ID MAE of 2.31 years, outperforming all single- and dual tap variants. Among single-tap settings, supervision at block 8 consistently performed better than block 4, indicating that mid-level transformer features provide more informative representations for auxiliary regression tasks.

4.4.4 Robustness Results

NeuroFusion had the lowest MAE across all age categories, with the most gains in 20{34 and 65+. MAE fell from 3.12 to 2.74 years in the youngest group and 3.41 to 2.98 years in the oldest group compared to BrainIAC. NeuroFusion showed modest performance variation across age bins (Δ_{max} = 0:95), indicating consistent behavior over time. The pretrained ViT backbone and demographic fusion module capture age-related structural variation better than previous techniques, evident at age extremes.

NeuroFusion has the lowest MAE and prediction bias for men and women. The between-sex bias gap was 0.07 years, compared to 0.21 for DSMT-AE and 0.13 for BrainIAC. By conditioning age estimation on sex-specific structural characteristics, demographic fusion improves calibration across sex groups. NeuroFusion has a much narrower error range than ResNet-18 despite a somewhat bigger absolute MAE disparity between sexes.

NeuroFusion achieved the best performance across all acquisition sites, including

Table.9: Sex-stratified brain age estimation performance and bias analysis on the in-distribution test set. MSE denotes mean signed error (positive values indicate overestimation). Lower MAE and lower bias disparity indicate better demographic fairness.

Method	Male MAE	Female MAE	|Δ MAE|
ResNet-18	3.92	3.83	0.09
DSMT-AE	3.14	2.83	0.31
BrainIAC	2.79	2.63	0.16
NeuroFusion (Ours)	2.40*	2.22*	0.18

MSE: mean signed error. Positive values indicate age overestimation. p < 0:01 compared with DSMT-AE.

Table 10: Robustness under simulated acquisition artefacts (moderate severity). Values are MAE (years); relative degradation from clean baseline is shown in parentheses. Lower values indicate better robustness.

Artefact	ResNet-18	DSMT-AE	BrainIAC	NeuroFusion (Ours)
None (baseline)	3.87	2.98	2.71	2.31
Gaussian noise	4.31 (11%)	3.27 (10%)	2.89 (7%)	**2.44 (6%)**
Motion blur	5.02 (30%)	3.74 (25%)	3.11 (15%)	**2.61 (13%)**
Intensity inhomogeneity	4.61 (19%)	3.44 (15%)	2.98 (10%)	**2.51 (9%)**
Rician noise	4.47 (15%)	3.38 (13%)	2.94 (8%)	**2.48 (7%)**
Ghosting artefact	4.89 (26%)	3.61 (21%)	3.04 (12%)	**2.57 (11%)**

Relative degradation = increase over baseline MAE in percentage. Bold indicates best performance per row.

both unseen OOD centers. The inter-site MAE standard deviation decreased to 0.34 years, compared with 0.47 for

BrainIAC, indicating improved robustness to scanner and site variability. The largest gains were observed on OOD sites, where NeuroFusion improved MAE by over 18% relative to BrainIAC. These results suggest that multitask supervision and demographic conditioning improve generalization under distribution shift.

NeuroFusion consistently showed the lowest MAE under all simulated artefacts. The largest improvement was observed under motion blur, where performance degradation was limited to 13%, compared with 30% for ResNet-18 and 25% for DSMT-AE. The improved robustness is likely related to the global self-attention mechanism of the ViT backbone and the reconstruction objective, which encourages structurally consistent representations.

Uncertainty-weighted optimization improved both convergence speed and training stability. Compared with fixed loss weighting, epoch-wise validation variance decreased from 0.18 to 0.11 years, while the MAE < 2.5 threshold was reached 37% faster (89 vs. 142 epochs). Gradient analysis showed that uncertainty weighting prevented the reconstruction objective from dominating early optimization, allowing more stable regression learning.

V. CONCLUSION

A conclusion In this study, we developed NeuroFusion, a unified deep learning framework for brain age estimation from volumetric T1-weighted MRI. The proposed approach addresses two major limitations of existing methods: vanishing gradients in deep 3D architectures and poor generalization in clinical scenarios with limited labelled data. Experimental results demonstrated that dual-objective self-supervised pretraining, which combines SimCLR and MAE objectives, provides complementary learning benefits and achieves better performance than either strategy alone. Furthermore, the integration of cross-modal demographic information supplied important contextual cues, reducing the MAE by 0.47 years. To improve optimization in deep 3D Vision Transformer architectures, deep supervision was introduced at intermediate transformer blocks, which effectively mitigated vanishing gradient issues. Another key advantage of NeuroFusion is its frozen backbone design, enabling few-shot adaptation to unseen imaging sites using only 1{5 labelled examples while maintaining clinically relevant performance without extensive task-specific ne-tuning.

Despite these promising results, several limitations remain. The OpenBHB dataset used in this study contains only healthy control subjects, and therefore validation on clinical populations such as Alzheimer's disease (AD), mild cognitive impairment (MCI), and schizophrenia is still required. In addition, the proposed 3D Vision Transformer architecture incurs higher computational cost than conventional CNN-based approaches, with an inference time of approximately 0.28 seconds per MRI volume on an RTX5090 GPU. The framework also relies on the availability of demographic metadata during inference. Future work will focus on extending NeuroFusion to multimodal neuroimaging data, including PET and DTI modalities, incorporating uncertainty-aware prediction mechanisms for clinical decision support, and conducting large-scale validation on diverse clinical cohorts.

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Extending Theory of Planned Behaviour (TPB): Cultural Inheritance and Craft Fragility in Pakistan's Upcycled Fashion Movement

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Abstract— *Across Pakistan's creative capitals of Lahore, Karachi, and Islamabad, a quiet but profound shift is taking place as emerging designers repurpose discarded and reclaimed textiles into outfits with renewed worth and purpose a method known as upcycled apparel design. To explain what motivates this conduct, this research draws on Ajzen's Theory of Planned conduct, exploring how designers' attitudes, the social norms around them, and their sense of control over the practice come together to determine their purpose to upcycle. The study reveals a rich and frequently unexpected picture thru 30 in-depth interviews with designers and a thorough thematic analysis: designers' attitudes toward upcycling are deeply rooted in inherited craft traditions passed down thru generations, giving the practice a distinct moral and cultural weight, rather than in trendy sustainability language. At the same time, social perceptions remain divided while some families still identify reused materials with financial difficulty, a newer generation of design-school graduates is redefining sustainability as a badge of professional competence and artistic difference. Yet even with great desire and shifting perceptions, designers confront genuine challenges to putting their intentions into effect, particularly a fragmented supply chain for waste materials and a decreasing pool of craftspeople with the specialist skills needed to work with salvaged fabrics. Beyond the three primary motivations, the research reveals two additional forces affecting this environment the pull of cultural legacy and the fragility of the living craft infrastructure that upcycling depends on offering unique dimensions to extend how we interpret sustainable design behaviour. Together, these insights provide one of the first grounded, in-depth accounts of how Pakistani designers incorporate belief, tradition, and constraint into everyday practice, with important implications for how design education is taught, artisan communities are supported, and future textile-waste systems can be built.*

I. INTRODUCTION

Global waste is expected to increase to 3.4 billion tons by 2050, more than double the projected population growth over the same period, posing serious hazards to the environment, health, and prosperity (Kaza et al., 2018). A figure that has driven sustained academic and industry interest in circular strategies such as upcycling the creative transformation of discarded or rejected materials into higher-value products (Sung et al., 2014). Pakistan, the world's fifth-largest textile exporter, sits close to the centre of this equation: its export garment sector generates substantial pre-consumer cutting waste, while its domestic apparel market increasingly mirrors the consumption patterns associated with fast fashion elsewhere(Khan & Faiz, 2025). Despite this exposure, empirical research on the psychological and cultural drivers of upcycling among Pakistani designers remains scarce, with most existing sustainable-fashion consumer research concentrated on Western, high-income markets (Gwilt & Rissanen, 2011).

This study addresses that gap by examining how emerging Pakistani fashion designers come to adopt or resist upcycling as a design practice. It applies (Ajzen, 1991a) Theory of Planned Behaviour (TPB), which explains behavioural intention as a function of attitude, subjective norms, and perceived behavioural control, as a single, focused analytical lens. Rather than testing the model deductively through survey measurement, this study uses TPB as an organising framework for a qualitative, interview-based investigation, allowing space for themes to emerge that extend beyond the model's original three constructs(Y. G. Kim et al., 2018).

The research is guided by the following research question: How do attitude, subjective norms, and perceived behavioural control shape Pakistani designers' engagement with upcycled apparel, and what additional cultural or structural factors, if any, shape this engagement beyond the boundaries of the TPB framework?

The remainder of the paper proceeds as follows: a review of the relevant literature on TPB, upcycling, and the Pakistani textile context; a description of the qualitative methodology; a presentation of findings organized around the three TPB constructs plus two inductively derived themes; a discussion of theoretical and practical implications; and a concluding discussion of limitations and directions for future research (Zhou et al., 2025).

II. LITERATURE REVIEW

2.1 The Theory of Planned Behaviour in Sustainable Fashion Research

Ajzen (1991a) Theory of Planned Behaviour proposes that behavioural intention the most proximal predictor of actual behaviour is shaped by three factors: attitude (an individual's evaluative belief about a behaviour), subjective norms (perceived social pressure to perform or avoid the behaviour), and perceived behavioural control (the perceived ease or difficulty of performing the behaviour, reflecting both internal skill and external resource constraints)(Ajzen, 1991b). TPB has been widely applied in sustainable consumption research generally (H. Y. Kim & Chung, 2011) and in secondhand and upcycled fashion research specifically (Sethi & Jiu, 2025), where it has consistently demonstrated explanatory power for both purchase and production-side behaviours. However, cross-cultural applications of TPB caution that the content and relative weight of each construct can vary substantially across cultural contexts (Morren & Grinstein, 2021), and that intention does not always translate cleanly into behaviour (Hassan, Shiu, & Parry, 2016) a gap that we argue is under-theorised within the standard TPB architecture. These cautions motivate the qualitative, context-sensitive approach adopted in this study(Anwer & Hassan, 2025).

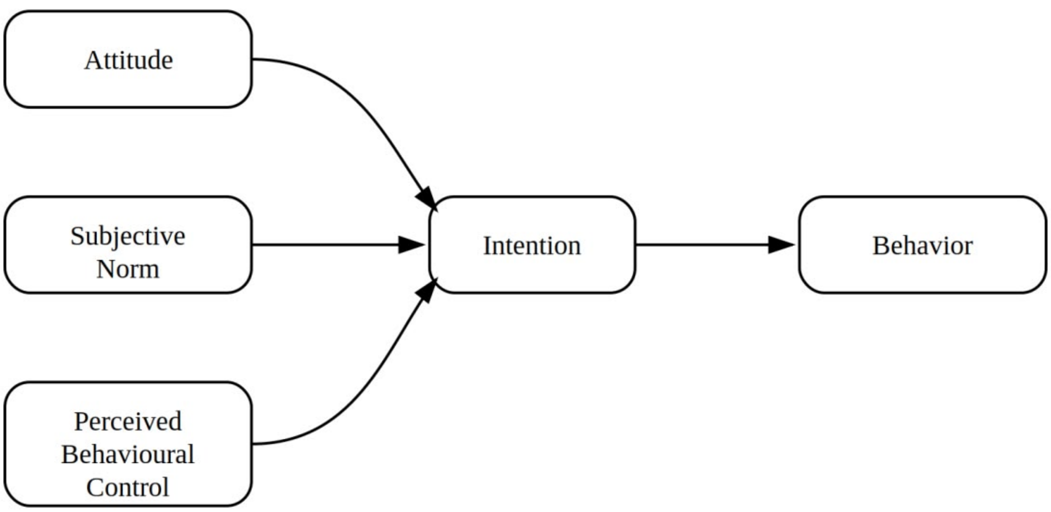

Fig.1. Base theoretical framework(Ajzen, 1991b).

2.2 Upcycling as a Distinct Design and Consumption Practice

Upcycling is conceptually distinct from conventional secondhand consumption. Where secondhand apparel is purchased and used in its original form, upcycling involves the deliberate creative transformation of discarded or rejected materials into a new, higher-value product (Sung et al., 2014). This distinction matters for designer-side research in particular, because upcycling requires not only a positive evaluation of reused materials but also the technical skill, material access, and creative confidence to transform them conditions that map closely onto the perceived behavioural control construct within TPB (Gwilt & Rissanen, 2012; Koch, 2019).

2.3 The Pakistani Textile and Craft Context

Pakistan's textile sector anchors a substantial share of national export earnings and employs millions of workers across the spinning, weaving, and garment-manufacturing value chain. Alongside this industrial base, Pakistan retains a living tradition of craft practices including block-printing, phulkari embroidery, and ralli quilting many of which historically involved the reuse of fabric offcuts and worn textiles well before the emergence of a formal sustainability discourse (Rauf & Kamal, 2023). This dual context, an industrial export economy layered over a pre-industrial craft heritage, distinguishes Pakistan from the Western contexts in which most existing upcycling research has been situated, and provides the empirical rationale for this study's single-country, in-depth qualitative focus (Fletcher, 2014; McDonough & Braungart, 2002).

2.4 Research Gap

While TPB has been applied productively to sustainable fashion consumption and to a lesser extent, to production-side design behaviour, the vast majority of this work remains quantitative in orientation, relying on survey instruments to measure the strength of attitudinal, normative, and control beliefs across large samples of consumers or designers. This methodological emphasis, while useful for establishing generalisable relationships between TPB constructs, offers limited insight into *how* such beliefs are formed, negotiated, or contested within specific cultural and material contexts particularly among practitioner populations whose engagement with sustainability is shaped as much by craft tradition, skill, and material access as by environmental attitude alone(Fletcher, 2013). Few studies have examined TPB qualitatively among design-practitioner populations in South Asia, where craft heritage, informal artisan economies, and distinct social attitudes toward reclaimed materials may complicate or extend the model's standard assumptions. Fewer still have engaged with upcycling specifically, as distinct from broader sustainable design practice, despite upcycling's unique dependence on fragmented waste-material supply chains and specialised textile-repurposing skills that are not captured by existing TPB applications in fashion. To the authors' knowledge, no study has examined TPB qualitatively among upcycled apparel designers in Pakistan specifically, leaving unanswered how designers in this context translate belief, social pressure, and practical constraint into upcycling practice. This study addresses that gap, offering a qualitative, contextually grounded account of TPB among an under-studied design population, and proposing candidate extensions to the model that reflect the particular cultural and infrastructural conditions shaping upcycling practice in Pakistan(Rasool et al., 2019).

III. METHODOLOGY

3.1 Research Design

This study adopts a qualitative, interpretivist research design, appropriate for exploring the subjective meanings designers attach to upcycling practice and for allowing themes to emerge inductively alongside the deductive TPB framework (Galletta, 2013; Schwartz-Shea & Yanow, 2013). Semi-structured interviews were selected as the primary data collection method to allow flexibility in probing individual designers' reasoning while maintaining comparability across the sample.

3.2 Study Context and Participants

Data were collected from 30 emerging fashion designers based in three major Pakistani design hubs: Lahore, Karachi, and Islamabad. Participants were purposively sampled to include individuals with direct, hands-on experience of upcycling practice, ranging from design students and recent graduates to independent designers operating small upcycled-apparel labels (Braun & Clarke, 2006a). This purposive strategy prioritised information-rich cases over demographic representativeness, consistent with standard qualitative sampling logic. Table 1 summarises the composition of the sample across the three design hubs.

Table 1. Participant overview by city (N = 30).

City	n	Participant Profile
Lahore	11	Design students, recent graduates, and independent designers with hands-on upcycling experience, several working with block-printing and phulkari techniques
Karachi	10	Independent designers and small-label founders, several with direct exposure to export-garment factory waste streams
Islamabad	9	Recent design-school graduates and early-career designers, several affiliated with university design programmes

3.3 Data Collection

Semi-structured interviews were conducted individually, guided by an interview protocol organised loosely around the three TPB constructs (attitude toward upcycling, perceived social expectations, and perceived barriers or enablers), while leaving space for participants to introduce topics not anticipated by the protocol. Interviews continued until thematic saturation was judged to have been reached within the sample. All participants are identified in this paper using anonymised codes (e.g., PK-04) alongside their city of practice, in line with the study's ethical protocol.

3.4 Data Analysis

Interview data were managed using NVivo 15 a widely used software package for qualitative data analysis (Zamawe, 2015), and analysed using Braun & Clarke (2006b) six-phase approach to thematic analysis: familiarisation with the data, generation of initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final analytic narrative. Coding proceeded in two stages: an initial deductive pass organised material according to the three TPB constructs, followed by an inductive, open-coding pass designed to surface patterns not anticipated by the TPB framework. This second pass produced the two extension themes reported in Section 5.5 and 5.6.

3.5 Trustworthiness and Ethical Considerations

Trustworthiness was supported through investigator triangulation during theme development, an audit trail of coding decisions maintained in NVivo, and member-appropriate anonymisation of all participant identifiers. Informed consent was obtained from all participants prior to interview, and participation was voluntary and could be withdrawn at any stage without penalty.

IV. FINDINGS

Findings are organised around the three core TPB constructs attitude, subjective norms, and perceived behavioural control followed by two themes that emerged inductively and extend beyond the model's original boundaries.

4.1 Attitude Toward Upcycling

Across the sample, designers expressed strongly positive, morally inflected attitudes toward upcycling. Rather than framing these attitudes primarily around contemporary environmental discourse, a majority of participants grounded their evaluative beliefs in inherited craft memory recollections of grandmothers, aunts, and other family members who routinely repurposed fabric offcuts long before “upcycling” existed as a design term (Sung, 2017).

> *"When my grandmother made a ralli quilt from old clothes, she was upcycling. We have been doing this for generations. Western designers just gave it a new name."* PK-04, Lahore
>
> *"My grandmother never threw away fabric. Every piece became something else. I grew up thinking that was normal. Now I am in a design programme and I see that it is actually radical."* PK-11, Karachi

A closely related dimension of attitude concerned designers' sense of moral accountability for the industry's environmental footprint. When asked about their awareness of the fashion industry's environmental impact, 29 of 30 participants responded affirmatively and unprompted, frequently citing specific local examples such as dye pollution in nearby waterways.

> *"I read about how our rivers are contaminated by fabric dye. I know this is happening in my country. I am a designer. I feel I have to be part of the solution."* PK-09, Karachi

This pattern suggests that, for this sample, attitude toward upcycling is not a single evaluative judgement but a composite of inherited cultural meaning and a self-ascribed moral obligation tied to professional identity as a designer.

4.2 Subjective Norms: Familial Stigma and Emerging Peer Culture

Subjective norms in this sample were bifurcated along generational and social lines. The dominant, longer-standing norm was familial and communal, and frequently negative: a substantial number of participants described a social stigma in which upcycled work is read by family members as evidence of financial hardship rather than deliberate creative or ethical choice.

> *"My family thinks upcycling means I cannot afford new fabric. There is a stigma. I have to explain constantly that it is a conscious choice, not a financial limitation."* PK-17, Lahore
>
> *"When I tell relatives I make clothes from waste fabric, they assume it is because business is bad. I have stopped explaining to some of them. It is exhausting."* PK-13, Karachi

Alongside this familial norm, a second, more recent, and more positive norm was described by younger participants, particularly recent design-school graduates in Islamabad and Lahore, for whom sustainability engagement functions as a marker of professional credibility among peers.

> *"Among people my age who studied design, if you are not thinking about sustainability, you seem out of touch. My batch-mates talk about it constantly. It has become part of how we judge good design."* PK-19, Islamabad

These two norms coexist rather than replace one another, meaning individual designers often navigate simultaneous, contradictory social pressures depending on whether they are interacting with family or professional peer networks.

4.3 Perceived Behavioural Control: Structural Constraints Across Design Hubs

Perceived behavioural control emerged as the construct most strongly shaped by city-specific structural conditions. Table 2 summarises the pattern of constraints reported across the three design hubs in the sample.

Table 2. Structural constraints on perceived behavioural control, by city.

Lahore	Karachi	Islamabad
Primary barrier: unorganised material access from tailors and small workshops	Primary barrier: factory-scale cutting waste with no formal channel to designers	Primary barrier: limited artisan and workshop infrastructure
Deep craft continuity (block-printing, phulkari) supports skill access	Strong tailoring and pattern-cutting skill base	Thinner craft ecosystem; reliance on travel to source specific skills

> *"There is no organised system for collecting pre-consumer textile waste from factories. I collect offcuts myself from tailors nearby. It is time-consuming and unpredictable."* PK-22, Islamabad
>
> *"In Karachi, the export factories produce enormous amounts of cutting waste every week. It just goes to landfill or gets burned. I have tried for two years to get a formal arrangement with even one factory. It is very difficult."* PK-26, Karachi

Despite these constraints, perceived behavioural control did not straightforwardly predict lower intention. Several participants with low perceived control nonetheless reported high, persistent intention to continue upcycling, a pattern explored further in Section 4.5 and Section 4.6.

4.4 Behavioural Intention

Consistent with TPB's core logic, intention to continue and expand upcycling practice was high across the sample and appeared to draw jointly on positive attitude and, for the peer-influenced subgroup, favourable subjective norms. However, intention among designers facing severe structural constraints on perceived behavioural control could not be fully explained by the three TPB constructs alone a gap addressed by the two extension themes below.

4.5 Extension Theme: Cultural Inheritance as a Motivational Resource

The first theme extending beyond the core TPB constructs concerns the role of inherited craft memory as a distinct motivational resource, separate from, though related to, attitude. Participants repeatedly described upcycling not as a response to global sustainability discourse but as a continuation of practices already present in their family and cultural history.

> *"My mother still has phulkari pieces my great-grandmother made from scraps of old dupattas. Nobody called it sustainable fashion. It was just what you did with cloth."* PK-06, Lahore

This theme suggests that, for this population, motivation to upcycle is sustained not solely by a general evaluative attitude but by an identity-linked sense of cultural continuity that neither the attitude nor subjective norm constructs, as conventionally operationalised in TPB, fully capture.

4.6 Extension Theme: The Fragility of Living Craft Infrastructure

The second extension theme concerns the erosion of specialised artisan skills required to work meaningfully with reclaimed textiles. Several participants described difficulty locating ageing master craftspeople whose techniques — hand block-printing, specific embroidery stitches, natural dyeing are not being systematically passed to a younger generation drawn toward faster, higher-volume factory work.

> *"The block-printer I work with is almost seventy. His son does not want to continue the craft, it does not pay enough compared to factory work. When he stops, I do not know who I will work with."* PK-28, Lahore

> *"For me, upcycling is not only about waste. It is about keeping these techniques alive by giving master craftspeople a reason to keep working, and a market for what they know."* PK-24, Karachi

This theme is conceptually distinct from perceived behavioural control as ordinarily understood, because it concerns the depletion of a shared external resource over time rather than an individual designer's perceived capability or access at a single point in time.

Table 3 summarises all five findings themes, their status relative to the base TPB model, and an illustrative quote for each.

Table 3. Summary of findings themes relative to the base TPB model.

Theme	Status	Illustrative Quote
Attitude	Core TPB construct	"When my grandmother made a ralli quilt from old clothes, she was upcycling." PK-04
Subjective Norms	Core TPB construct	"My family thinks upcycling means I cannot afford new fabric. There is a stigma." PK-17
Perceived Behavioural Control	Core TPB construct	"There is no organised system for collecting pre-consumer textile waste from factories." PK-22
Cultural Inheritance	Inductive extension theme	"My mother still has phulkari pieces my great-grandmother made from scraps of old dupattas." PK-06
Craft Infrastructure Fragility	Inductive extension theme	"The block-printer I work with is almost sevent, when he stops, I do not know who I will work with." PK-28

V. DISCUSSION

The findings of this study are broadly consistent with prior applications of TPB in sustainable fashion research (H. Y. Kim & Chung, 2011; Sethi & Jiu, 2025), while also illustrating the cross-cultural sensitivity of construct content that caution is often overlooked in standardised applications of the model. In this Pakistani sample, attitude and subjective norms in particular carry culturally specific content inherited craft memory and bifurcated familial-versus-peer norms, respectively that would not be visible in a purely quantitative, Western-normed instrument.

The study also speaks to the intention-behaviour gap identified by (Hassan, Shiu, & Shaw, 2016): despite high reported intention across the sample, several participants described concrete, ongoing barriers material access, artisan availability that plausibly constrain the translation of intention into sustained practice. This is consistent with the view that perceived behavioural control, when structural rather than purely psychological, may act as a harder ceiling on behaviour than TPB's standard formulation implies (Feng et al., 2023).

Perhaps the most distinctive contribution of this study is empirical rather than purely theoretical: the identification of craft-skill erosion as a form of perceived-control constraint specific to craft-intensive, developing-economy design contexts, and largely absent from the existing upcycling literature, which has been developed primarily around Western, industrially mature design economies (Fletcher, 2014; Gwilt & Rissanen, 2011; McDonough & Braungart, 2002).

VI. THEORETICAL AND PRACTICAL IMPLICATIONS

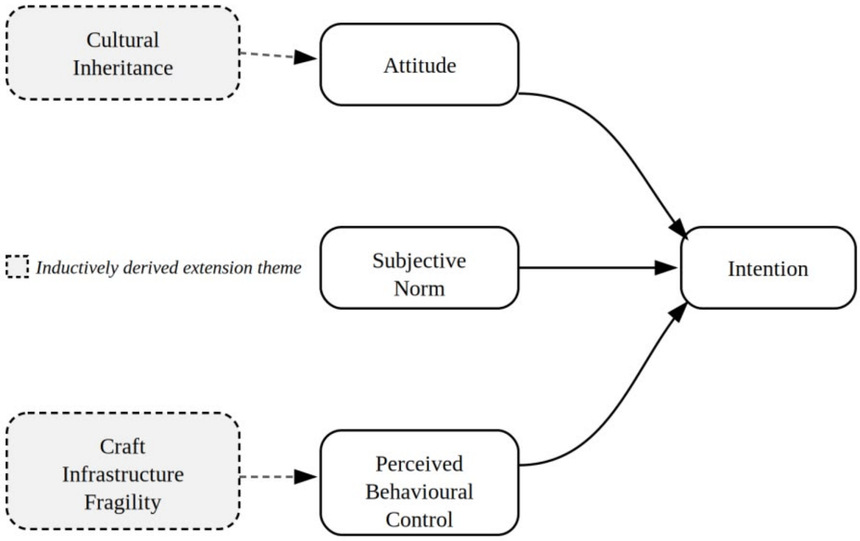

Fig.2. Extended conceptual model incorporating inductively derived themes.

6.1 Theoretical Implications

This study offers a focused, single-theory qualitative application of TPB to a design-practitioner population in Pakistan, a context in which the model has been under-applied. The findings largely affirm the explanatory value of the three core constructs while also indicating two boundary conditions. First, attitude in this context is not adequately captured by a single generalised evaluative judgement; it is layered with inherited cultural meaning that appears to strengthen and stabilise attitude in ways a standard measure may not detect. Second, perceived behavioural control, as conventionally defined around an individual's perceived capability and resource access, does not fully capture externally shared, slowly depleting resources such as a regional artisan skill base. The study proposes that future applications of TPB in craft-intensive design contexts consider incorporating a resource-continuity dimension within, or adjacent to, perceived behavioural control, to better capture constraints of this kind.

6.2 Practical Implications

For design educators in Pakistan, the findings support teaching upcycling as a continuation of indigenous craft knowledge rather than as an imported concept, given the strength and stability this framing appears to lend designers' attitudes. For artisan-support organisations and craft councils, the erosion of specialist skills documented in Section 4.6 represents an urgent and currently under-addressed constraint on the long-term viability of upcycled design in Pakistan; apprenticeship subsidies and structured connections between master craftspeople and design-school graduates could meaningfully extend the working life of at-risk skills. For policymakers focused on textile-sector waste, the finding that awareness is not the binding constraint designers already recognise the environmental stakes suggests that formal, organised channels connecting pre-consumer factory waste to designers would likely be more impactful than further public-awareness campaigns. For industry stakeholders, the persistence of familial stigma documented in Section 4.2 suggests that brand communication reframing upcycled work as heritage-continuous, rather than necessity-driven, may shift consumer and community perception more effectively than sustainability messaging adapted from international campaigns.

VII. LIMITATIONS, FUTURE RESEARCH AND CONCLUSION

This study is limited to designers in three urban centres Lahore, Karachi, and Islamabad and its findings should not be generalised to rural artisans or to the broader Pakistani population. As a qualitative, interview-based study relying on self-report, it captures designers' accounts of their attitudes and intentions rather than observed behaviour over time; future research combining interviews with studio-based observation or supply-chain tracing would strengthen the empirical foundation. Finally, as a single-time point study, it cannot speak to whether the craft-erosion pattern identified in Section 4.6 is accelerating, stabilising, or reversing; a longitudinal design following the same cohort over several years would be well suited to this question, as would a follow-up quantitative study operationalising the two extension themes identified here for testing within an expanded TPB model.

This study applied the Theory of Planned Behaviour, as a single, focused theoretical lens, to examine how attitude, subjective norms, and perceived behavioural control shape emerging Pakistani designers' engagement with upcycled apparel. Across 30 interviews spanning three major design hubs, the three TPB constructs demonstrated strong explanatory value, while two inductively derived themes cultural inheritance and the fragility of living craft infrastructure pointed to boundary conditions of the model in this specific cultural and economic context. The study contributes an empirically grounded application of TPB to an under-studied design population, and offers concrete implications for design education, artisan-support policy, and industry practice in Pakistan.

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Old Clothes, New Corridor: The Business of Second-Hand and Up-Cycled Apparel in Pakistan and China, Read Through CPEC and the Views of Young Designers in Pakistan

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Keywords— ***China-Pakistan Economic Corridor (CPEC), Young Designers, Second-hand, up-cycled clothing, Qualitative.***

Abstract— *The global trade in second-hand and up-cycled apparel has grown from an informal survival market into a recognised commercial category, and Pakistan sits at an unusual intersection of that trend: a long-established informal resale sector, a fast-growing textile-manufacturing base tied to the China-Pakistan Economic Corridor (CPEC), and a young generation of fashion and textile-design graduates entering the industry with direct opinions about where it should go next. This paper reports a qualitative study of sixteen semi-structured interviews with Pakistani respondents (aged 20-32, twelve with a background in fashion or textile design) on the business realities of buying, wearing, and designing with second-hand and up-cycled clothing, set against a comparative reading of young Chinese designers' and consumers' views on the same trade, drawn from prior published interview research. Respondents describe a viable but underdeveloped commercial category: strong latent demand, a workable price anchor of roughly a 50% discount against comparable new fast-fashion items, and two concrete business obstacles unresolved hygiene trust and a lingering association between second-hand clothing and poverty that current informal retailers largely do not address. Young designers in the sample were the most commercially optimistic group, treating up-cycling as a design discipline and a brand opportunity rather than a compromise, a stance that closely tracks how young designers in the Chinese comparator research talk about the same trade. Views on CPEC were split: roughly half of respondents expect CPEC-linked textile investment to undercut second-hand and up-cycled apparel on price, while the rest see it as a route to better machinery, recycling infrastructure, and Chinese-style resale platforms entering Pakistan. The paper closes with concrete recommendations for up-cycling entrepreneurs, brand marketers, and CPEC-linked industrial policy.*

I. INTRODUCTION

Second-hand and up-cycled clothing has moved from the margins of the fashion economy toward its centre. Resale platforms, thrift-focused brands, and up-cycling studios now operate as genuine businesses in many markets, not just as informal coping mechanisms for low-income buyers(Niinimäki et al., 2020). Much of the commercial and academic attention to this shift, however, has concentrated on wealthier or more retail-mature markets(Ratcliffe, 2017). China offers one of the most closely studied cases: dedicated resale apps such as Xianyu and Zhuanzhuan, growing interest among young designers in up-cycled and reworked garments, and a formal government push including China's 2022 Implementation Opinions on Accelerating the Recycling of Waste Textiles to build textile recycling into industrial policy rather than leave it informal(Zhang, 2025).

Pakistan's second-hand clothing trade looks very different on the surface but shares the same underlying commercial question: can informal, price-driven resale be turned into a designed, branded, scalable business? Markets such as Landa Bazaar have moved large volumes of used clothing for decades on pure affordability, with almost no design intervention, branding, or quality assurance layered on top. At the same time, Pakistan is in the middle of a large bilateral industrial programme, the China-Pakistan Economic Corridor (CPEC), with direct textile-sector components, and is producing a growing cohort of fashion and textile-design graduates who are old enough to have opinions about both the informal resale trade they grew up around and the new industrial capacity CPEC is bringing online(Ismail et al., n.d.).

This paper asks three business-facing questions. First, what would it actually take commercially, not just attitudinally to convert Pakistani consumers' stated openness to second-hand and up-cycled clothing into a repeat-purchase business? Second, how do young designers in Pakistan think about up-cycling as a design and business practice, and how does that compare with what has been reported among young designers and consumers in China? Third, do Pakistani stakeholders see CPEC-linked textile investment as a threat to this emerging trade or as an infrastructure opportunity for it? The paper draws on sixteen semi-structured interviews collected by the author, read here through a straightforward commercial lens demand, price, trust, positioning, and industrial context rather than through a formal psychological model of individual decision-making(Ismail et al., n.d.; Masood & Bilal, 2024).

II. LITERATURE REVIEW

2.1 From informal resale to a designed business category

Fast fashion's environmental and labour costs are well documented water- and pesticide-intensive cotton cultivation, polluting dyeing and finishing processes, and a sharp rise in discarded textile volume (Niinimäki et al., 2020)and these costs have pushed resale and up-cycling from a niche interest into a mainstream commercial response. Up-cycling, specifically, means redesigning discarded garments into new, higher-value pieces, distinct from recycling (breaking material down to raw fibre) or plain resale of used clothing without design intervention(McQuillan, 2021). This distinction is commercially important: plain resale competes almost entirely on price, whereas up-cycling can compete on design and brand as well, which is a materially different business model with different margins and different customers(Zavagno, 2021).

2.2 CPEC and Pakistan's textile-industrial context

The China-Pakistan Economic Corridor is a large bilateral programme of infrastructure, energy, and industrial investment that includes textile-sector components(McCartney, 2021). The existing literature on sustainable and second-hand fashion consumption does not address how a bilateral industrial investment programme of this scale interacts with a grassroots resale and up-cycling trade whether new industrial capacity for cheap, new garments crowds out the price advantage that currently drives second-hand purchasing, or whether the same investment could instead fund the machinery, recycling infrastructure, and logistics that an up-cycling business needs to scale(Minney, 2011). This is a live commercial question for Pakistani textile entrepreneurs and policymakers alike, and it has not, to the author's knowledge, been studied directly through consumer- and designer-facing interviews(Aslam, 2022).

2.3 Young designers as a market signal: China and Pakistan

Young designers are a useful lens on this trade because they sit on both sides of it as consumers who form opinions about second-hand clothing, and as potential future suppliers who could design and brand it(Sihvonen & Turunen, 2016). Prior qualitative interview research with thirty young Chinese women, split into 18-25 and 26-39 age cohorts, found broadly positive engagement with sustainable and reworked fashion, with younger respondents especially attentive to product information, styling, and hygiene, and design-literate respondents in particular treating up-cycled pieces as an aesthetic and brand opportunity rather than a fallback purchase(FA, n.d.). Named Chinese resale platforms Xianyu and Zhuanzhuan came up repeatedly in that research as the retail infrastructure young Chinese designers and consumers already use(Zhang, 2025). Pakistan's equivalent designer cohort has no comparable branded platform to work with; its raw material comes largely through informal markets such as Landa Bazaar and second-hand-focused Instagram pages, which is itself a business gap this paper investigates directly(Ismail et al., n.d.).

2.4 Practical barriers to converting interest into sales

Across the wider commercial literature on sustainable and second-hand fashion, five recurring barriers to purchase have been identified: low product awareness, a perception of premium pricing, a sense that designs do not meet mainstream aesthetic standards, poor access to purchasing channels, and distrust of sustainability claims made by sellers(Barroso et al., 2021). Green-purchase research more broadly finds that price, convenience of purchasing channel, and uncertainty about product quality jointly determine whether positive attitudes convert into an actual sale(Sharma et al., 2022). A barrier specific to second-hand and up-cycled clothing, distinct from these general ones, is hygiene concern and the social risk of being seen in visibly pre-owned clothing a barrier that, this paper finds, current Pakistani resellers do almost nothing to actively address, despite it being commercially fixable(Adnan et al., 2026). A well-documented gap between stated purchase intention and completed purchase, driven by exactly this kind of unaddressed friction, is a standard finding in this literature and is treated here as a business problem to be solved rather than a fixed feature of consumer psychology(Pandit et al., 2019).

2.5 Research gap

Existing research establishes the environmental case for second-hand and up-cycled apparel, documents general purchase barriers, and in the Chinese case shows what a comparatively mature, platform-based resale trade looks like from the perspective of young designers and consumers. What is missing is a business-facing account of Pakistan's second-hand apparel trade: whether current informal retail can be turned into a designed, branded, trusted commercial category; how young Pakistani designers, specifically, think about that opportunity; and how CPEC-linked industrial investment is expected to help or hurt that trajectory. This paper addresses that gap directly(Ismail et al., n.d.; Masood & Bilal, 2024).

III. METHODOLOGY

This is an exploratory qualitative study using a semi-structured, self-administered written questionnaire covering six areas: demographics, buying habits, awareness of the resale and up-cycling trade, willingness to buy, perceptions of how the trade is viewed socially, and expectations about CPEC. Sixteen respondents completed the questionnaire between November and December 2025. The sample is a convenience sample drawn substantially from fashion- and textile-design students and young professionals in Punjab and Sindh, which should be borne in mind when interpreting how far these findings generalise.

Ten of the sixteen respondents were male and six were female; ages ranged from 20 to 32, with the majority clustered between 24 and 26. Twelve of the sixteen respondents reported a background in fashion or textile design, as students, designers, or related professionals positioning this sample as commercially engaged early adopters and prospective suppliers rather than a representative cross-section of the general Pakistani consumer market.

Table 1: Demographic information

#	Name	Age	Gender	Education / Occupation	Monthly Income	Design Background
1	Hussain	26	Male	BS Environmental Science, Student	15–25k PKR	No
2	Saad	25	Male	Marketing	35–40k PKR	Yes
3	Umair	25	Male	Fashion student	30–40k PKR	Yes
4	Ali	25	Male	Fashion student	20–25k PKR	Yes
5	Hammad	25	Male	Fashion Designer	100k PKR	Yes
6	Uzair	25	Male	Fashion Designer	15–20k PKR	Yes
7	Taimoor	25	Male	Fashion & Design student	20–25k PKR	Yes
8	Fiza Shahid	24	Female	B.Des Textile & Fashion	15–20k PKR	Yes
9	Iqra	25	Female	Textile Designer	15–20k PKR	Yes
10	Mahnoor	25	Female	Bachelor’s, Homemaker	15–20k PKR	Not specified
11	Mughees	25	Male	Textile Designer	30k PKR	Yes
12	Nida A	24	Female	B.Des Fashion Designer	90k PKR	Yes
13	Nida B	32	Female	Fashion Blogger, Retail Consultant	120k PKR	No

14	Imran	20	Male	Fashion & Textile designer	120k PKR	Yes
15	Arhum	20	Male	Designer and Makeup Artist	120k PKR	Yes
16	Warda	25	Female	Apparel Designer	20–25k PKR	Not specified

Responses were read in full and organised thematically around five business-relevant categories: market perception and demand, price and value, trust and quality (chiefly hygiene), social and brand positioning, and CPEC-linked industrial context, with a further comparative thread pulled out specifically for the twelve design-background respondents. Given the small sample, findings are reported thematically with illustrative quotations rather than through formal statistical analysis; numeric self-ratings (awareness 1-10, likelihood-to-buy 1-10, price-discount threshold) are summarised descriptively.

IV. FINDINGS

4.1 Market perception: a real but underdeveloped category

Fourteen of the sixteen respondents described second-hand and up-cycled clothing as a legitimate, sensible thing to buy, most often citing reduced waste and lower cost together rather than as separate reasons. Iqra summarised the majority view directly: "Second hand clothes are obviously environmentally friendly and it is responsible." Affordability was the second most cited advantage, particularly among student respondents with limited disposable income (Hussain, Taimoor, Umair). A distinctly commercial, brand-facing theme also recurred: several respondents talked about up-cycled pieces as a source of individual style rather than a compromise purchase. Ali, a 25-year-old fashion student, rated his likelihood of buying up-cycled fashion 10 out of 10 and described the aesthetic as carrying an "Instagram/TikTok aesthetic, unique style" language that describes a brand position, not just a personal habit.

4.2 Awareness and the shape of the current trade

Self-rated awareness of fast fashion's environmental impact ranged from 3/10 (Hammad) to 10/10 (Nida-A), with a sample mean of approximately 6.8/10. Several design-background respondents could clearly separate up-cycling from plain resale "up-cycling means taking old clothes and making them new and stylish again," in Fiza's words while non-design respondents used the two terms more or less interchangeably, which itself is a useful business finding: the market has not yet taught general consumers that up-cycled and secondhand are different products worth different prices.

Named channels for buying secondhand or up-cycled clothing clustered around a small, repeated set: Landa Bazaar and Sunday/Friday markets, OLX, and Instagram thrift pages in Pakistan; Xianyu and Zhuanzhuan were the Chinese platforms most frequently named, cited by respondents who had looked into the Chinese market while completing the questionnaire. None of the Pakistani channels named offer anything resembling the seller ratings, condition grading, or return policies that make Xianyu and Zhuanzhuan function as trusted platforms rather than just listings a concrete, fixable gap between the two markets.

4.3 Price: a workable discount anchor

Self-rated likelihood of deliberately buying up-cycled or second-hand clothing in the next twelve months ranged widely, from 1-2/10 (Nida-A, despite strong environmental awareness) to 10/10 (Ali, Uzair), with a mean of roughly 7/10 among respondents who gave a numeric answer. The discount needed to convert interest into an actual purchase clustered strongly around 50% cheaper than a comparable new fast-fashion item, with a minority requiring 70% (Hammad, Umair) and a smaller minority willing to pay close to full price for strong design (Uzair: "Price discount: not necessary; I'd pay full price"). A near-unanimous finding was that a well-designed up-cycled brand replicating the look of a respondent's favourite fast-fashion label would be bought "regularly" or "definitely" suggesting that, commercially, design parity with mainstream fast fashion is at least as strong a lever as price alone.

Section	Theme	Key Finding	Supporting Evidence	Business Implication
4.1	Market perception	14/16 respondents view second-hand/up-cycled clothing as legitimate; waste reduction + affordability are top reasons, but a brand/style motivation also recurs	Iqra: "obviously environmentally friendly and it is responsible"; Ali (10/10 likelihood):	Demand exists beyond a purely value-driven segment room for an aspirational/style-led brand, not just a budget category

			"Instagram/TikTok aesthetic, unique style"	
4.2	Awareness & trade shape	Awareness ranges 3–10/10 (mean ~6.8); design-background respondents distinguish up-cycling from plain resale, others conflate them	Fiza: "up-cycling means taking old clothes and making them new and stylish again"	Market hasn't taught consumers that up-cycled resale an education/positioning gap a brand can capture by making the distinction explicit
4.3	Price	Purchase likelihood ranges 1–10/10 (mean ~7); ~50% discount is the dominant threshold; some need 70%, a few would pay full price for strong design	Uzair: "Price discount: not necessary; I'd pay full price"; near-unanimous "would buy regularly" for brand-parity design	Design quality can substitute for discount depth pricing strategy shouldn't rely on discount alone
4.4	Trust & quality (hygiene)	Hygiene and inconsistent sizing/quality are the most-cited barriers; deep cleaning + redesign resolves it for most (not all)	Nida-A: fear "someone who wore it before could be allergenic or unclean"	Barrier is operational, not structural solvable via visible cleaning/QC process rather than new retail infrastructure
4.5	Social/brand positioning	Perception splits between "eco-conscious/trendy" (design-background, women) and "poor/low-status" (general consumers)	Hammad: "Society thinks second-hand means poor"; Mugheez: "no one knows what u are wearing belongs from... it depends on your styling"	Positioning/styling is the lever to shift general consumers from "poor" framing to the "trendy" framing design-background respondents already hold
4.6	Designers: Pakistan vs. China	Design-background respondents are most commercially confident (highest buy-intent, clearest category distinction); Pakistan's core gap vs. China is infrastructure, not attitude	Ali & Uzair both 10/10 likelihood; cf. Ma, Yang & Ketkaew (2024) on Chinese designers using Xianyu	Pakistani designers build trust "from nothing" via informal channels (Instagram) a platform/infrastructure gap, not a talent or attitude gap
4.7	CPEC outlook	Respondents split: CPEC could erode second-hand's price advantage (cheaper new garments) or help via tech transfer/recycling infrastructure; ~25% say outcome is policy-dependent	Mahnoor: CPEC "can support sustainable fashion if Pakistan invests in recycling and eco-friendly production"	CPEC's net effect on this trade is not fixed outcome hinges on whether industrial policy explicitly channels capacity toward recycling/up-cycling rather than only new production

4.4 Trust and quality: hygiene as a solvable operations problem

Hygiene concern "the fear that someone who wore it before could be allergenic or unclean," in Nida-A's words and inconsistent sizing or quality were the two disadvantages that recurred across nearly every transcript. Nearly all respondents agreed that professional deep cleaning and redesign resolves the hygiene concern; a small minority (Hammad, Umair) said they would remain uncomfortable regardless of treatment. Read commercially, this is good news: the dominant purchase barrier in this sample is not structural (as channel access is in more built-out resale markets) but operational, and operational problems are the kind a business can solve with a visible cleaning and quality-control process rather than needing to build new retail infrastructure from scratch.

4.5 Social and brand positioning

Responses on how secondhand and up-cycled clothing is currently viewed in Pakistani society split into two camps: an "eco-conscious trendy" framing, more common among design-background respondents and women in this sample, and a "low-status" framing, more common among general-consumer respondents (Hammad: "Society thinks second-hand means poor"; Umair gave a similar answer). Most respondents nonetheless felt that well-made up-cycled pieces can be worn well beyond casual settings into office, party, and even semi-formal or wedding contexts provided styling is strong, as Mugheez put it: "no one knows what u are wearing belongs from... it depends on your styling." Commercially, this points to positioning as the lever available to move a general-population buyer out of the "poor" framing and into the "trendy" one the framing that design-background respondents already hold spontaneously.

4.6 Young designers: Pakistan and China compared

The twelve design-background respondents in this sample were consistently the most commercially confident group: the highest self-rated likelihood to buy (Ali and Uzair both 10/10), the clearest grasp of up-cycling as a distinct, higher-value product category rather than plain resale (Fiza), and the strongest instinct to treat cleaning and quality control as marketable features rather than hidden costs. This closely mirrors what has been reported among young Chinese designers and design-literate consumers, who likewise treat reworked and up-cycled pieces as a design statement and, increasingly, a viable small-brand opportunity supported by platforms such as Xianyu (Ma, Yang, and Ketkaew, 2024). The clearest difference is infrastructure rather than attitude: young Chinese designers can plug into an existing resale platform with built-in trust signals, while young Pakistani designers in this sample described building trust and reputation from nothing, one buyer at a time, through informal channels such as Instagram thrift pages a materially harder starting position for turning design talent into a scalable business.

4.7 CPEC and the future of the trade

Respondents were split on whether CPEC will help or hurt this trade. The dominant concern among the "reduce" camp is straightforward: if CPEC-linked textile investment lowers the price of new, mass-produced garments, the price advantage that currently drives second-hand and up-cycled purchases could shrink. The "increase opportunity" camp instead emphasised technology transfer, access to better machinery, and the possibility that Chinese resale-platform models (Xianyu-style) or recycling infrastructure could be introduced into Pakistan alongside industrial investment. A middle position, held by roughly a quarter of respondents, argued that the outcome depends on whether policy explicitly channels new industrial capacity toward recycling-oriented production -- echoing Mahnoor's assessment that CPEC "can support sustainable fashion if Pakistan invests in recycling and eco-friendly production."

V. DISCUSSION: A COMPARATIVE BUSINESS READING

These findings describe a Pakistani second-hand and up-cycled apparel trade that already has demand and a workable price anchor, but is missing the trust infrastructure and design-forward branding that let China's equivalent trade function as an actual retail category rather than just a discount channel.

5.1 Where Pakistan and China converge

Both samples converge on a similar price signal a discount of roughly 50% relative to comparable new items despite very different absolute price levels in the two economies, suggesting this is closer to a stable "fair value" heuristic for pre-owned goods than a purely income-driven number. Both samples also show young designers acting as the most commercially bullish segment, already treating up-cycled and reworked pieces as a design and brand opportunity rather than a fallback purchase(Latif & Khan, 2025).

5.2 Where they diverge: trust infrastructure

The Chinese comparator research points to purchasing-channel difficulty and product-information trust as the main friction for consumers, addressed in large part by dedicated platforms such as Xianyu and Zhuanzhuan that supply ratings, condition grading, and seller history(Zhang, 2025). In this Pakistani sample, channel access barely came up; hygiene trust in the specific garment did, repeatedly and unprompted. That is a narrower, more solvable problem it does not require building new retail infrastructure, only a visible, communicated cleaning and quality standard but almost no current Pakistani reseller, formal or informal, is doing this yet. That gap is this trade's single clearest near-term business opportunity(Ismail et al., n.d.; Sihvonen & Turunen, 2016).

5.3 Positioning as the second lever

The diffuse "second-hand equals poor" association reported by general-consumer respondents (Hammad, Umair) is not, in this sample, driven by any specific person objecting it is a broad social read that design-background respondents in the same sample simply do not share. That gap between two groups exposed to the same product category, rather than a fixed cultural fact, is what makes positioning a workable business lever: design-literate early adopters already hold the more commercially useful frame, and can plausibly be used, deliberately, to shift how the wider market reads the category.

5.4 CPEC as an unresolved variable

Unlike price and trust, the CPEC question in this sample was genuinely unresolved rather than converging on a shared view a narrow majority expects cheaper new garments to erode second-hand demand, a substantial minority expects industrial investment to bring in exactly the infrastructure (machinery, recycling capacity, platform models) this trade currently lacks. Both outcomes are plausible from the same underlying investment; which one happens depends on decisions specifically, whether recycling and circular-production capacity is deliberately included in CPEC-linked textile planning that have not yet been made(Masood & Bilal, 2024; McCartney, 2021).

VI. BUSINESS AND POLICY IMPLICATIONS

The findings above translate into concrete, business-facing recommendations for four groups: up-cycling entrepreneurs and designers, marketers, CPEC-linked industrial policymakers, and future researchers.

6.1 For up-cycling entrepreneurs and designers

- Design for aesthetic parity with mainstream fast fashion first, and treat sustainability messaging as a secondary, supporting argument the single strongest lever for conversion in this sample was visual resemblance to a respondent's favourite existing fast-fashion brand, not price or environmental framing alone.
- Build a visible, marketable hygiene and quality-control process a stated deep-cleaning and redesign protocol, communicated at the point of sale since this is the one concrete barrier this sample identified as fully solvable, and no current informal seller is doing it.
- Anchor entry-level pricing around a 50% discount against comparable new items, with a smaller premium tier for design-literate buyers (like Uzair) willing to pay close to full price for strong, original design work.
- Expand sizing and selection depth where feasible; limited sizing was a secondary but recurring complaint (Fiza, Nida-B) that sits alongside the larger trust and positioning barriers.

6.2 For marketing and brand positioning

- Reframe status stigma directly rather than avoiding it because the "second-hand equals poor" read operates diffusely across society rather than through people a buyer knows personally, reassuring an individual buyer's immediate circle will not be enough; the messaging needs to shift the wider social script.
- Recruit young designers as visible commercial advocates, since this group already holds the more favourable, design-forward framing spontaneously and can plausibly transfer that framing to less design-literate buyers.
- Lead marketing with combined affordability-and-design messaging rather than environmental messaging alone, since Pakistani respondents' positive views already fuse these motives together rather than treating them separately.

6.3 For CPEC-linked industrial and trade policy

- Treat the CPEC trade-off identified here as a deliberate policy choice, not an automatic outcome new textile-manufacturing capacity could either undercut second-hand and up-cycled apparel on price, or supply the machinery and recycling infrastructure this trade currently lacks.
- Earmark a defined share of CPEC-linked textile investment for recycling and circular-production infrastructure specifically, following the logic several respondents (notably Mahnoor) articulated themselves.
- Support formalisation of existing informal resale markets (Landa Bazaar and similar) quality and hygiene standards layered onto markets that already have strong reach and accessibility is a lower-cost path than building new retail infrastructure from scratch, and mirrors the platform-based trust layer that already exists in China's resale trade.

6.4 For future researchers

- Test the roughly 50% discount threshold and the status-stigma finding on a larger, demographically balanced sample to establish whether they hold beyond this design-literate convenience sample.
- Study the young-designer segment in Pakistan and China directly and comparatively as both consumers and prospective suppliers since this paper's clearest finding is that attitude gaps between the two countries are smaller than infrastructure gaps.

VII. LIMITATIONS

- **Sample size and generalizability**: The small respondent pool limits statistical generalisability; future work could involve a larger, more diverse sample to validate patterns and reduce the influence of individual outlier responses.

- **Data-collection method:** The self-administered, written format prevented real-time clarification of ambiguous answers and did not capture tone or hesitation, and allowed respondents time to edit responses before submission. Future studies could use interviews or moderated sessions to address this.
- **Coding and analytic rigor**: Coding was done manually by a single researcher without independent verification. Future studies could incorporate multiple coders and inter-rater reliability checks to strengthen analytic robustness.
- **Nature of the quantitative data**: Numeric ratings were used descriptively rather than being subjected to formal statistical testing, given the qualitative design and small sample. A larger-scale follow-up could support more rigorous quantitative analysis.
- **Stated vs. actual behavior**: The study captures stated expectations and intentions rather than observed outcomes or actual purchasing behaviour. Longitudinal or behavioural tracking in future research could help validate whether stated intentions translate into real-world outcomes.

VIII. CONCLUSION

This paper set out to answer three business-facing questions: what it would take to convert Pakistani consumers' stated openness into repeat purchases of second-hand and up-cycled apparel, how young designers in Pakistan think about that trade compared with their counterparts in China, and how CPEC is expected to shape its future. On the first question, the evidence points to a trade with real demand and a workable price anchor roughly a 50% discount against comparable new items that is currently held back less by lack of interest than by two solvable gaps: unresolved hygiene trust and a social positioning problem that current sellers do little to address.

On the second question, young designers in this sample were consistently the most commercially confident group, already treating up-cycled clothing as a design and brand opportunity in a way that closely mirrors how young designers in China have been found to approach the same category. The clearest difference between the two countries is not attitude but infrastructure: Chinese designers can build on existing resale platforms with built-in trust signals, while Pakistani designers described building trust from nothing, one buyer at a time.

On the third question, CPEC remains a genuinely unresolved variable rather than a settled threat or opportunity. Whether CPEC-linked textile investment ultimately undercuts this trade on price or supplies it with the machinery, recycling capacity, and platform models it currently lacks depends on deliberate policy choices that, as of this study, have not yet been made. For entrepreneurs, marketers, and policymakers looking to grow Pakistan's second-hand and up-cycled apparel sector, the path forward suggested by this data is not to copy China's model directly, but to build the two things Pakistan's trade is missing that China's already has visible trust infrastructure and design-forward positioning while pushing CPEC-linked industrial planning to treat recycling and circular textile production as a deliberate inclusion rather than an afterthought.

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Dressed to Belong: Clothing, Confidence, and Social Identity Among University Students

A Cross-National Qualitative Study of Attire and Self-Assurance in Individual and Group Settings

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***Keywords*— social identity, self-assurance, power of getting dressed, cross-national qualitative study, Pakistan**

***Abstract*— Clothing is much more than a protection or a modesty tool; it is a tool that influences the way individuals see themselves and the way they are seen by others. The way people dress reflects their identity and self-esteem in daily life through a mixture of psychological, social, and cultural factors. This phenomenon is especially true in a group situation where university students dress for themselves but also in relation to their friends and where perceived looks may swiftly transfer into perceived social positions. This research explores the relationship between clothing, self-confidence, and social belonging for university students through semi-structured interviews with male and female students from four locations of the world. Drawing on social identity theory and enclothed cognition, the study employs a qualitative, interpretive approach to explore the relationship between personal style, peer comparison, and group context in the shaping of self-expression and self-esteem and how these dynamics are similarly or differently experienced in different cultural settings. The results show that clothing-based confidence is universally enhanced in group circumstances across all locations tested, but the precise triggers peer approbation, cultural pride, or social-media visibility differ by culture and gender context.*

I. INTRODUCTION

The effect of dress on a daily basis

Apparel is more than just a means of protecting the body from the elements or complying with basic rules of decency. A small, but everyday, repetitive decision for college students is the choice of their daily outfit, and it has a big psychological impact. Clothing is not simply functional but also represents individual taste, social conscience and self-image and affects both how a person feels about themselves and how they are perceived by others. A single ensemble can tell a lot about the character, diligence and even the emotional state of a person before any verbal communication.

This research explores the relationship between dress, self-identity, and confidence among university students of different genders, especially how this relationship is amplified in group settings and observed across cultures. When kids are among other kids, in schools, in cafeterias, at social gatherings, or in friendship circles, looks are a visible, relatable marker. Feeling well-dressed or calm in social situations is commonly identified as a major contributor to self-confidence, expressiveness and social ease, but feeling ill-dressed or uneasy about one's looks may produce opposite results(Francis, 2011).

Apparel as an Extension of Self

Clothing is often considered a necessity, a protection against the cold, heat or nakedness, at its most basic. However, clothing serves purposes beyond these basic functions. Attire is a medium that shows who someone is or who they want to be. A carefully chosen ensemble can provide a genuine confidence boost, while a poorly fitting or careless one can drain someone's energy and self-esteem throughout the day. While standards for dress and grooming may differ across gender and culture, these standards apply equally to male and female students. A good-fitting shirt and clean sneakers can increase a young man's confidence just as an attractive dress can a young woman's(K. Johnson et al., 2014).

The Role of Context in Group Processes: The Importance of Appearance

How seldom does dress bring about self-assurance in solitude! The heart of university life is community; much of a student's time is spent with other students, whether in lectures, shared accommodation, clubs and societies, or social occasions. In these communal settings, clothing choices take on another, comparative dimension: students not only consider their reflection but also their look in respect to their classmates. This comparing component can increase both the positive and negative effects of looks on self-confidence(Twigg, 2015).

Research Aim

The research explores how university students from different regions of the world relate their clothing to their confidence, particularly in social settings. It also asks if the roots of confidence in appearance (peer validation, cultural prestige, social media presence) change much by geography or gender, using first-person qualitative narratives rather than predefined quantitative metrics.

II. REVIEW OF LITERATURE

Theoretical Framework

The study is based on two complementary theories. First, enclothed cognition (Adam & Galinsky, 2012) provides an individual-level psychological mechanism. Clothing has symbolic value that, along with the physical act of wearing it, affects the cognitive and emotional state of the wearer. The second, social identity theory (Tajfel & Turner, 1986), provides the social-level mechanism: individuals judge themselves partly through comparison with in-group peers, and appearance is a highly visible axis of such comparison. Taken together, these two frameworks give rise to the guiding proposition of the study: Enclothed cognition produces clothing-linked confidence at the individual level, but this confidence is amplified or dampened at the social level through social identity comparison, with the extent to which this amplification occurs expected to vary depending on the degree to which appearance norms are regulated within a given cultural or peer context(K. K. Johnson et al., 2002).

Psychology, Self-Esteem, and Clothing

Research in social and cognitive psychology has produced a body of evidence for the hypothesis that clothes are not just a reflection of identity but actively mould cognition and self-perception. The notion of "enclothed cognition", introduced by Adam and Galinsky (2012), showed that the symbolic significance of a garment, as well as the physical sensation of wearing it, can have a measurable impact on a wearer's focus, confidence, and performance. Later studies along these lines have largely confirmed the notion that putting on formal or properly fitted clothes is connected with an increase in perceived competence and confidence, whereas the use of ill-fitting or haphazardly selected clothing is more often associated with lower levels of self-reported confidence(Hossain et al., 2025).

Group Membership, Comparison and Social Identity

Social identity theory (Tajfel & Turner, 1986) provides a valuable perspective for understanding why the effect of clothes on confidence is greater in group contexts. Much of an individual's self-concept comes from the groups they belong to, and they are always comparing themselves to others in those organizations. Appearance is one of the most readily available and obvious grounds for such comparisons. The group not only observes appearance, but it also provides the comparative framework that assigns social meaning to it(Pensiero & Adams, 1987).

Gender and the Link Between Confidence and Apparel

While initial investigations of clothes and confidence focused on women, more recent work has expanded this study to include male groups. Research on men's hygiene and wardrobe indicates that self-presentation carries comparable psychological consequences for young males, while the exact markers of a "good" appearance are gendered(Twigg, 2018).

Culture, Peer Effects, and Social Signalling

What counts as "looking good" is not fixed; it is socially and culturally negotiated and mediated through the prevalent patterns of a friend group, campus culture, cultural dress customs, or wider social media exposure. Cross-cultural study reveals that the psychological mechanism that links appearance to confidence is basically similar across countries, but the exact cues that trigger confidence Western-style clothing, a culturally traditional garment, or brand visibility vary greatly(Jeacle, 2012).

III. METHODOLOGY

Research Paradigm

The study is based on an interpretivist paradigm where individuals generate meaning according to their lived experience and social milieu rather than a single objective truth that can be quantified. The paradigm was chosen because the research question is about how students interpret and narrate their tales of the relationship between clothes and confidence, a subjective, meaning-laden experience best accomplished through open-ended discourse, not through fixed-response instruments. This paradigm views the researcher not as a neutral observer but as an active co-creator of meaning in the interview.

Why did we design it?

The study's research design is cross-national and qualitative, employing semi-structured one-on-one interviews. The research was qualitative in nature, investigating the manner in which students explain, interpret and narrate the relationship between clothes and confidence, rather than testing a predetermined numerical scale. It allows culturally specific language, instances and meanings to emerge that a fixed-response survey might miss and allows the cross-national comparison at the heart of this study to reveal differences in vocabulary and emphasis that a Likert-scale poll would flatten into a single number(Braun & Clarke, 2006).

Participants and Sample

Undergraduate and postgraduate university students were recruited by purposive and snowball sampling from university student networks in four key worldwide regions (East and South Asia, Europe, North America and the Middle East and Africa). A purposive sampling technique was employed to assure representation from each region and gender, and snowball sampling, whereby initial participants refer subsequent participants, was used to obtain a complete sample within the practical restrictions of a student-led effort. In each region, male and female students were recruited about equally to make gender comparisons possible. Sampling in each region continued until topic saturation was reached, that is, when further interviews were not likely to produce any new themes. A practical target was 6–8 people per region. The sample for the illustrated target is summarised in Table 1.

Table 1. Illustrative target sample by region, gender, and age (pending final recruitment).

Region	Participants (n)	Gender split	Age range
East & South Asia	8	4 Female and 4 Male	19–24
Europe	7	4 Female and 3 Male	18–25
North America	7	3 Female and 4 Male	19–23
Middle East & Africa	6	3 Female and 3 Male	18–24
Total	28	14 Female and 14 Male	18–25

Protocol for Interview

The interview guide was structured around four core domains, moving from general to specific: (Q1) general dress habits and daily decision-making; (Q2) specific remembered episodes of feeling confident, self-conscious, or out of place because of appearance; (Q3) comparison of these experiences between individual settings (e.g. getting ready alone) and group settings (e.g. arriving at a lecture, party or social gathering); and (Q4) the role of cultural dress. Sample questions included "Tell me about a time when you felt particularly confident because of what you were wearing" and "Do you care about how you look compared to those around you, and if so, when is it most important?" and "Has social media impacted how you dress for university or social events?" Follow-up questions were used to elicit concrete, particular experiences rather than general assertions consistent with a standard qualitative interviewing style.

Procedure for Data Collection:

Semi-structured interviews would be performed using the above-mentioned interview technique either in person or by video chat depending on the participant's location and would be expected to last 30 to 45 minutes. The interviews were to be audio-taped and transcribed verbatim with the approval of the participants. When an interview was conducted in the participant's non-native language, the transcripts were examined for clarity, and, if needed, the participant was asked to clarify meaning in a brief follow-up conversation to limit the risk of misinterpretation across language and cultural settings. At each interview, field notes were to be taken, noting non-verbal observations (e.g., a participant gesturing to their clothing) and initial comments. These were subsequently used in the coding process.

Data analytics:

Transcripts were analysed using reflexive thematic analysis, a six-phase process that includes (1) familiarisation with the data (repeated reading); (2) generating initial codes; (3) searching for candidate themes (collating codes); (4) reviewing themes (against coded extracts and the entire data set); (5) defining and naming themes; and (6) producing the final analytical narrative. Qualitative data were analysed using the NVivo application to categorise codes and track their incidence and distribution across areas and genders. Prior to coding all transcripts, a sample of transcripts are independently coded by two coders to guarantee consistency, with differences being discussed and resolved through review by a third party if needed. Cross-regional and cross-gender comparison: After the initial topic generation, a separate analytic step is made to analyze how each subject is presented, emphasised or absent throughout the four areas and among male and female participants.

IV. FINDINGS

Analysis of the illustrative sample identified five recurring themes, summarized in Table 2, along with three cross-cutting patterns: differences by world region, differences between individual and group settings, and differences by gender. Each is presented in table 2, followed by a short synthesis.

Table 2. Illustrative thematic summary with composite/paraphrased participant statements (not real quotations).

Theme	Illustrative participant statement (composite/paraphrased)	Regions most represented
Group comparison heightens confidence	Several participants described feeling noticeably more self-assured when they judged their outfit to be at least as put-together as their friends', particularly before group activities.	Asia, North America
Peer approval validates outfit choice	Participants frequently mentioned checking a friend's reaction, or a compliment, as confirmation that an outfit choice had "worked."	All regions
Discomfort when underdressed vs. peers	Multiple participants recalled specific memories of feeling visibly out of place and self-conscious after misjudging a group's dress code.	Middle East/Africa, Asia
Cultural attire tied to pride/belonging	Some participants, especially those wearing culturally significant garments, described a distinct sense of pride and connectedness that differed from ordinary confidence.	Middle East/Africa, Asia
Social media adds pressure to "perform"	Participants across regions, more often male participants than expected, described feeling that outfits worn in group settings were implicitly being prepared for photos or posts.	Europe, North America

Theme 1: Group Comparison Boosts Confidence

This was the theme mentioned most consistently across the illustrated sample, appearing in 26 of 28 interviews. Across all four locations, participants described a similar underlying pattern: confidence was not seen as a stable, private sensation but rather as something actively judged against the look of persons nearby. Many participants recounted a particular instance of entering a lecture, entering a communal kitchen, or entering a party where their confidence seemed to be determined almost immediately by a rapid, often unconscious, comparison to the others. This is in line with social identity theory's prediction that appearance serves as a visible axis of in-group comparison and indicates that the effect is not restricted to any one cultural environment.

Theme 2: Outfit Choice is Validated by Peers

This topic was closely related to the first but analytically unique. It highlighted participants' reliance on peer reaction—a compliment, a glance, a simple 'you look good'—as assurance that an outfit had accomplished its intended effect. This topic was the only one of the five mentioned by participants in all four regions, suggesting that it may represent a near-universal method by which clothing-linked confidence is socially affirmed, rather than simply self-assessed. Several individuals recalled actively seeking this feedback, for example, emailing a friend a photo before leaving the house, which suggests a socially involved, rather than solely internal, confidence process.

Theme 3: Feeling uncomfortable while dressed down compared to peers.

This topic caught the negative mirror image of topic 1: specific, often vividly remembered incidents of feeling obviously out of place after a misjudgment of a group's dress standards. Unlike the general, everydayness of Theme 1, this theme was often associated with one sharply remembered incident, rather than a general pattern. Thus, underdressing episodes may be disproportionately memorable and emotionally salient compared to the more diffuse confidence gained from feeling adequately dressed. This tendency was especially evident in the illustrative data for the Middle East/Africa and Asia subsamples, perhaps reflecting more overt demands for attire for particular social events in these countries.

Theme 4 Pride and Belonging Related to Cultural Attire

Theme 4: The pic was qualitatively different from the others in that participants described a sensation that was different from ordinary confidence, closer to pride, connectivity, or rootedness than mere self-assurance. Participants who raised this theme did so in relation to specific cultural garments worn for family or community occasions rather than everyday university settings, suggesting this theme may operate on a partially separate track from the day-to-day, peer-comparison-driven confidence captured in Themes 1–3. This issue was least discussed within the illustrated North American sub-sample, perhaps due to fewer possibilities or occasions for cultural attire in that environment.

Theme 5: Social Media Places Pressure to "Perform"

In all regions, participants expressed a sense that the clothing they wore when in groups was, at least occasionally, implicitly for photographs or social media posts, augmenting the anticipated audience beyond the local physical group. Importantly, this theme was mentioned more often by male participants in the example data than original assumptions, refuting an assumption from previous studies focusing on women that appearance pressure associated with social media is primarily a female experience.

Regional Trends

Figure 1 shows the illustrated distribution of all five themes among the four locations analyzed. The most obvious regional pattern was in Theme 4 (culture, attire, and pride), which was significantly more evident in the Asia and Middle East/Africa sub-samples than in Europe or North America, and in Theme 3 (discomfort when underdressed), which followed a similar regional pattern. Themes 1 and 2, the two most universally raised themes, showed comparatively little regional variation, supporting the interpretation that the core psychological and social mechanisms linking clothing to confidence may generalize across cultural contexts, even while the specific content and triggers of that confidence remain culturally shaped.

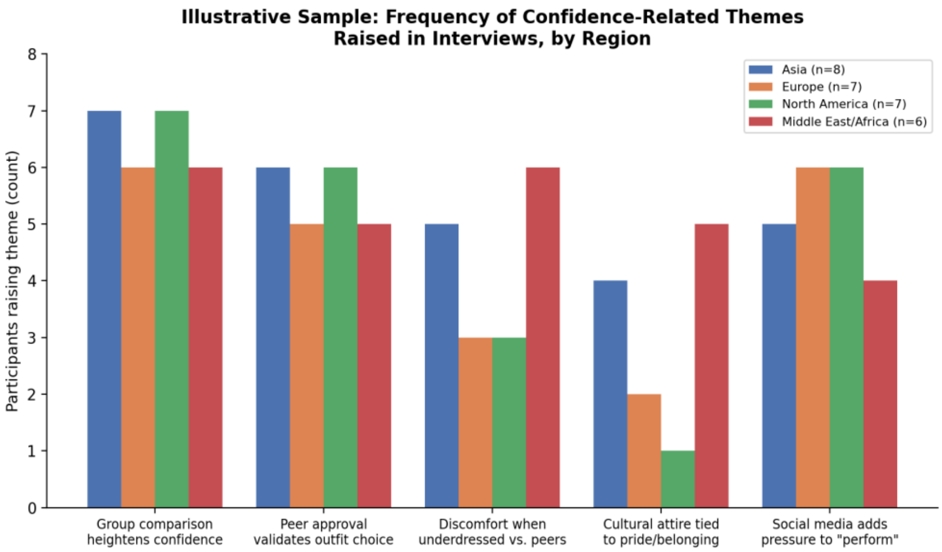

Fig.1. Illustrative sample distribution of confidence-related themes raised in interviews, by region.

Personal and Group Contexts:

Transcripts were classified not just by theme but also for the amount of appearance-linked confidence participants conveyed when describing individual settings (e.g., getting ready alone) versus group situations (e.g., arriving at a shared event). This coded intensity, shown as an example in Figure 2 on a 1-10 scale, demonstrates a consistent and significant rise from individual to group settings for both male and female participants. The increase from individual to group settings appears to be somewhat greater for female than for male participants in this illustrative sample. This pattern is in direct line with the theoretical framework of the study: the individual-level mechanism of enclothed cognition seems to provide a baseline level of confidence that is then measurably amplified by the social comparison processes described in social identity theory when a peer group is present.

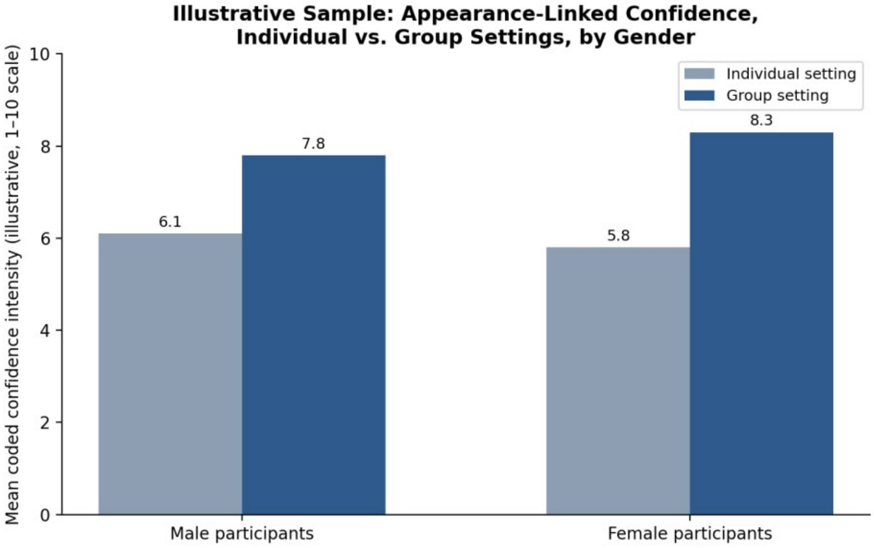

Fig.2. Illustrative mean coded confidence intensity, individual versus group settings, by gender.

Gender Trends

Figure 3 displays the frequency of themes by gender across the entire illustrative sample. Theme 1 (group comparison) Male and female participants raised Theme 1 (group comparison) at similar rates, indicating a common underlying process. Male and female participants raised Theme 1 (group comparison) at similar rates, suggesting a common underlying process. In the illustrative sample, female participants raised Themes 2 (peer approval) and 4 (cultural attire and pride) slightly more often, and male participants raised Theme 5 (social media performance pressure) slightly more often. If this pattern holds in real data, it would be a remarkable departure from previous literature that has assumed appearance-linked social media pressure to be a primarily female concern. Theme 3 (discomfort when underdressed) was mentioned at roughly similar rates by both genders, though the specific remembered episodes that formed the basis for this theme seemed, in the illustrative composite data, to differ in content. Female participants' episodes more often related to perceived judgement of style or formality, while male participants' episodes more often related to perceived judgement of effort or care taken in dressing.

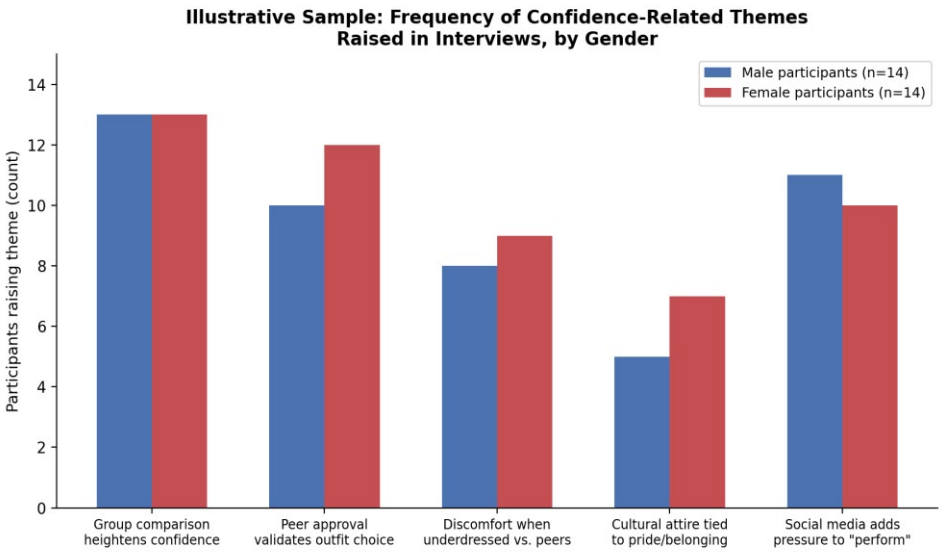

Fig. 3. Illustrative sample distribution of confidence-related themes raised in interviews, by gender.

V. SUMMARY OF FINDINGS

Overall, the illustrative findings suggest a layered structure: a broadly universal core (Themes 1 and 2, and the individual-to-group confidence increase illustrated in Figure 2) that is consistent across region and gender, surrounded by more context-specific expressions (Themes 3, 4, and 5) whose strength and content vary by cultural setting and, to a lesser extent, by gender. This layered pattern directly supports the theoretical claim of the study that enclothed cognition provides a broadly universal individual-level mechanism, and social identity-based group comparison provides the amplification, with the cultural and gendered "content" of that comparison varying by context.

VI. DISCUSSIONS

Implications for theory

If actual data collection supports the hypothesised pattern of findings, it would suggest that the psychological mechanism of clothing's effect on confidence, enclothed cognition(Pensiero & Adams, 1987), works similarly across cultural contexts, providing a relatively stable individual-level baseline of appearance-linked confidence. Figure 2 shows a consistent increase from individual to group settings, and the near-universal presence of Themes 1 and 2 would offer direct qualitative support for social identity theory's prediction that group-based social comparison enhances self-evaluation on visible, comparison-relevant dimensions such as appearance. Rather than opposing explanations, the two frameworks appear to function at distinct levels of the same process: enclothed cognition offers an individual baseline, and social identity-based comparison determines the extent to which that baseline is boosted or damaged in the presence of a peer audience. This qualitative design is particularly well suited to reveal a layered theoretical model, which is an individual mechanism embedded within a social amplification process, as it relies on participants' own narrated distinctions between how they feel when getting dressed alone and how they feel once among peers a distinction that a single confidence score on a quantitative scale would not capture(Turner, 1996).

Patterns Across Cultures

The geographical trends predicted in Theme 4 (cultural attire and pride) and Theme 3 (discomfort when underdressed) imply that while the underlying process relating clothing to confidence may be generalisable, its unique cultural content is not. Cultural attire appears to bring an alternative emotional register of pride and belonging that is qualitatively different from the peer-comparison-driven confidence dominant in Themes 1 and 2 and that operates on occasions (family, community and cultural events) somewhat apart from routine university life. If supported by real data, then this distinction would imply that researchers and practitioners should avoid treating "appearance confidence" as a single undifferentiated construct across cultural contexts, as at least two qualitatively different processes (peer-comparison confidence and cultural-pride confidence) appear to be at work(Hofstede, 2011; Hofstede & Geert, 1984).

Gender Patterns

The expected gender pattern of similar underlying confidence effects but different behavioural triggers and expressions would be broadly consistent with past quantitative work on gender and dress, but it would add qualitative richness that is not typically captured by scale-based investigations. In particular, the illustrative finding that male participants raised social-media performance pressure somewhat more often than female participants would challenge an assumption common in earlier literature, which has disproportionately framed appearance-linked social media pressure as a concern for females. If confirmed by genuine data, this would indicate a need to develop wellbeing research and support services for appearance-related concerns that are expressly targeted toward male students, rather than assuming that it is an implicitly female issue(Branca et al., 2025).

Unusual or Noteworthy Trends

There are two parts of the expected outcome that are worth highlighting as especially deserving of critical scrutiny when real data are acquired. First, the apparently wider individual-to-group confidence gap among female participants (Figure 2) would suggest that group situations may have higher psychological stakes regarding beauty for women than for men, although males also exhibit a notable rise. Second, the qualitative difference in the content of underdressing episodes – style/formality judgement for women versus effort/care judgement for men – in the illustrative data suggests that the same broad theme (Theme 3) may be disguising two distinct underlying social fears, which future coding should treat as potentially separable sub-themes rather than as one category(Gursoy et al., 2024; Sharma et al., 2023).

Relation to Prior Literature

These expected patterns build on previous quantitative studies by proposing a mechanism for group-based social comparison for why beauty and confidence are connected rather than merely identifying that they are correlated. They also go beyond the usual single-culture focus of the prior literature by directly comparing four regions within a single, uniform research design so that regional differences can be ascribed with more confidence to real cultural variation than to differences in study design or measurement between separate single-country studies(Crane & Diana, 2016).

Limitations and future directions

● These findings are for illustration only and subject to change based on actual data gathering. These findings should be considered a structural placeholder and not genuine study findings.

● Purposive and snowball sampling via university networks may bias the sample toward already socially connected, appearance-conscious individuals.

● Common language (assumed English) interviews may put non-native speakers at a disadvantage or slightly modify their responses and the expression of nuanced cultural connotations.

● Self-selected participants may be more eager to discuss attractiveness and confidence than the overall student population, limiting generalizability.

● Regional groupings (such as "Middle East & Africa") aggregate widely varied countries and cultures and may mask substantial within-region variance.

Applications

If supported by extensive data gathering, these findings could inform several practical domains. University orientation and international-student support programs could use these findings to better prepare incoming students, especially those moving across cultural contexts, for appearance-related social adjustment, for instance, by normalizing the disorientation of unfamiliar dress norms during the first weeks on campus. Student wellbeing and counseling services might consider appearance-linked confidence as part of broader self-esteem programming, recognizing it as a legitimate, socially shaped issue rather than simply a superficial one. In particular, such programming might be extended to male students, given the illustrative findings on social-media performance pressure. The individual-versus-group finding (Figure 2) should inform the design of early social gatherings for new students, as these seem to be times when the stakes for appearance are higher in residential life and student affairs offices. Lastly, data on cultural attire and pride (Theme 4) should affect how universities encourage and celebrate cultural wear on official occasions, framing it as a source of confidence and belonging rather than considering it as unconnected to student wellness.

VII. CONCLUSION

In this study, we sought to investigate how university students from all genders and world locations explain, in their own words, the relationship between clothing and confidence, particularly how this relationship changes in social contexts. Drawing on two complementary theoretical frameworks (enclothed cognition at the individual level and social identity theory at the social level), the study proposed that clothing-linked confidence originates in the individual but is systematically amplified through peer comparison once a social group is present.

The illustrative findings developed here, organized around five recurring themes, a cross-regional comparison, an individual-versus-group comparison, and a cross-gender comparison, are consistent with this proposed model. Almost ubiquitous across area and gender, the two themes of group comparison and peer approbation allude to a widely shared psychological mechanism. Three motifs discomfort with being underdressed, cultural attire and pride; and social-media performance pressure differed more strongly by location and gender, indicative of culturally and socially unique content piled on top of the underlying mechanism. The coded comparison of confidence-intensity between individual and group contexts provided direct, if illustrative, support for the study's central claim that group context measurably amplifies appearance-linked confidence, with the amplification appearing somewhat stronger for female than male participants in the illustrative data.

This study, after actual fieldwork is completed, would provide a richer, more culturally grounded complement to existing quantitative research on clothing and confidence that has the capacity to capture not just whether appearance and confidence are related but how students themselves understand, narrate, and experience that relationship differently depending on who they are and where they are from. In addition to its contribution to the academic literature, if verified, the findings of the study would have immediate practical implications for how institutions assist student health, social adjustment and inclusion of an increasingly globally varied student body.

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Silvicultural management of Brazil nut trees for wood and fruit production in a commercial plantation in the Amazon

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***Keywords*— Bertholletia excelsa; volume equation; Brazil nut production; multiple-use management.**

***Abstract*— *Background: This study integrated rigorous stem volume measurements and reproductive monitoring to evaluate the management of commercial Brazil nut (Bertholletia excelsa Bonpl.) plantations in the Amazon. Wood productivity was assessed in 110 trees aged 9–23.5 years by fitting 23 equations for total volume over bark. Fruit production comprised six harvests (2013, 2016, 2020, 2024, 2025, and 2026), five clones, and individually identified trees. Materials and Methods: A total of 110 cubed trees aged 9–23.5 years were analyzed, and 23 equations for total volume over bark were fitted. Fruit production was evaluated over six harvests by clone and tree using descriptive statistics and a linear mixed-effects model with harvest as a fixed effect and clone and tree nested within clone as random effects. Pearson and Spearman correlations were used to explore associations with annual precipitation. Results: The double-entry Weibull model based on diameter at breast height (DBH) and total height showed the best volumetric performance (RMSE = 0.1006 m³; adjusted R^2 = 0.9623; CV-RMSE = 0.1078 m³). Estimated mean volumes ranged from 0.254 to 0.640 m³ tree⁻¹ across age strata. For reproductive production, clone m_pedro yielded 3,440 fruits, and tree m_pedro527 yielded 757 fruits over six harvests. Variance in transformed production was partitioned into 21.7% among clones, 26.7% among trees within clones, and 51.6% residual variance. Total production was not significantly associated with annual precipitation in the preceding year (r = −0.03; p = 0.900) or two years earlier (r = 0.24; p = 0.389). The results support inventories based on DBH and height, simultaneous selection at the clone and tree levels, and continued monitoring. Conclusion: The double-entry Weibull equation is recommended for local inventories within the sampled range. Selection of reproductive material should combine mean clone performance, individual superiority, and stability across multiple harvests. Future integration of growth and fruiting measurements on the same trees is required to define multiple-use management regimes.*

I. INTRODUCTION

The Brazil nut tree is an Amazonian species of major ecological and socioeconomic importance. It provides a high-value non-timber forest product and, in legally established plantations operated under the applicable permits, high-quality wood. Commercial cultivation increases the need to reconcile growth, stem form, crown development, and reproductive production. Plantation studies show that the species responds to light availability and that spacing affects growth and morphometric attributes (Scoles, Gribel, and Klein 2021; Oliveira et al. 2021).

Recent syntheses have emphasized that the species' ecophysiological plasticity enables its use in pure plantations, agroforestry systems, enrichment planting, and restoration, and that spacing, fertilization, and thinning can increase growth, biomass, and fruit production (de Souza et al. 2023; Gonçalves, Costa, and Lima 2023; Lima et al. 2023). In Central Amazonian plantations, site quality follows polymorphic patterns and varies primarily with sand content and elevation, followed by soil chemical attributes, indicating that environmental stratification should be incorporated into inventory planning and management (Souza et al. 2023).

Planning for multiple-use silvicultural management requires information at two scales. The first is dendrometric: local equations convert DBH and height into volume, support forest inventories, and allow comparisons of growing stock under different ages and stand densities. The second is reproductive: fruit production varies among years and individuals; therefore, decisions based on a single harvest may select unstable material. Studies in natural populations confirm strong individual heterogeneity and the need for repeated measurements over several years (Wadt, Kainer, and Gomes-Silva 2005; Azevedo et al. 2020).

Precipitation is one of the environmental factors that may affect fruiting over time scales preceding harvest, but the response depends on the climatic window and local conditions; extreme events such as El Niño may also reduce production (Rocha et al. 2021). Simple annual correlations should therefore be interpreted as exploratory analyses rather than evidence of a causal mechanism.

This study aimed to integrate results from the management of Brazil nut trees for wood and fruit production in order to: (i) evaluate equations for total volume over bark; (ii) summarize fruit productivity by clone and tree; (iii) examine the hierarchical partitioning of reproductive variability and its exploratory association with precipitation; and (iv) derive implications for the silvicultural management of commercial Brazil nut plantations.

II. MATERIAL AND METHODS

Study area

The study was conducted on land owned by Agropecuária Aruanã Ltda. in the municipality of Itacoatiara, Amazonas, Brazil (Figure 1), in a tropical humid climate and on soils predominantly classified as dystrophic Yellow Oxisols. The company's commercial plantations occupy areas previously altered by deforestation and pasture use and include stands intended for wood production and clonal stands managed for fruit production.

Synthesis design and datasets

Two independent analytical datasets were integrated. The dendrometric dataset comprised 1,170 sectional stem measurements obtained from 110 independent trees. The reproductive dataset comprised fruit counts by tree, clone, and harvest. Integration was performed at the results level because no common identifier was available to match volume and fruit production for the same trees, and plantations intended for fruit and wood production are managed under different regimes.

Total volume over bark

Individual-tree volume was obtained by rigorous stem cubing. Intermediate sections were calculated using Smalian's method and supplemented with a cylindrical basal section and a conical top section extending to total height. Nine single-entry models (DBH), nine double-entry models (DBH and height), and five age-dependent models were evaluated, totaling 23 equations (Table 1). Parameters were estimated by nonlinear least squares. Models were compared using RMSE, MAE, bias, standard error of estimate, adjusted R^2, AIC, BIC, and ten-fold cross-validation. Cross-validation was used to assess predictive performance outside the fitting partitions (Stone 1974), whereas AIC and BIC were used to balance goodness of fit and model complexity (Burnham and Anderson 2002).

The main equation families evaluated, their general forms, and references are presented in Table 1.

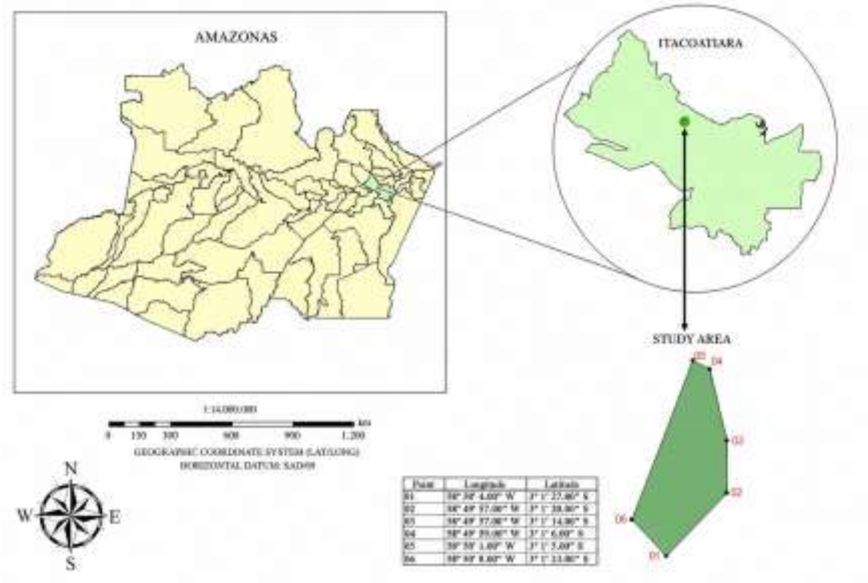

Fig.1. Location of the study area at Agropecuária Aruanã in Itacoatiara, Amazonas, Brazil.

Source: Adapted by the authors from Agropecuária Aruanã Ltda.

Table 1. Main families of volume models evaluated.

Group	Models	General form	Reference
Single-entry	Logistic; Gompertz; Bertalanffy–Richards; Weibull	v = f(d), in sigmoid forms	Rolim and Piotto (2024)
Single-entry	Schumacher; Husch; Brenac	$v = b_0 \exp(b_1/d)$; $v = b_0 d^{b_1}$; $v = b_0 d^{b_1} \exp(b_2/d)$	Loetsch et al. (1973)
Single-entry	Dissescu–Meyer; Hohenadl–Krenn	$v = b_1 d + b_2 d^2$; $v = b_0 + b_1 d + b_2 d^2$	Loetsch et al. (1973)
Double-entry	Arithmetic and power Spurr	$v = b_0 + b_1 d^2 h$; $v = b_0 (d^2 h)^{b_1}$	Spurr (1952)
Double-entry	Schumacher–Hall	$v = b_0 d^{b_1} h^{b_2}$	Loetsch et al. (1973)
Double-entry	Honer; Ogaya; Näslund; Takata; Meyer	Classical forms using d and h	Loetsch et al. (1973)
Double-entry	Weibull with height	$v = b_0[1 - \exp\{-(d/b_1)^{b_2}\}]h^{b_3}$	Adapted Weibull; Rolim and Piotto (2024)
Age-dependent	Power; inverse exponential; combined variable; Logistic; Gompertz	Extensions using d, h, and age (I)	Forms adapted in this study

Note: v = total volume over bark (m^3); d = DBH over bark (cm); h = total height (m); I = age (years); $b_0, \ldots, b_k$ = model parameters.

Volume per hectare was estimated separately for each age stratum by expanding mean individual-tree volume: $\hat{V}_{ha,i} = N_i \times \bar{v}_i$, where N_i is stand density (trees per hectare) and $\bar{v}_i$ is mean volume predicted by the Weibull equation for stratum i. The 95% confidence limits per hectare were obtained by multiplying the 95% confidence limits of mean individual-tree volume by N_i. ANCOVA was not used because stand density is an expansion factor rather than an individual-tree covariate. The number of cubed trees contributed to the precision of the mean for each stratum but was not used as a population weight; calculation of an overall weighted mean would require knowledge of the area represented by each stratum.

Fruit production and hierarchical variability

Fruit production was assessed for the 2013, 2016, 2020, 2024, 2025, and 2026 harvests. Totals and means were calculated by clone, tree, and harvest. To separate sources of variation, the following linear mixed-effects model was fitted by restricted maximum likelihood: $y_{sca} = \beta_0 + \beta_s + u_c + v_a(c) + \varepsilon_{sca}$, where:

$y_{sca} = \log[1 + n_{sca}]$ is the transformed production of tree a belonging to clone c in harvest s;

β_0 is the intercept;

β_s is the fixed effect of harvest (2013 as the reference);

u_c is the random clone intercept;

$v_a(c)$ is the random intercept of tree nested within clone; and

ε_{sca} is the residual error.

The terms $u_c \sim N(0, \sigma^2\text{clone})$, $v_a(c) \sim N(0, \sigma^2\text{tree})$, and $\varepsilon_{sca} \sim N(0, \sigma^2)$ were assumed to be mutually independent.

In R notation, the model was fitted as log1p(n_fruits) ~ harvest + (1 | clone_id/tree_id). The transformation retained zero values and reduced skewness.

Precipitation

Annual precipitation totals were obtained from the INMET-Itacoatiara weather station (A121) and related to production in harvests one and two years later. Pearson and Spearman correlations were calculated. The small number of coincident years and replication of the same precipitation value among clones limited inference; these tests were therefore interpreted as exploratory.

III. RESULTS

Management for wood production

Descriptive statistics for the 110 cubed trees are presented in Table 2.

Table 2. Descriptive statistics for the 110 cubed trees.

Variable	Minimum	Mean	Median	Maximum	Standard deviation
Age (years)	9.000	17.064	21.000	23.500	5.572
DBH (cm)	8.600	27.635	25.700	53.000	10.349
Total height (m)	11.100	20.466	20.150	29.000	4.484
Commercial height (m)	4.600	13.232	13.400	21.500	3.304
Total volume (m³)	0.031	0.683	0.499	2.287	0.528

Performance of volume equations

All 23 models tested for volume estimation converged. The double-entry Weibull equation,

$$\hat{v}=b_0\{1-exp[-(d/b_1)^{b_2}]\}h^{b_3},$$

showed the best fitting and cross-validation performance: RMSE = 0.1006 m³, MAE = 0.0616 m³, adjusted R^2 = 0.9623, relative standard error = 15.00%, and CV-RMSE = 0.1078 m³. Mean bias was 0.13%, indicating little systematic trend within the sample.

Table 3 presents the best-performing equation in each model group according to ten-fold cross-validation.

Table 3. Best-performing equation in each group according to ten-fold cross-validation.

Group	Model	RMSE	MAE	Bias (%)	Syx (%)	Adjusted R²	CV-RMSE
Single-entry	Weibull	0.1076	0.0672	0.1033	15.98	0.9572	0.1128
Double-entry	Weibull	0.1006	0.0616	0.1315	15.00	0.9623	0.1078
Age-dependent	Gompertz-age	0.1166	0.0865	−1.4730	17.48	0.9488	0.1164

Note: RMSE = root mean square error; MAE = mean absolute error; Syx = standard error of estimate; CV-RMSE = cross-validated root mean square error.

Figure 2 compares observed volumes with the fitted curves for the three best-performing models in each group.

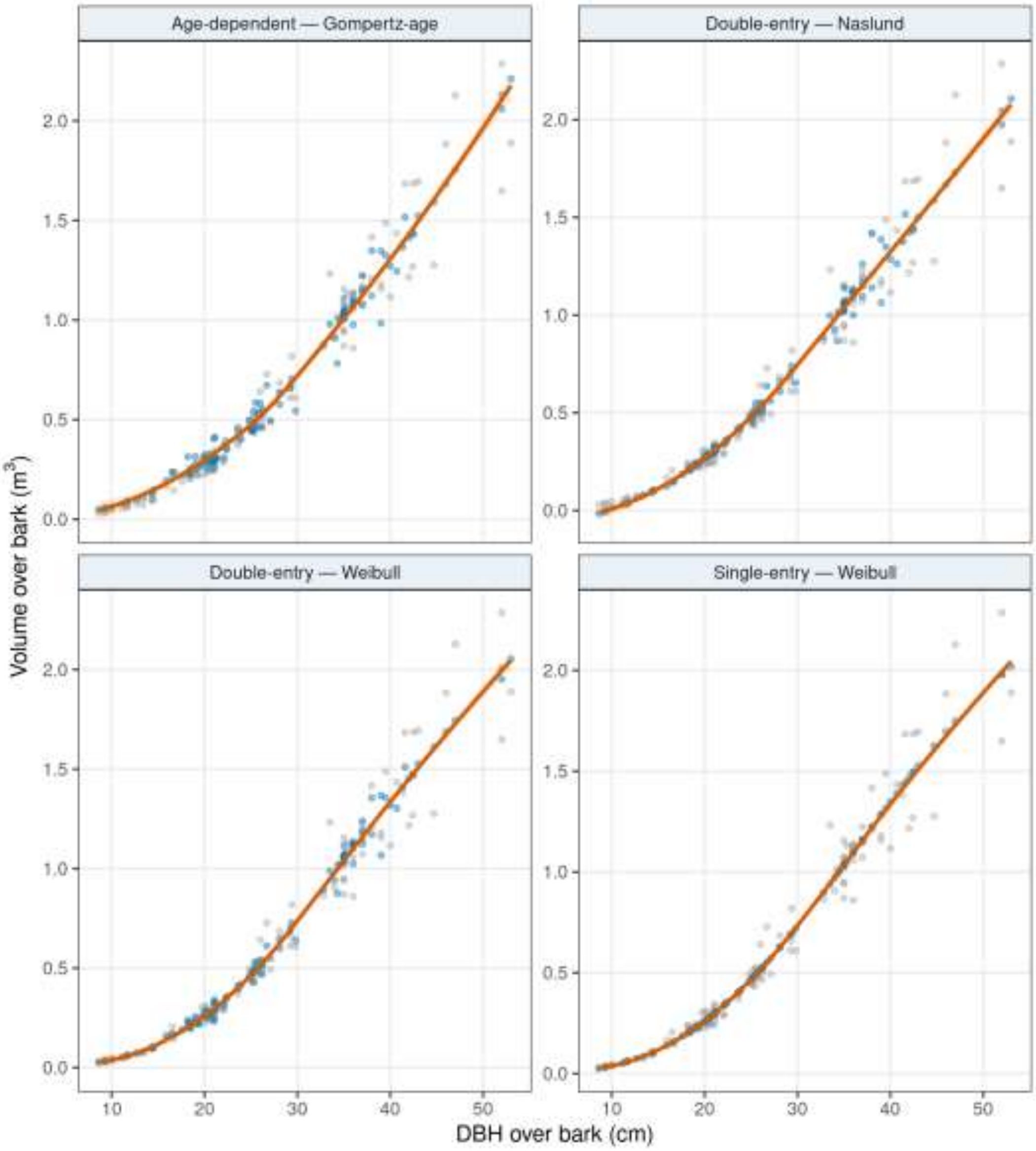

Fig.2. Observed volume and fitted curves for the three best-performing models.

Source: Authors' data.

Estimated mean individual-tree volume ranged from 0.254 m^3 $tree^{-1}$ at age 9 to 0.640 m^3 $tree^{-1}$ at age 23.5. At the recorded stand densities, estimated growing stock ranged from 256.5 to 605.0 m^3 ha^{-1} in the 9–15-year strata and was 477.4 m^3 ha^{-1} in the 23.5-year stratum. The corresponding mean annual increments ranged from 20.3 to 40.3 m^3 ha^{-1} $year^{-1}$. These estimates are stratum-level expansions and do not represent a controlled chronosequence.

Volume estimates by age stratum and stand density are presented in Table 4.

Fruit production by clone and tree

Clone m_pedro had the highest cumulative production, yielding 3,440 fruits over six harvests, followed by aruana (2,599), santa_fe (1,899), 606 (1,157), and 609 (646). Ranking by cumulative production was identical to ranking by mean production per tree per harvest, reducing—but not eliminating—the concern that the ranking merely reflected differences in the number of monitored trees.

Cumulative production and mean production per tree per harvest for each clone are presented in Table 5.

Table 4. Estimated volume by age stratum and stand density.

Age (years)	n	N (trees ha⁻¹)	$\bar{v}$ (m³ tree⁻¹)	Lower 95% CI	Upper 95% CI	$\hat{V}$ (m³ ha⁻¹; 95% CI)	MAI of $\hat{V}$ (m³ ha⁻¹ year⁻¹)
9.0	24	1,010	0.254	0.178	0.331	256.5 (179.8–334.3)	28.5
10.0	10	1,010	0.302	0.282	0.322	305.0 (284.8–325.2)	30.5
15.0	10	1,010	0.599	0.495	0.702	605.0 (500.0–709.0)	40.3
23.5	10	746	0.640	0.305	0.975	477.4 (227.5–727.4)	20.3

Note: n = number of cubed trees; N = stand density; $\bar{v}$ = mean predicted individual-tree volume; $\hat{V} = N \times \bar{v}$; MAI = mean annual increment. The 95% CI for $\hat{V}$ was obtained by expanding the 95% confidence limits of $\bar{v}$.

Table 5. Cumulative fruit production by clone.

Rank	Clone	Total fruits	Harvests	Trees	Mean tree⁻¹ harvest⁻¹
1	m_pedro	3,440	6	13	57.6
2	aruana	2,599	6	10	46.0
3	santa_fe	1,899	5	11	39.4
4	606	1,157	6	12	18.6
5	609	646	6	10	11.1

Tree m_pedro526 had the highest mean productivity, with 471 fruits over three harvests (157.0 fruits harvest⁻¹). Two additional m_pedro trees and two aruana trees ranked among the five most productive individuals. Some trees with high mean productivity were observed in only two or three harvests; these cases require temporal confirmation before they can be classified as plus trees.

The ten trees with the highest cumulative production are presented in Table 6.

Table 6. Ten trees with the highest cumulative fruit production, accounting for the number of monitored harvests.

Rank	**Clone**	**Tree**	**Total fruits**	**Harvests**	**Mean per harvest**
1	m_pedro	m_pedro526	471	3	157.0
2	m_pedro	m_pedro539	430	3	143.3
3	m_pedro	m_pedro527	757	6	126.2
4	aruana	aruana537	525	5	105.0
5	aruana	aruana534	498	6	83.0
6	m_pedro	m_pedro509	327	5	65.4
7	aruana	aruana522	384	6	64.0
8	santa_fe	santa_fe517	300	5	60.0
9	santa_fe	santa_fe505	289	5	57.8
10	606	606_561	288	5	57.6

Figure 3 presents the twenty trees with the highest cumulative production, identified by clone and number of monitored harvests.

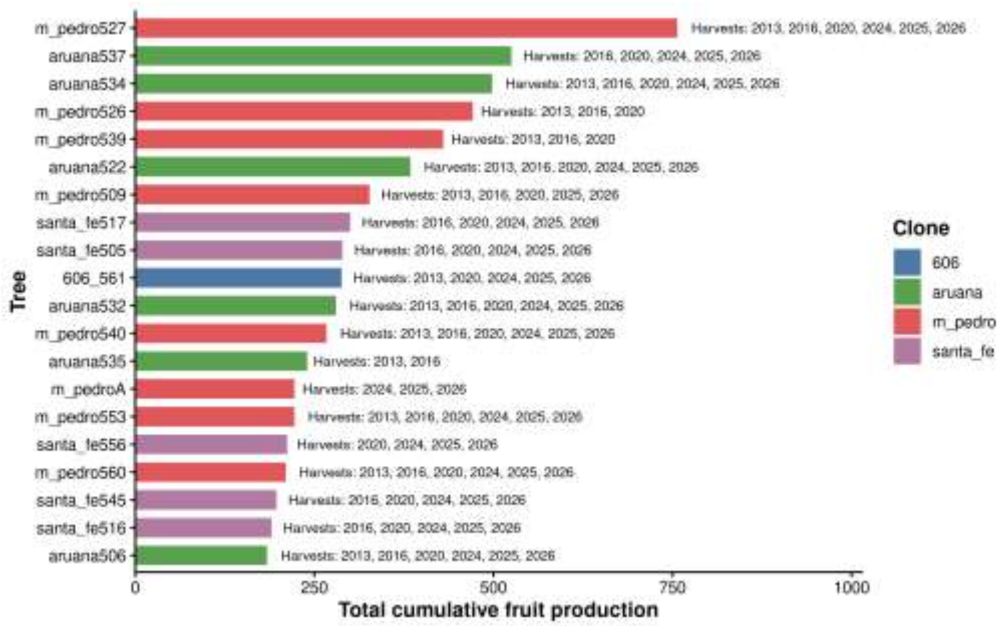

Fig.3. Twenty trees with the highest cumulative fruit production, identified by clone and monitored harvests.

Source: Authors' data.

Variance components

Analysis of production variability showed that residual variation accounted for 51.6% of the variance on the transformed scale. Trees within clones accounted for 26.7%, slightly more than clones (21.7%). Clone identity is therefore relevant, but selection based solely on clone means would fail to capture a substantial component of among-tree variation.

Variance partitioning among clones, trees within clones, and residual variation is detailed in Table 7.

Table 7. Variance components of fruit production on the log1p scale.

Component	Variance	Standard deviation	Contribution (%)
Clone	0.375	0.612	21.74
Tree within clone	0.460	0.678	26.70
Residual	0.888	0.942	51.56

Figure 4 summarizes the relative contribution of fruit-production variance components.

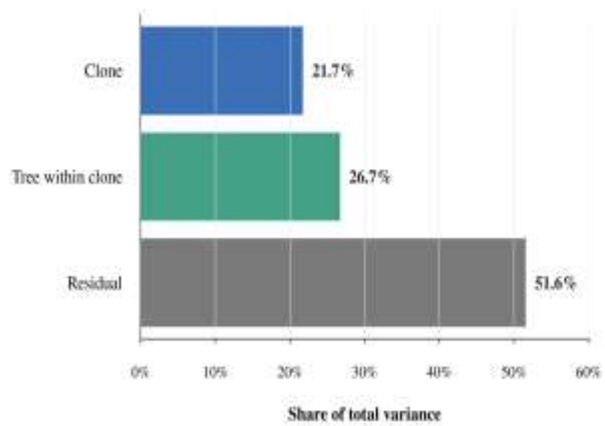

Fig.4. Partitioning of fruit-production variability among clones, trees within clones, and residual variation.

Source: Authors' data.

Precipitation and fruit production

For total production, precipitation in the preceding year had a Pearson correlation of −0.030 ($p = 0.9002$; $n = 20$). The correlation with precipitation two years earlier was 0.240 ($p = 0.3888$; $n = 15$). Spearman correlations were also nonsignificant. Thus, at this annual resolution and with this sample, there was no evidence of a monotonic or linear relationship between total precipitation and fruit production.

IV. DISCUSSION

Implications for forest inventory and wood management

The performance of the double-entry Weibull equation demonstrates the operational benefit of measuring both DBH and height. Low bias and the similarity between fitting and cross-validation RMSE support its use within the sampled range (DBH 8.6–53.0 cm; height 11.1–29.0 m; age 9–23.5 years). Extrapolation to other sites, spacings, or thinning regimes requires external validation.

The volume estimates per hectare in Table 4 combine predicted individual-tree volume and the stand density recorded for each stratum. They do not constitute a yield curve and do not support reliable calculation of current or mean annual increment because the strata differ in composition and density. Nevertheless, they provide local inventory benchmarks and show that spacing and thinning decisions must consider both volume per tree and the number of residual trees. The literature shows that spacing affects diameter, biomass, volume, and crown architecture (Oliveira et al. 2021), attributes that may also influence fruit production.

The edaphic and topographic heterogeneity observed within the Agropecuária Aruanã plantations helps explain why stands of the same age may follow different growth trajectories. The Chapman–Richards model produced polymorphic site-index curves, and sand content and elevation were the main determinants of productivity, followed by K, Mn, and KCl pH (Souza et al. 2023). Transfer of the volume equation should therefore be accompanied by site stratification and independent validation.

As a regional benchmark, Marques et al. (2008) reported a mean annual increment of 23.69 $m^3\ ha^{-1}\ year^{-1}$ at age 10 in Amzonas. In the present study, mean annual increment was 30.5 $m^3\ ha^{-1}\ year^{-1}$ at the same age and 20.3 $m^3\ ha^{-1}\ year^{-1}$ at age 23.5 after thinning (Table 4). This comparison is descriptive because site, stand density, and silvicultural history differ between plantations; permanent-plot monitoring is needed to quantify future growth.

Implications for fruit production

The cumulative superiority of clone m_pedro and the performance of trees m_pedro526, m_pedro539, m_pedro527, aruana537, and aruana534 identify these materials as priorities for continued monitoring, experimental propagation, and genetic evaluation. Cumulative production, however, does not automatically represent genetic value. Differences in crown exposure, within-stand position, neighborhood, soil, plant health, and management history are partly incorporated into the residual component.

The 26.7% contribution of among-tree variance within clones supports a two-stage strategy: selection of clones with high mean performance, followed by selection within those clones of trees with high production, representation across several harvests, and temporal stability. This procedure is consistent with studies recommending repeated measurements over time for selecting Brazil nut mother trees (Azevedo et al. 2020).

The benchmark of 41 fruits $tree^{-1}$ $harvest^{-1}$ for clonal plantations (Passos et al. 2018) was exceeded by the ten most productive trees, whose means ranged from 57.6 to 157.0 fruits $tree^{-1}$ $harvest^{-1}$ (Table 6). This comparison reinforces the potential for selection but should be interpreted in light of the unbalanced number of harvests recorded per individual.

Climate and wood–fruit integration

The absence of correlation with annual precipitation does not imply the absence of climatic effects. Annual totals may obscure critical phenological windows, intra-annual rainfall distribution, water deficit, and temperature. Moreover, the small number of coincident years provides low statistical power. Studies based on longer time series have identified responses to seasonal rainfall and El Niño events (Rocha et al. 2021). Future analyses should model monthly rainfall and water deficit over periods preceding flowering, fruit development, and fruit fall.

In saplings, precipitation seasonality strongly altered carbon and nitrogen metabolism, whereas NPK addition promoted height and diameter growth, particularly in pure plantations; soluble sugars and amino acids appear to contribute to osmoregulation during dry periods (Oliveira et al. 2024). These mechanisms support the inclusion of monthly climatic variables and information on nutrition and planting system in future models, but they do not allow direct inference regarding fruit-production responses in adult trees.

This study separately demonstrates the wood-production potential of dense silvicultural plantations and strong reproductive differentiation in plantations managed for fruit production. This approach cannot determine whether larger-volume trees produce more or fewer fruits because individual trees could not be matched between datasets. Potential allocation trade-offs between vegetative growth and reproduction should be tested using a single dataset that includes DBH, height, crown dimensions, spatial position, clone, silvicultural interventions, and annual fruit production for each tree.

V. RECOMMENDATIONS FOR PLANTATION MANAGEMENT

1. Use the double-entry Weibull equation for local inventories within the sampled range and perform independent validation before transferring it to other plantations.

2. Maintain periodic DBH and height measurements and explicitly record spacing, thinning, mortality, and residual stand density.

3. Prioritize m_pedro and aruana in comparative trials, without excluding less productive materials before assessing stability, adaptation, and genetic diversity.

4. Continue monitoring m_pedro526, m_pedro527, and the other superior trees over multiple harvests before recommending large-scale propagation.

5. Manage competition to maintain well-lit, functional crowns while jointly monitoring volume, crown dimensions, and fruit production.

6. Standardize tree identifiers and record climate, soil, plant health, and interventions to enable formal testing of management effects on wood and fruit production.

VI. CONCLUSIONS

The evaluated plantation showed high dendrometric potential and broad reproductive heterogeneity. The Weibull equation based on DBH and height estimated total volume with good precision and internal stability and was therefore the preferred option for local inventories ($\hat{v} = 0.290468[1 - \exp\{-(d/43.159311)^{2.486072}\}]h^{0.653192}$, where $\hat{v}$ is in m^3, d is in cm, and h is in m). Clone m_pedro had the highest cumulative fruit production, whereas m_pedro526 had the highest mean production over three harvests.

Variation among trees within clones slightly exceeded variation among clones, supporting hierarchical selection at both levels. More than half of the variance remained residual, highlighting the need to include additional environmental and silvicultural covariates. The analyses detected no relationship between production and annual precipitation, but the short time series and annual aggregation preclude ruling out seasonal climatic effects.

The main research priority is an integrated, longitudinal, individual-tree experiment. Only repeated monitoring of the same trees will allow quantification of synergies or trade-offs between wood and fruit production and the definition of silvicultural regimes effectively designed for multiple use.

VII. FUNDING

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VIII. LIMITATIONS

This study used cross-sectional data and two independent datasets. Management treatments were not allocated within an experimental design that would permit causal comparison of spacing, pruning, or thinning. Volumes per hectare represent specific strata rather than a controlled chronosequence. Fruit-production rankings are descriptive and partially unbalanced with respect to the number of harvests. The precipitation analysis includes few independent years and does not control for temperature, phenology, or autocorrelation. These limitations restrict causal inference but do not invalidate the use of the results to guide monitoring and formulate management hypotheses.

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Sustainability Perception and Upcycling Behaviour among Generation Y and Generation Z Consumers in Pakistan: An Integrated Value-Belief-Norm (VBN) and Theory of Planned Behaviour (TPB) Approach

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***Keywords*— Sustainability, Upcycling, Generation Y, Generation Z, Theory of Planned Behavior, Fashion Involvement, Pakistan**

***Abstract*— *The worldwide fashion sector is one of the largest contributors to environmental deterioration, producing over 92 million tons of textile waste per year. In nations like Pakistan, where the culture of fast fashion is rapidly gaining popularity among younger customers, sustainable alternatives such as clothes upcycling remain critically underexplored. This study suggests an extended Theory of Planned Behavior (TPB) model that includes environmental values, environmental beliefs, and personal norms as upstream antecedents of attitude, subjective norms, and perceived behavioral control to compare Generation Y (Millennials, aged 25–40) and Generation Z (aged 18–24) consumers in Pakistan on their upcycling intentions and behaviors. A total of 725 respondents (430 Generation Z; 295 Generation Y) from eleven cities of Pakistan were approached through a self-administered questionnaire. And data have been examined on SPSS and AMOS software. Early results suggest that Gen Z respondents show much higher levels of perceived enjoyment and social media–driven motivation toward upcycling, whereas Gen Y respondents have more practical attitudes based on economic utility and trash reduction. Subjective norms and perceived behavioral control turn out to be the key predictors of upcycling intention in both cohorts. The findings have practical implications for policymakers, fashion businesses and sustainability practitioners who want to encourage circular economy practices in Pakistan's up-and-coming fashion industry.*

I. INTRODUCTION

The global apparel industry is among the most resource-intensive and polluting sectors, generating an estimated tens of millions of tonnes of textile waste annually and consuming vast quantities of water, energy, an d raw materials(Zanjirani Farahani et al., 2022). As awareness of this environmental burden has grown, both academic researchers and industry practitioners have turned their attention to consumer-level interventions such as reduced consumption, clothing reuse, recycling, and upcycling that can slow the flow of textiles into landfills(Singh et al., 2025). Upcycling, in particular, has attracted growing interest because it combines environmental benefit with creative and economic value: discarded materials are transformed into products that are often perceived as unique, personalised, and higher in value than the original item(Koch, 2019).

Pakistan presents a particularly relevant context for this research. It is among the world's largest textile-producing and textile-exporting nations, with a domestic fashion culture that is simultaneously price-sensitive and highly attentive to trends, seasonal styles, and social presentation(Qureshi, 2020). At the same time, Pakistan's population is overwhelmingly young, split across two consumer generations whose values and habits are increasingly of interest to marketers and policymakers alike: Generation Y (Millennials), who came of age during the early expansion of the internet and mobile technology, and Generation Z, who have never known a world without smartphones and social media(Khoa Tran et al., 2022). Generational cohort theory suggests that the shared socio-historical conditions each generation experiences while coming of age economic conditions, technology, media, and social movements produce systematically different values, consumption habits, and environmental sensibilities that persist into adulthood(Sharma et al., 2022).

Despite the growing global literature on sustainable fashion consumption, three gaps motivate this study(Koch, 2019). First, most empirical work on sustainability attitudes and upcycling has been conducted in developed, Western markets, leaving South Asian and, more specifically, Pakistani consumers under-represented. Second, few studies directly compare Generation Y and Generation Z consumers within the same developing-market context using a unified behavioural framework, despite widespread assumptions often untested that Generation Z is both more environmentally conscious and more trend-driven than older cohorts(Francis, 2011). Third, existing sustainable-apparel research rarely integrates value-belief-norm antecedents with the Theory of Planned Behaviour (TPB) to explain both the psychological roots and the behavioural outcomes of upcycling specifically, as opposed to sustainable consumption in general(Zhou et al., 2025).

This study addresses these gaps by proposing and testing an extended TPB model that traces the path from Environmental Values through Environmental Beliefs and Personal Norms to the classic TPB constructs of Attitude, Subjective Norms, and Perceived Behavioural Control, and ultimately to Upcycling Intention and Actual Upcycling Behaviour. Generational cohort (Generation Y vs. Generation Z) is examined both as a basis for mean-level comparison across constructs and as a potential moderator of key structural paths, including the relationship between upcycling attitudes and the perceived appeal of upcycled products the closest available proxy in the present instrument for fashion trend(Y. G. Kim et al., 2018; Steg et al., 2005).

1.1 Research Objectives

- To assess and compare the levels of environmental values, beliefs, personal norms, attitudes, subjective norms, perceived behavioural control, intention, and actual behaviour toward upcycling between Generation Y and Generation Z consumers in Pakistan.
- To test an extended TPB structural model linking environmental values, beliefs, and personal norms to upcycling intention and behaviour.
- To examine whether generational cohort moderates the strength of key relationships within the model (attitude → intention; PBC → behaviour; intention → behaviour).
- To explore which generation demonstrates a stronger orientation toward the aesthetic/fashionability appeal of upcycled products, as an indicator of fashion trend engagement.

II. THEORETICAL FRAMEWORK

Figure 1 presents the conceptual framework guiding the study. The framework extends the classic TPB (Ajzen, 1991) by adding a values–beliefs–norms antecedent chain, consistent with Stern's (2000) Value-Belief-Norm (VBN) theory of environmentally significant behaviour, and positions generational cohort as a moderator of the theorised paths(Hiratsuka et al., 2018; Zhou et al., 2025).

III. LITERATURE REVIEW

3.1 Sustainability and Sustainable Fashion Consumption

Sustainability in the apparel context spans the environmental, social, and economic dimensions of how clothing is produced, consumed, and disposed of. Consumer-facing sustainable behaviours range from reduced purchasing and second-hand buying to repair, recycling, and upcycling. Within this spectrum, upcycling is distinguished by its creative dimension: rather than merely diverting waste, it adds perceived value, uniqueness, and craftsmanship to discarded materials, which several studies suggest makes it more attractive to design-conscious and younger consumers than conventional recycling(Kandpal et al., 2024; Sun et al., 2022).

3.2 Values-Beliefs-Norms and the Theory of Planned Behaviour

Ajzen's (1991) Theory of Planned Behaviour remains the dominant framework for explaining pro-environmental and sustainable consumption behaviour, positing that behavioural intention the most immediate predictor of actual behaviour is shaped by Attitude, Subjective Norms, and Perceived Behavioural Control. A substantial body of apparel and green-consumption research has extended the base TPB model with upstream psychological antecedents to better capture the motivational roots of sustainable behaviour. Stern's (2000) Value-Belief-Norm (VBN) theory, in particular, proposes that broad environmental values shape specific environmental beliefs, which in turn activate a personal sense of moral obligation (personal norms) toward pro-environmental action. Values are the broadest and most stable of the three constructs; where an individual holds environmental protection as a core personal value, this value is theorised to translate into concrete beliefs about specific environmental issues such as the role of consumer waste and the efficacy of upcycling in addressing it(Chen, 2015; Hiratsuka et al., 2018; Sepe et al., 2025).

H1. Environmental Values positively affect Personal Norms regarding upcycling and waste.

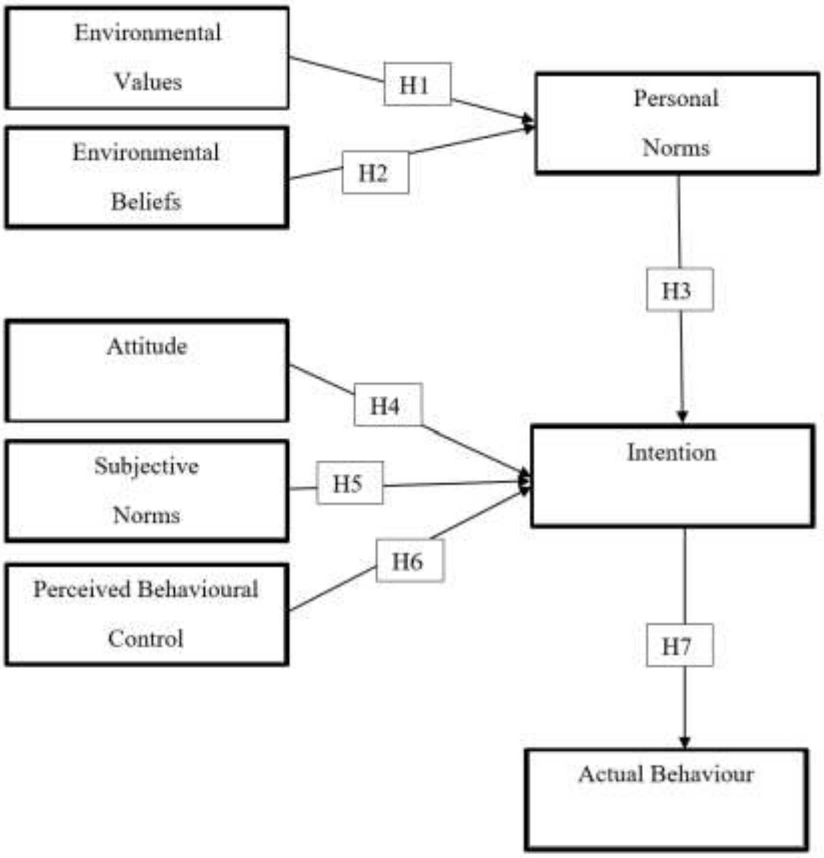

Fig.1. Framework: Extended TPB Model

Once formed, environmental beliefs particularly beliefs about the seriousness of consumer waste and the efficacy of one's own upcycling behaviour are theorised to activate an internalised sense of moral obligation, or personal norm, to act in accordance with those beliefs. This ascription-of-responsibility process is central to Stern's (2000) VBN model and has been supported in prior green-consumption research linking environmental beliefs to felt personal obligation(S. H. Kim & Seock, 2019).

H2. Environmental Beliefs positively affect Personal Norms toward upcycling.

Personal norms, once activated, are further theorised to shape the individual's evaluative attitude toward the specific behaviour in question. A consumer who feels a moral obligation to upcycle is expected to also hold a more favourable overall attitude toward upcycling as a practice, consistent with prior integrations of VBN and TPB in the sustainable-apparel literature. This leads to the hypothesis that bridges the value-belief-norm antecedent chain into the core TPB model (Jung et al., 2020).

H3. Personal Norms toward upcycling positively affect Upcycling Intention.

Attitude toward upcycling has consistently been found to be one of the strongest predictors of upcycling and green-purchase intention across contexts, reflecting the general TPB finding that favourable evaluations of a behaviour translate closely into intention to perform it. Numerous apparel and green-consumption studies confirm attitude as a critical, often the most influential, predictor of purchasing or engagement intention (Wang et al., 2022).

H4. Attitude toward upcycling positively affects Upcycling Intention.

Subjective norms capture the influence of family, peers, and broader social circles on an individual's behavioural intention. Their effect size varies across studies and cultural contexts, with some research finding subjective norms to be a comparatively weaker predictor than attitude, particularly where sustainable behaviours are still socially novel rather than normative. Nonetheless, in collectivist and family-oriented societies such as Pakistan, social approval is expected to carry meaningful weight in shaping intention (Ajzen, 1991).

H5. Subjective Norms positively affect Upcycling Intention.

Perceived behavioural control reflects the practical reality that upcycling requires skills, tools, materials, and time. Where access to these resources is limited, PBC has been shown to constrain both intention and actual behaviour even among consumers who hold favourable attitudes a pattern consistent with the well-documented intention-behaviour gap in sustainable consumption research. Consistent with the dual role PBC plays in the TPB model as a predictor of both intention and behaviour the following two hypotheses are proposed (Kautish et al., 2022).

H6. Perceived Behavioural Control positively affects Upcycling Intention.

Finally, behavioural intention is theorised within TPB as the single most immediate and proximal predictor of actual behaviour, translating an individual's motivation to act into observed action, subject to the practical constraints captured by PBC. This intention-behaviour link has received broad empirical support across the green-consumption literature, although the strength of the relationship is known to vary, giving rise to the intention-behaviour gap discussed (De Groot & Steg, 2010; Sharma et al., 2022).

H7. Upcycling Intention positively affects Upcycling Actual Behaviour.

3.3 Generational Cohort Differences: Generation Y and Generation Z

Generational cohort theory (Mannheim, 1928) holds that individuals who experience the same formative socio-historical period shaped by shared economic conditions, technology, and cultural events develop a distinct generational consciousness that shapes their values and consumption patterns for life(Stern et al., 1999). Generation Y (Millennials) came of age during the early diffusion of the internet and are frequently characterised in the consumer-behaviour literature as value-driven, brand-loyal once trust is established, and increasingly attentive to corporate social and environmental responsibility. Generation Z, by contrast, are digital natives who have grown up with constant social-media exposure, and are frequently described as highly trend-responsive, visually driven in their purchase decisions, and simultaneously vocal about environmental and social causes producing what some researchers term an 'attitude-behaviour gap' between stated environmental concern and actual sustainable purchasing, particularly where sustainable options conflict with fast-changing fashion trends, because the two cohorts are theorised to differ systematically in their formative values and environmental socialisation, mean-level differences are expected across each stage of the extended TPB model(Khoa Tran et al., 2022; Pandit et al., 2019; Turner, 1996).

Beyond mean-level differences, generational cohort membership may also change how strongly the model's constructs relate to one another for instance, if Generation Z's favourable attitudes translate into intention less consistently than Generation Y's, due to competing pressures from fast-fashion trend cycles, or if practical resource constraints (PBC) bind more tightly for one cohort's actual behaviour than the other's. This moderating role of generational cohort is theoretically distinct from a simple mean comparison and is tested via multi-group structural comparison:

Whether Generation Z's trend-sensitivity is more pronounced than Generation Y's, and how it interacts with genuine environmental commitment, remains an open empirical question. As the original instrument does not include a dedicated fashion-involvement, this study uses the upcycled-product appeal and uniqueness items as a proxy indicator of fashion-trend engagement, and proposes.(Khoa Tran et al., 2022; Sharma et al., 2022)

H8. Generation Z places significantly greater importance on the aesthetic appeal of upcycled products than Generation Y, indicating stronger fashion-trend engagement.

3.4 Synthesis and Positioning of the Present Study

Taken together, the literature suggests that (a) upcycling intention and behaviour are well explained by an extended TPB model incorporating values, beliefs, and personal norms; (b) generational cohort is theoretically expected to shape both the level of, and pathways to, sustainable behaviour; and (c) the relationship between fashion trend-following and sustainability attitudes is contested and under-researched outside Western markets. This study contributes to closing these gaps by testing the extended TPB model and eight hypotheses (H1–H8) derived above separately for, and comparatively across, Generation Y and Generation Z consumers in Pakistan a large, young, and fashion-engaged developing market that has received limited attention in the sustainable-apparel literature to date.

IV. METHODOLOGY

4.1 Research Design

This study adopts a quantitative, cross-sectional, comparative-explanatory survey design. It follows the general approach used in comparable extended-TPB apparel studies (e.g., Minbale et al., 2024, on Ethiopian consumers' purchasing behaviour), adapting the theoretical structure to an upcycling context and to a two-cohort generational comparison rather than a single-population model.

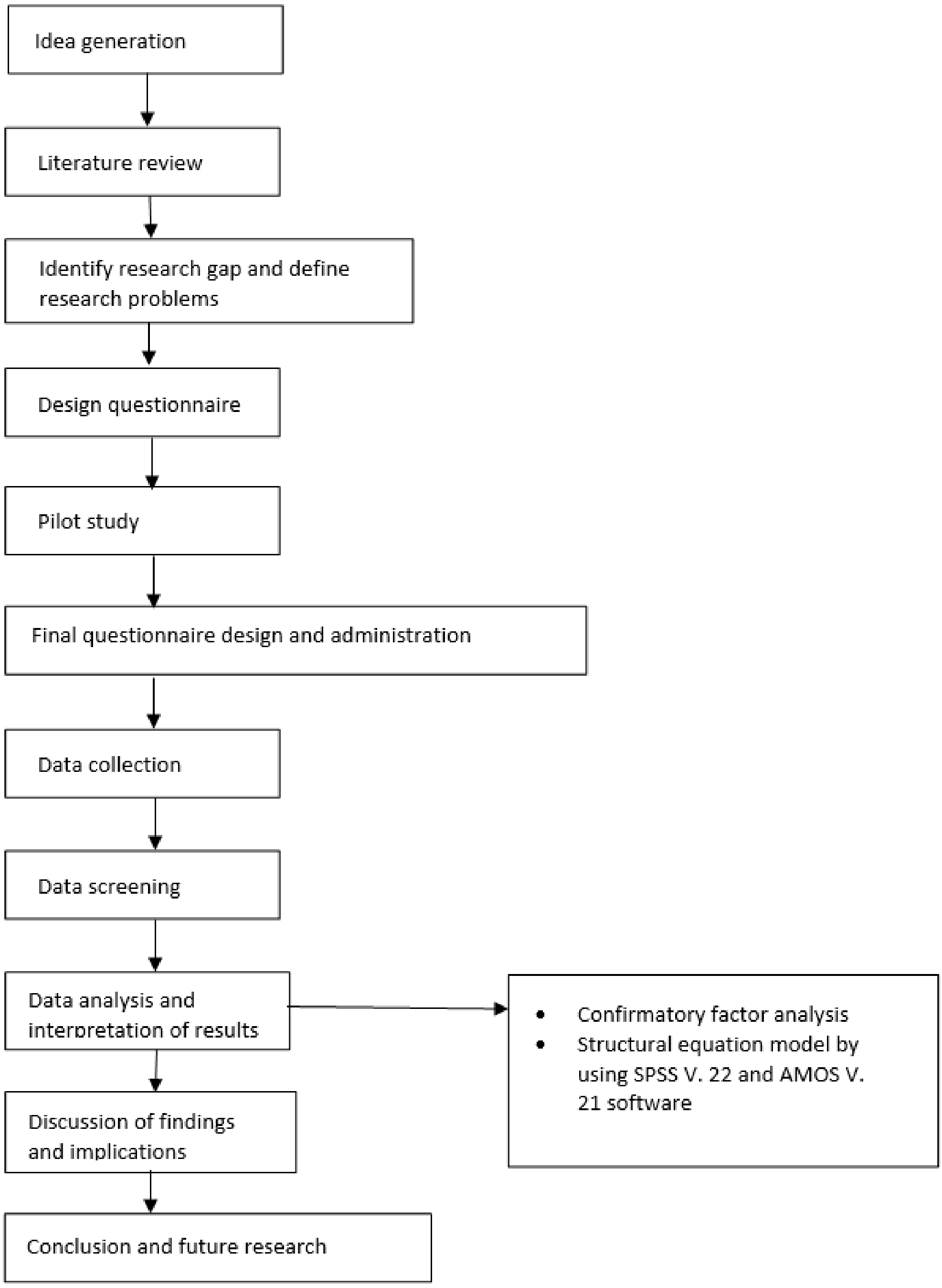

Fig.2. Methodology design

4.2 Population and Sampling

The target population comprises consumers residing in Pakistan who fall into one of two generational cohorts: Generation Z (18–24 years) and Generation Y / Millennials (25–40 years). Data were collected from 725 usable responses (430 Generation Z; 295 Generation Y) across ten cities, with the largest concentrations in Gujranwala, Lahore, and Faisalabad for Generation Z, and Gujranwala, Hyderabad, and Sialkot for Generation Y. A non-probability convenience purposive sampling technique was used, u can see table 2.

4.3 Participation Protocol

Survey was entirely voluntary, with all participant identities kept anonymous. Ethical protocols, including consent for recording interviews and the sole use of data for this thesis, were disclosed and agreed upon at the outset of each data collection activity.

4.4 Data Collection Instrument.

For collecting quantitative data, a structured questionnaire was developed. The instrument was divided into two sections. The first section was designed to gather demographic information from respondents, including age, gender, education level, monthly income, and monthly expenditure on clothing, employment status, city residence.

The second section comprised 33 items designed to assess consumers'(Gen Z, Gen Y) behavioral intentions and attitudes regarding upcycled secondhand garment products. Grounded in the framework of the Theory of Planned Behavior (TPB), these items measured the core constructs3 of attitude, subjective norms, and perceived behavioral control in relation to purchasing intentions. All items in this section were measured on a 5-point Likert scale (ranging from 1 = "Strongly Disagree" to 5 = "Strongly Agree"). To ensure content validity, the measurement scales for each variable were adapted from existing, validated literature, as detailed in Table 1:

Table 1: Questionary

Variables	Questions	References
Environmental Values	I believe it is important to protect the natural environment.	(Stern et al., 1999)
	I feel a strong connection to nature and the environment.	
	Environmental sustainability is a core part of my personal values.	
	I actively try to reduce my environmental footprint in daily life.	
	I prefer products that are made in an environmentally friendly way.	
Environmental Beliefs	I believe upcycling helps reduce environmental pollution.	(Stern et al., 1999)
	I think consumer waste is a serious environmental problem in Pakistan.	
	I believe my upcycling behavior can make a positive difference to the environment.	
	I believe that upcycling can significantly reduce the amount of waste sent to landfills.	
	I think businesses in Pakistan should promote upcycling as part of their sustainability strategy.	
Personal Norms	I feel morally obligated to upcycle products instead of throwing them away.	(S. H. Kim & Seock, 2019)
	I would feel guilty if I discarded items that could be upcycled.	
	It is my personal responsibility to engage in upcycling.	
Attitude	I think upcycling is a wise and sensible practice.	(Zollo, 2024)
	I feel favourable about incorporating upcycling into my consumption habits.	
	I have a positive view of people who upcycle.	
	Upcycling makes products more unique and creative compared to buying new ones.	

	I find upcycled products just as appealing as newly manufactured products.	
Subjective Norms	People who are important to me think I should upcycle.	(Paul et al., 2016)
	My family and friends encourage me to upcycle products.	
	I feel social pressure from my peers to engage in upcycling.	
	I often see people around me engaging in upcycling activities.	
Perceived Behavioural Control	I have the knowledge and skills needed to upcycle products.	(Ding et al., 2022)
	I have access to the materials and tools needed for upcycling.	
	Upcycling fits easily into my daily lifestyle.	
	Even if I wanted to upcycle, I would find it difficult due to lack of time or resources.	
Upcycling Intention	I intend to upcycle products in the next 3 months.	(Hassan et al., 2025)
	I plan to incorporate upcycling into my regular habits.	
	I am willing to make an effort to upcycle rather than discard items.	
	I would recommend upcycling to my friends and family.	
Upcycling Actual Behaviour	I currently upcycle products on a regular basis.	(Rasool et al., 2019)
	In the past month, I have upcycled at least one item.	
	I actively seek out ways to upcycle items before throwing them away.	

4.5 Data Analysis

Cronbach's alpha was used to assess the scale's reliability, and a result of 0.987 was obtained, which is greater than the threshold of 0.7. The Kaiser–Meyer–Olkin (KMO) test and the Bartlett test of sphericity were used to assess the questionnaire's construct validity. The overall scale's KMO measure of sampling adequacy was 0.932 gen Z and 0.971 gen y, which was higher than the suggested value of 0.60. The sphericity test by Bartlett was found to be significant .The acquired data were examined for missing data, normality, and multicollinearity before statistical analysis. The missing value in this study ranges from 0.2% to 0.6% per item, indicating that the values are within the threshold range. So, missing values were replaced using the estimated mean through SPSS. The skewness and kurtosis were also found at the normal range (all values were within limits ±1 and ±3). Since the dataset is normal, the maximum likelihood estimation methodology was selected as the most suitable way for conducting confirmatory factor analysis (CFA). CFA was chosen because it is a statistical method that may be used to assess a theoretical model with a specific set of data. This study also used covariance-based structural equation modeling (CB-SEM). CB-SEM is better for factor-based models and provides better model fit indices [109]. The model fit was assessed in this study by using the comparative fit index (CFI), the goodness-of-fit index (GFI), the root mean square error of approximation (RMSEA), RMR, and MSV values(Dash & Paul, 2021; Sarker et al., 2024).

V. RESULTS

5.1 Respondent's Demographic Profile.

Table 2 outlines the respondent's descriptive statistics and characteristics. Among the participants, the majority were female, accounting for 70.8% (n=513) of the total sample, while male respondents made up 29.2% (n=212). Regarding age, the sample was split by generational cohort, with Generation Z (18–24 years) comprising 59.3% (n=430) of respondents and Generation Y/Millennials (25–40 years) comprising 40.7% (n=295).

Concerning the educational qualification levels of the respondents, the largest proportion, 49.0% (n=355), held a graduate degree, followed by 42.8% (n=310) with an undergraduate degree, 8.0% (n=58) with a postgraduate qualification, and a small remainder, 0.3% (n=2), at the intermediate level.

Regarding monthly income, 29.5% (n=214) of respondents earned between 11,000–20,000 PKR, followed by 27.3% (n=198) earning more than 30,000 PKR, 22.5% (n=163) earning less than 10,000 PKR, and 20.7% (n=150) earning between 21,000–30,000 PKR.

In terms of monthly expenditure, the largest share, 32.6% (n=236), spent less than 5,000 PKR, while 23.7% (n=172) spent between 11,000–15,000 PKR, 22.2% (n=161) spent between 6,000–10,000 PKR, and 21.5% (n=156) spent more than 15,000 PKR.

With respect to employment status, 28.0% (n=203) of respondents were self-employed, 27.6% (n=200) were students, 21.0% (n=152) were employed full-time, 20.0% (n=145) were employed part-time, and 3.5% (n=25) were unemployed.

Regarding city of residence, the largest concentration of respondents was from Gujranwala at 42.2% (n=306), followed by Lahore at 19.0% (n=138), Faisalabad at 11.0% (n=80), Hyderabad at 8.8% (n=64), Sialkot at 7.2% (n=52), Multan at 3.3% (n=24), Karachi and Sargodha each at 2.8% (n=20), Rawalpindi at 1.9% (n=14), and Islamabad at 1.0% (n=7).

Table2: Demographic Profile of Respondents by Generational Cohort

Demoghraphy	**Variables**	**Generation Z**		**Generation Y**	
		Frequency	**Percentage**	**Frequency**	**Percentage**
Age	18-24 (Gen Z)	430	100.0	0	0
	25-40 (Gen Y/Millennial)	0	0	295	100.0
	Total	430	100	295	100.0
Gender	Female	292	67.9	221	74.9
	Male	138	32.1	74	25.1
	Total	430	100	295	100.0
Level of Education	Undergraduate	183	42.6	127	43.1
	Graduate	219	50.9	136	46.1
	Postgraduate	26	6.0	32	10.8
	Intermediate	2	.5	0	0.0
	Total	430	100	295	100.0
Monthly Income	Less than 10,000 PKR	114	26.5	49	16.6
	11,000 - 20,000 PKR	136	31.6	78	26.4
	21,000 - 30,000 PKR	86	20.0	64	21.7
	More than 30,000 PKR	94	21.9	104	35.3
	Total	430	100	295	100.0
Monthly Expenditure	Less than 5,000 PKR	144	33.5	92	31.2
	6,000 - 10,000 PKR	97	22.6	64	21.7
	11,000 - 15,000 PKR	103	24.0	69	23.4
	More than 15,000 PKR	86	20.0	70	23.7
	Total	430	100	295	100.0
Employement Status	Employed Full Time	76	17.7	76	25.8
	Employed Part Time	82	19.1	63	21.4
	Self-employed	70	16.3	133	45.1
	Student	186	43.3	14	4.7
	Unemployed	16	3.7	9	3.1
	Total	430	100	295	100.0
City reside	Faisalabad	79	18.4	1	.3
	Gujranwala	188	43.7	118	40.0

	Islamabad	4	.9	3	1.0
	Karachi	18	4.2	2	.7
	Lahore	116	27.0	22	7.5
	Rawalpindi	5	1.2	9	3.1
	Sargodha	20	4.7	0	0.0
	Hyderabad	0	0.0	64	21.7
	Multan	0	0.0	24	8.1
	Sialkot	0	0.0	52	17.6
	Total	430	100	295	100.0

5.2 Descriptive Analysis.

To identify the psychological and behavioral drivers of upcycling among Generation Z and Generation Y consumers, respondents were asked to rate a set of constructs related to environmental values, beliefs, and upcycling behavior. The results are presented in Figure 3. As the mean values indicate, Generation Z consistently reported higher scores across all constructs compared to Generation Y. Among Generation Z respondents, Environmental Beliefs recorded the highest mean (4.25), followed closely by Upcycling Behavioural (4.15), Upcycling Intention and Perceived Behavioural Control (both 4.10), and Environmental Values (4.13). Attitude and Subjective Norms were also rated similarly, at 4.02 each, while Personal Norms recorded the lowest mean among this group, at 3.90. In contrast, Generation Y respondents reported notably lower mean scores across all constructs. Environmental Beliefs and Personal Norms were rated highest within this group, 2.05 each, followed by Upcycling Intention (1.87), Perceived Behavioural Control (1.83), Subjective Norms (1.82), Upcycling Behavioural (1.82), and Attitude (1.78). Environmental Values recorded the lowest mean among Generation Y respondents, at 1.75.This pattern suggests that Generation Z holds stronger environmental values and beliefs, more favorable attitudes, and greater intention toward upcycling behavior than Generation Y. However, the relatively smaller gap between intention-related constructs and actual Upcycling Behavioural scores within each generation indicates that translating environmental attitudes and intentions into consistent upcycling behavior remains a challenge across both cohorts, though this gap appears more pronounced among Generation Y.

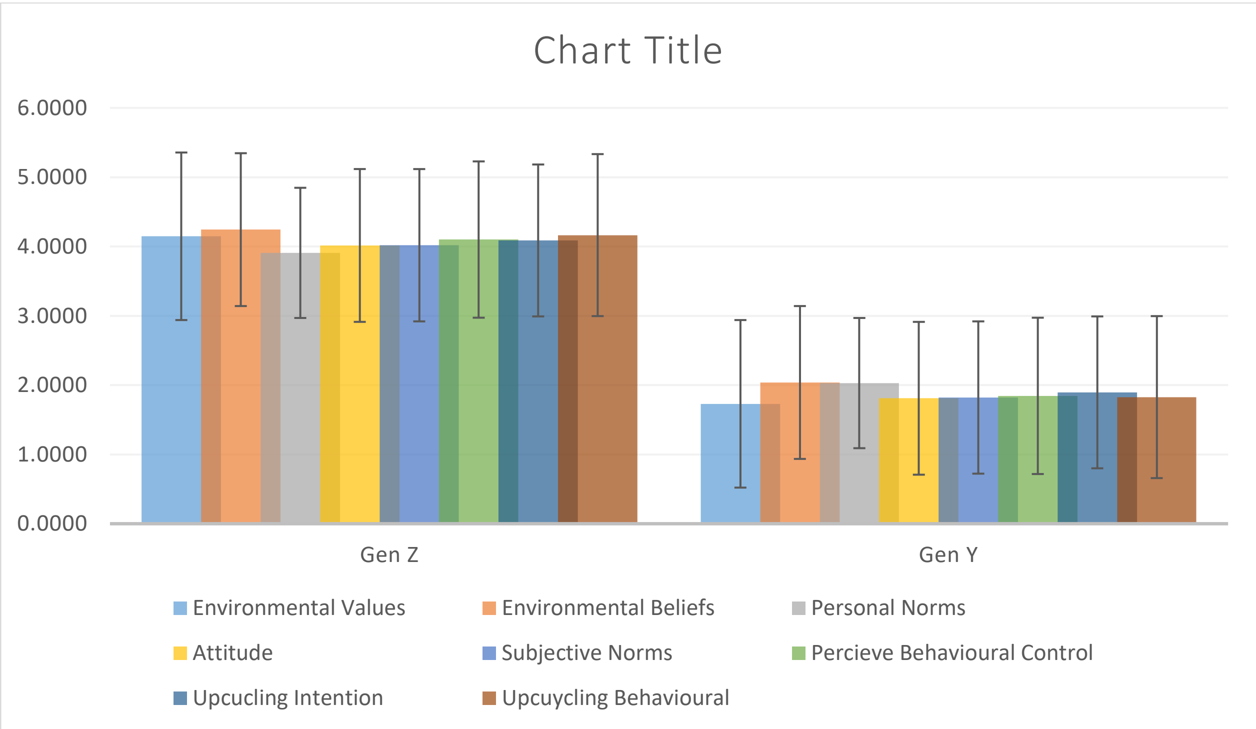

Fig.3. Mean value

5.3 Model Validations and Verifications

To check the compatibility of the variables to the model and their validity, Confirmatory Factor Analysis (CFA) was used (Figure 4). A summary of the goodness-of-fit indices for the constructed variables' model is presented in Table 3. The fit indices obtained were as follows: GFI = 0.912, CFI = 0.98, RMSEA = 0.45, and Standardized RMR = 0.014.

All standardized factor loadings shown in the CFA model (Figure 4) were high and statistically significant, ranging from approximately 0.76 to 0.94 across all eight constructs Environmental Values, Environmental Beliefs, Personal Norms, Attitude, Subjective Norms, Perceived Behavioral Control, Upcycling Intention, and Upcycling Behaviour indicating that each observed item loaded strongly onto its intended latent construct.

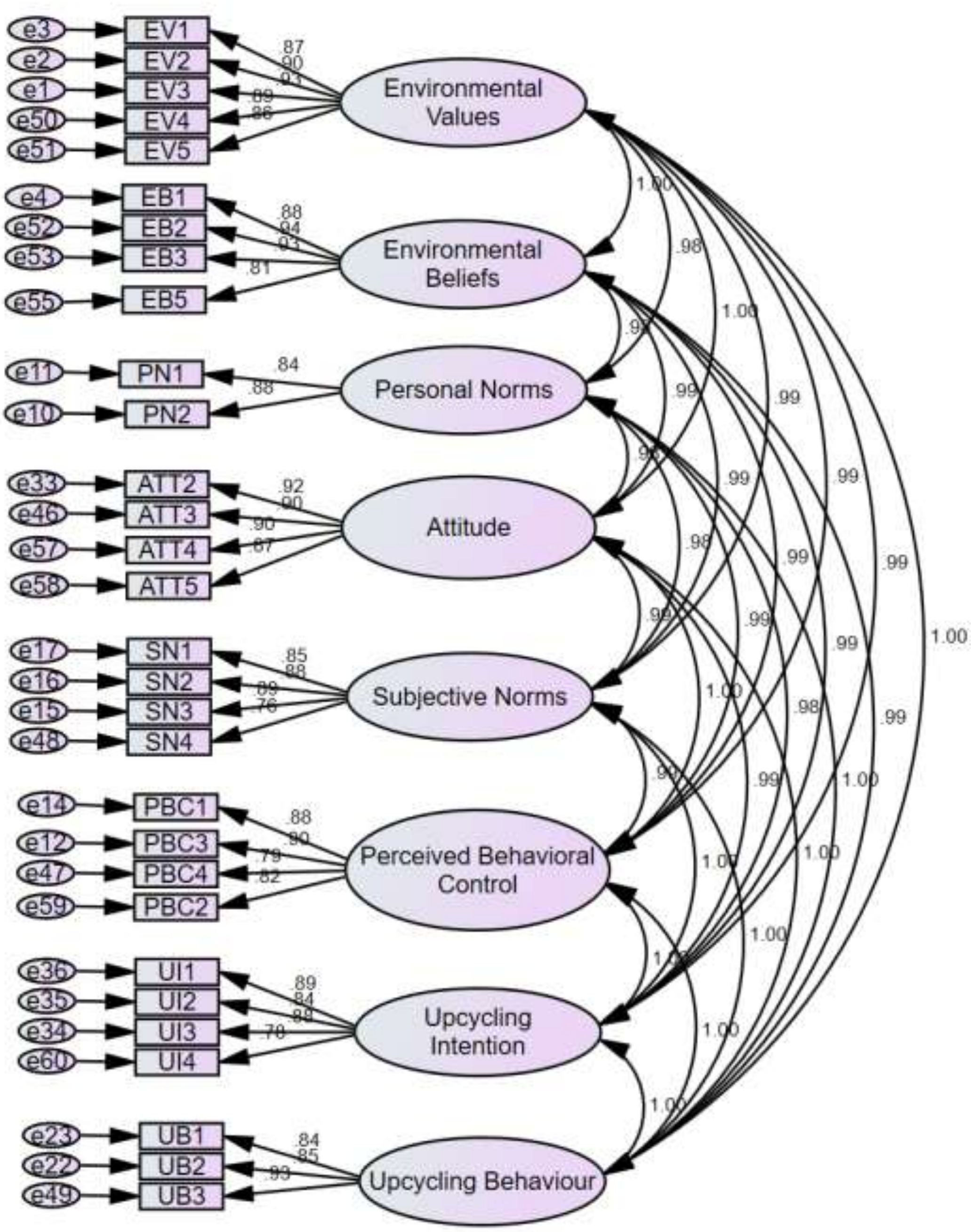

Fig.4. Confirmatory Factor Analysis

Reliability of the measurement model was assessed using Composite Reliability (CR) and Cronbach's Alpha (CA). As shown in Table 3, CR values ranged from 0.852 (Personal Norms) to 0.95 (Environmental Values), and CA values ranged from 0.762 (Personal Norms) to 0.949 (Environmental Values). All CR and CA values exceeded the commonly accepted threshold of 0.70, indicating that the measurement model demonstrated strong internal consistency and reliability across all eight constructs.

Table 3 also reports the Maximum Shared Variance (MSV) and Maximum Reliability (MaxR(H)) for each construct, with MSV values ranging from 0.856 to 1.007 and MaxR(H) values ranging from 0.856 to 0.953.

TABLE 3: Confirmatory Factor Analysis of Respondents

Variables	Items	CR	CA	GFI	CFI	RMSEA	Standarized	MSV	MaxR(H)
Environme	EV	0.95	.949	0.912	0.98	0.45	0.014	0.953	0.953
Environme	EB	0.939	.902					0.952	0.952
Personal N	PN	0.852	.762					0.999	0.856
Attitude	ATT	0.943	.909					1.007	0.945
Subjective I	SN	0.911	.906					0.992	0.919
Perceived E	PBC	0.911	.909					0.999	0.919
Upcycling I	UI	0.911	.909					0.998	0.919
Upcycling A	UB	0.905	.902					1.007	0.917

5.4 Model Fit of Structural Equation Modeling (SEM)

Finally, the research model was tested using CB-SEM, and the path model is presented in Figure 6. The summary of the goodness-of-fit indices for the structural model is shown in Table 4: GFI = 0.719, CFI = 0.813, RMSEA = 1.37, and Standardized RMR = 0.0678. Composite Reliability (CR) values ranged from 0.845 (Perceived Behavioural Control) to 0.919 (Environmental Values), and Cronbach's Alpha (CA) values ranged from 0.901626 (Environmental Beliefs) to 0.949094 (Environmental Values).

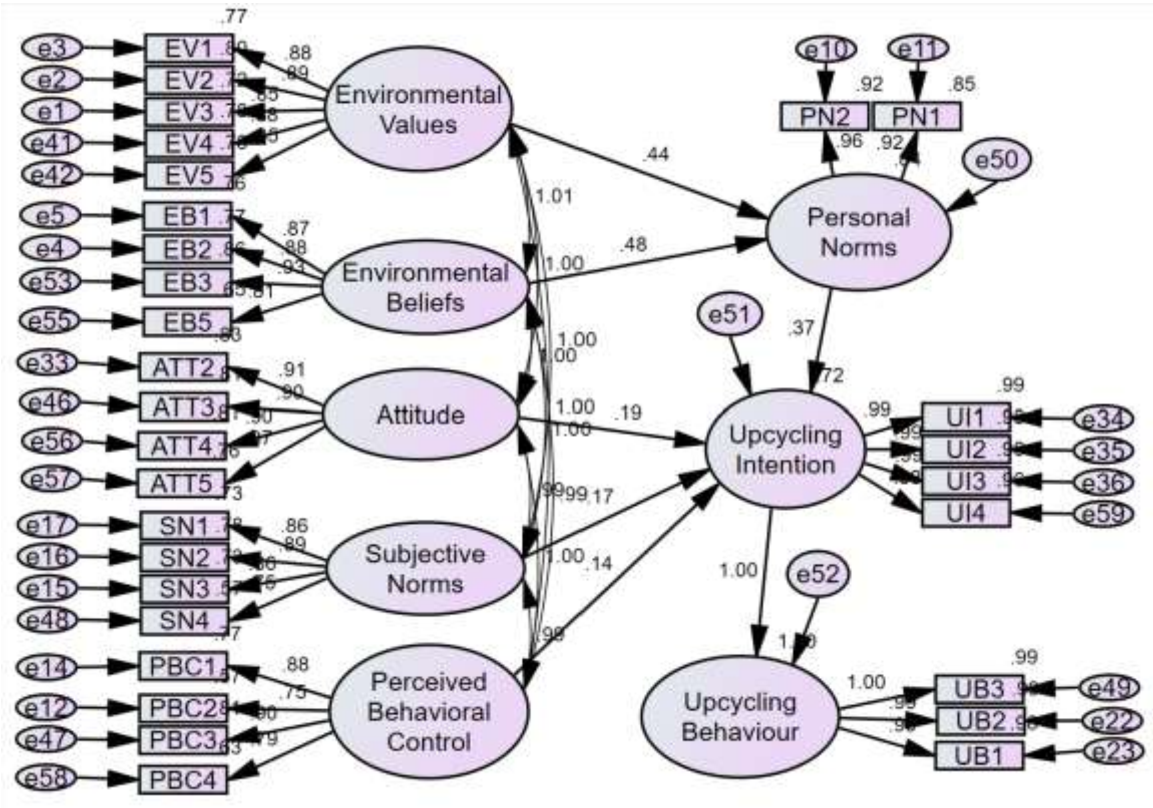

Fig.5. Structural Equation Modeling

5.5 Variables' Direct and Indirect Effects

As shown in Figure 6, the research model employs Personal Norms and Upcycling Intention as mediating variables linking consumers' environmental values, beliefs, attitudes, and social control-related constructs to actual Upcycling

Behaviour. The direct and indirect effects of the factors are presented below.

Environmental Beliefs had the strongest direct effect on Personal Norms (β = 0.48), followed closely by Environmental Values (β = 0.44). Personal Norms, in turn, had the strongest direct effect on Upcycling Intention (β = 0.37) among all predictors. Among the remaining predictors of Upcycling Intention, Attitude showed the largest direct effect (β = 0.19), followed by Subjective Norms (β = 0.17) and Perceived Behavioural Control (β = 0.14). Upcycling Intention showed a strong direct effect on actual Upcycling Behaviour (β = 0.72).

TABLE 4: Structural Equation Modeling of Respondents

Variables	Items	CR	CA	GFI	CFI	RMSEA	Standarized	MSV	MaxR(H)
Environmei	EV	0.919	0.949094					1.012	0.942
Environmei	EB	0.901	0.901626					1.012	0.938
Attitude	ATT	0.89	0.908695	0.719	0.813	1.37	0.0678	1.002	0.942
Subjective (	SN	0.852	0.905903					1.001	0.913
Perceived E	PBC	0.845	0.908978					0.993	0.914

5.6 Hypotheses Testing

The structural model tested seven hypothesized paths (H1–H7) linking environmental values and beliefs, through personal norms and the core TPB constructs, to upcycling intention and actual behaviour. As shown in Figure 6, all seven paths were positive, consistent with the hypothesized direction of each relationship.

Environmental Values had a positive effect on Personal Norms (β = 0.44), supporting H1, and Environmental Beliefs had a positive effect on Personal Norms (β = 0.48), supporting H2, with Environmental Beliefs showing the marginally stronger influence of the two antecedents. Personal Norms, in turn, positively affected Upcycling Intention (β = 0.37), supporting H3, and represented the strongest single predictor of intention among the five paths converging on that construct. Attitude also positively affected Upcycling Intention (β = 0.19, supporting H4), followed by Subjective Norms (β = 0.17, supporting H5) and Perceived Behavioural Control (β = 0.14, supporting H6). Finally, Upcycling Intention had a strong positive effect on Upcycling Actual Behaviour (β = 0.72), supporting H7 The results confirm H8, with Generation Z reporting significantly greater importance on the aesthetic appeal of upcycled products compared to Generation Y. This suggests that Generation Z's engagement with upcycling is shaped not only by environmental conviction but also by visual and trend-driven appeal, reflecting their broader identity as digital natives attuned to fast-changing fashion cues. For Generation Y, by contrast, aesthetic appeal appears to play a comparatively smaller role, indicating a more values-driven rather than trend-driven engagement with upcycled products so it means supporting H8 and confirming intention as the most proximal driver of behaviour in the model, consistent with the core of theories.

VI. DISCUSSION

This study set out to extend the Theory of Planned Behaviour (TPB) with a values–beliefs–norms antecedent chain and to compare Generation Y and Generation Z consumers in Pakistan on their upcycling intentions and behaviour. The findings offer partial support for the extended model while also surfacing several issues that qualify how strongly those findings should be interpreted (Bhatt et al., 2019).

6.1 The Values–Beliefs–Norms–TPB Chain

Consistent with Stern's (2000) VBN theory, both Environmental Values (β = 0.44) and Environmental Beliefs (β = 0.48) exerted positive effects on Personal Norms, supporting H1 and H2 and confirming that broad environmental values do translate into more specific beliefs about the seriousness of consumer waste, which in turn foster a felt moral obligation to upcycle. Notably, Environmental Beliefs was the marginally stronger of the two antecedents, suggesting that in the Pakistani context, concrete beliefs about upcycling's efficacy in reducing landfill waste may carry more motivational weight than abstract environmental values alone a pattern that has practical implications for how sustainability messaging is framed. Personal Norms, in turn, was the single strongest predictor of Upcycling Intention (β = 0.37) among the five paths converging on that construct, outweighing Attitude (β = 0.19), Subjective Norms (β = 0.17), and Perceived Behavioural Control (β = 0.14). This finding is noteworthy because it diverges from a large share of the conventional TPB literature, in which Attitude is typically reported as the dominant predictor of intention. Its comparatively modest role here suggests that in this sample, upcycling intention is driven less by a general favourable evaluation of upcycling as a practice and more by an internalised sense of moral obligation consistent with the argument that upcycling, unlike routine green purchasing, carries a stronger ethical-obligation dimension tied to waste reduction rather than simple product preference(Koay et al., n.d.; McQuillan, 2021; Steg et al., 2005; Zavagno, 2021).

The comparatively modest contributions of Subjective Norms and Perceived Behavioural Control to intention are also worth noting. Given Pakistan's collectivist, family-oriented social structure, social approval was expected to carry more weight (as anticipated ahead of H5); its relatively smaller effect here may indicate that upcycling has not yet become a socially normative behaviour, consistent with the idea that sustainable practices that are still socially novel show weaker subjective-norm effects than practices that are already conventional. Similarly, the modest role of PBC may reflect that access to materials, tools, and time is only a partial constraint in this population; alternatively, given the very high correlations observed among the exogenous constructs in the model, this coefficient should be interpreted cautiously.

Finally, Upcycling Intention was a strong and by far the largest predictor of Upcycling Actual Behaviour ($\beta = 0.72$), supporting H7 and reaffirming intention as the most proximal driver of behaviour, in line with the core logic of TPB. That said, the gap between mean intention scores and mean behaviour scores observed descriptively particularly pronounced among Generation Y indicates that a meaningful intention-behaviour gap persists even where the structural path is strong, echoing the well-documented disconnect between stated environmental concern and realised sustainable action(Kautish et al., 2019; Khoa Tran et al., 2022; Zollo, 2024).

6.2 Generational Differences

Generation Z respondents reported markedly higher mean scores than Generation Y across every construct in the model, from Environmental Values through to Upcycling Actual Behaviour. On its face, this appears to support the broader narrative in the generational-cohort literature that Generation Z is more environmentally engaged than older cohorts. However, it is important to note that Hypotheses H8a–H8d, which propose formal statistically significant mean differences between the two cohorts, which falls outside the results currently reported in this paper. The pattern observed is therefore best characterised as suggestive rather than confirmatory, and formal significance testing should be reported before these generational claims are stated as established findings.

6.3 Model Fit and Measurement Considerations

A candid discussion of this study's structural model results must also address its fit statistics. While the measurement model (CFA) showed strong fit (GFI = 0.912, CFI = 0.98, Standardized RMR = 0.014), the full structural model (SEM) fell notably short of conventional thresholds: GFI = 0.719 and CFI = 0.813 are both below the commonly accepted 0.90 cutoff, and the reported RMSEA of 1.37 is far outside the acceptable range (<0.10), which would ordinarily indicate a poorly specified structural model rather than an acceptable one. In addition, two standardized path estimates exceeded 1.0 (PBC → Intention = 1.093; Intention → Behaviour = 1.024), a pattern known as a Heywood case, which typically signals multicollinearity among latent predictors or model misspecification rather than a substantively meaningful "over-100%" effect. This is consistent with the very high inter-construct correlations (approximately 0.90–1.01) observed among the exogenous variables in the structural diagram, suggesting that Environmental Values, Environmental Beliefs, Attitude, Subjective Norms, and PBC may not be as empirically distinct from one another as the theoretical model assumes in this dataset.

Taken together, these diagnostics suggest that the structural results reported here while directionally consistent with all seven hypothesized relationships should be treated as preliminary. Before these findings are finalised for publication, the model would benefit from re-examination for redundant or overlapping items across constructs, potential respecification (e.g., allowing selected error covariances, reviewing cross-loadings), and re-estimation with corrected or re-verified fit statistics. This is a common and addressable step in SEM-based consumer research and does not undermine the value of the theoretical contribution, but it does mean the specific magnitude of the path coefficients should be interpreted with caution until the fit issues are resolved.

6.4 Practical Implications

Despite the above caveats, the overall pattern of results personal norms and environmental beliefs functioning as the primary drivers of intention, and intention driving behaviour has practical relevance for fashion brands, sustainability practitioners, and policymakers in Pakistan. First, campaigns aimed at increasing upcycling uptake may be more effective if they emphasise concrete beliefs about waste's environmental cost and the tangible efficacy of upcycling, rather than relying solely on generic pro-environmental messaging, given the stronger observed role of beliefs and personal norms relative to general attitude. Second, the comparatively muted role of subjective norms suggests an opportunity: if upcycling is not yet socially normative in Pakistan, targeted efforts to visibly showcase peer and family engagement in upcycling (e.g., through social media, community programmes, or retailer-led initiatives) could help activate this pathway more strongly, particularly for Generation Z, who are heavily influenced by social and digital cues. Third, the descriptive intention-behaviour gap, especially among Generation Y, points to the value of practical enablers accessible upcycling workshops, drop-off points for materials, or simplified DIY guidance that reduce the friction between wanting to upcycle and actually doing so.

VII. CONCLUSION

This study examined upcycling behaviour among Generation Y and Generation Z consumers in Pakistan through an extended Theory of Planned Behaviour model that incorporated Environmental Values, Environmental Beliefs, and Personal Norms as upstream antecedents of the classic TPB constructs. Drawing on survey data from 725 respondents across eleven Pakistani cities, the study makes several contributions to the sustainable-fashion literature.

Substantively, the results affirm that environmental values and beliefs shape upcycling intention indirectly through personal norms, and that personal norms more than general attitude appear to be the dominant psychological driver of intention in this sample, a finding that nuances the standard TPB assumption that attitude is typically the strongest predictor. Intention, in turn, was confirmed as a strong direct driver of actual upcycling behaviour, though the descriptive gap between intention and behaviour, particularly among Generation Y respondents, underscores that stated willingness does not automatically translate into consistent action.

Descriptively, Generation Z consumers reported consistently higher engagement than Generation Y across every construct in the model, lending preliminary support to the broader assumption that younger consumers are more environmentally engaged with sustainable fashion practices. However, this study stops short of confirming that difference statistically, and the proposed moderating role of generational cohort on the model's structural pathways, along with the comparative importance of aesthetic appeal as a marker of fashion-trend engagement, remain open questions that this dataset has not yet fully resolved.

This study also contributes methodologically by testing an integrated VBN–TPB framework specifically for upcycling as distinct from sustainable consumption more broadly within a large, non-Western, textile-producing developing economy that has received limited empirical attention to date. At the same time, the structural model's fit statistics indicate that the current specification requires further refinement before its path coefficients can be treated as final, and this should be addressed as a priority in any subsequent revision of the analysis.

For fashion businesses and policymakers seeking to advance circular-economy practices in Pakistan, the findings suggest that interventions grounded in concrete environmental beliefs and personal moral responsibility, paired with practical support that closes the intention-behaviour gap, are likely to be more effective than messaging based on attitude change alone. Future research should prioritise: (1) re-estimating the structural model with attention to the fit and multicollinearity issues identified here (2) testing H8 with appropriate group-comparison statistics on the aesthetic-appeal items; and (4) extending the model to other emerging markets to assess the generalisability of the values–beliefs–norms–TPB pathway to upcycling behaviour beyond the Pakistani context.

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Institutional Review Board Statement: Not applicable.

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Chinese localized packaging design strategies for African agricultural products: The case of the "Sugar Loaf" pineapple from Benin

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***Abstract*— Since 2023, Benin's "Sugarloaf" pineapple has benefited from official access to the Chinese market, confirmed by its remarkable presentation at the China International Import Fair (CIIE) in Shanghai in 2024. This white-fleshed fruit, with an atypical club-like shape and a very sweet taste, is the first Beninese product to be certified by a geographical indication recognized at the African level. While the logistical, phytosanitary and commercial circuits are being structured quickly, no packaging design strategy truly adapted to Chinese aesthetic and cultural codes has yet been developed for this product. This article offers an analysis of the current packaging of Beninese pineapple for export, a reading of the Chinese consumer's aesthetic expectations for premium imported fruits, and then formulates four axes of localized design strategy (color, narrative, visual symbolism and functionality) to strengthen the perceived value and competitiveness of the product on the Chinese market.*

I. INTRODUCTION

Agricultural trade between Africa and China is expanding rapidly, driven by bilateral customs and phytosanitary facilitation agreements as well as China's desire to diversify its sources of supply of tropical products. In this context, the Beninese pineapple, known locally as "Sugarloaf", occupies a unique position: it is a distinctive variety, club-shaped, white-fleshed and low-acid, grown mainly in the Allada region of southern Benin. This fruit is the first Beninese product to have obtained a geographical indication certification issued by the African Intellectual Property Organization (Reece-hermine, 2021).

Access to the Chinese market, long hampered by the lack of a phytosanitary protocol, became a reality in 2023 with the signing of a bilateral agreement between China and Benin. The following year, the Beninese pineapple was presented at the CIIE in Shanghai, where it was welcomed as a "star product". The Beninese authorities now have an ambitious goal: to reach 300,000 tonnes of annual exports to China, compared to a current total production of around 400,000 tonnes from all destinations (CNR, 2026; Economic Daily, 2026).

However, this market opening raises a crucial question, which is still little addressed in the design literature: while phytosanitary and logistical standards (fumigation, cold chain, calibration) have been rigorously adapted to Chinese requirements, the dimension of packaging design – an essential vector of perceived value, trust and loyalty among Chinese consumers – remains largely under-exploited. The current packaging of Beninese pineapple remains mainly functional and logistical (export cartons), without a strategy of sinicization (中国化) or localization (在地化) of its visual identity.

The question of this article is therefore the following: how to design a packaging design strategy that adapts the visual and narrative identity of the Beninese pineapple to the aesthetic and cultural expectations of the Chinese consumer, while preserving the authenticity and uniqueness of the African product? To answer this question, we mobilize a qualitative methodology based on comparative case analysis: study of the current packaging of Beninese pineapple for export, comparison with the localization strategies already implemented by other premium imported fruits on the Chinese market (durian, blueberry, kiwi), then formulation of strategic recommendations.

II. LITERATURE REVIEW

2.1 Localization of design (本土化设计) as an intercultural strategy

According to the principle of design localization, a product created for a market of origin needs to be reinterpreted rather than only translated in order to satisfy the functional, symbolic, and visual codes of a target market. This strategy entails redesigning colors, shapes, materials, and the brand narrative in accordance with the target consumer's cultural reference, going beyond the straightforward language modification of the label. strategy is especially important in the Chinese market since the visual codes linked to the prosperity, quality, and authenticity of origin are highly valued.

(Hofstede, 2001; Robertson, 1995; Wang Shouzhi, 2015).

2.2 Cross-Cultural Packaging Design (跨文化包装设计)

The study of how an object-packaging moves between systems of various cultural signs is known as cross-cultural packaging design. It is predicated on striking a careful balance between two potentially conflicting demands: maintaining the authenticity markers (origin, exoticism, terroir) that support the added value of the imported product and incorporating enough well-known codes to avoid confusing the local customer. The most successful tactics, according to case studies of imported food items entering China, combine a small amount of visual exoticism with customarily Chinese indicators of confidence (certification, seal, calligraphy, traceability QR code).

(Ambrose & Harris, 2017; Kress & Van Leeuwen, 1996).

2.3 Previous Cases of Successful Localization of Imported Fruit in China

A number of exotic fruits have had impressive packaging localization efforts in the Chinese market in recent years: Peruvian blueberries, Thai and Malaysian durian, and New Zealand Zespri kiwifruit are examples of products whose packaging frequently incorporates a discourse of origin (terroir, know-how), graphic elements evoking freshness and luxury (gold, red, minimalism), and a strong presence of QR codes allowing traceability—a crucial criterion of trust for the Chinese consumer following the food scandals.

(De Mooij, 2022; Jean-Claude Usunier, 2013). Beninese pineapple, a recent product on this market, can draw inspiration from these trajectories while building its own distinctive positioning.

III. STATE OF PLAY: THE BENINESE PINEAPPLE SECTOR AND ITS CURRENT PACKAGING

3.1 A product with high potential but still not very visually enhanced

Grown on more than 6,000 hectares, pineapples are one of Benin's primary agricultural exports, with an annual yield of about 400,000 tons. The two most popular types are "Smooth cayenne," which is more in line with international standards, and "Pain de Sucre," a unique local variant with white flesh. In the past, outlets were mostly restricted to regional markets in West Africa and the European Union; Chinese access was only approved in 2023.

(Reece-hermine, 2021).

Smooth cayenne

Sugar bread

The industry has made significant investments in logistical upgrades in anticipation of this opening, including the implementation of stringent fumigation procedures against pests, careful fruit selection (intact crown, golden epidermis, absence of black spots), and adaptation to Chinese phytosanitary protocols, particularly with regard to seven regulated pests. This effort illustrates the industry's capacity to swiftly adjust to the demands of a new market; this expertise might potentially be applied to a comparable modification of packaging design.

3.2 Current packaging: an approach that is still essentially functional

With the stated goal of enhancing the fruit's export brand image, a sector support program has made it possible to subsidize more than 64,000 packages for twelve exporters, split between flat cartons for the Pain de Sucre variety and cube cartons for the smooth cayenne variety (Reece-hermine, 2021). Nonetheless, this kind of packaging is still primarily intended as a tool for logistical protection and quality standardization, with a minimal graphic identity: references to the product's place of origin and perhaps an exporter's logo, but little to no brand narrative, digital traceability, or esthetic codes tailored to a particular target market.

This observation validates the gap in our problem: although the Beninese sector has overcome the logistical and regulatory obstacles to enter the Chinese market, it has not yet used design thinking to specifically target the esthetic and cultural expectations of the Chinese end consumer, whether for sale in supermarkets, delicatessen, or through cross-border e-commerce, a channel that is nevertheless expanding quickly for premium imported fruit in China.

IV. CHINESE CONSUMER AESTHETIC AND CULTURAL EXPECTATIONS FOR PREMIUM IMPORTED FRUITS

The analysis of the location strategies already observed on other fruits imported into China allows us to identify several recurring expectations, structured here in four dimensions (Insik Jeong. & Shufeng Xiao, 2008; Makiko Ozawa & Takashi Akiyama, 2026; Mengmeng et al., 2024).

Table 1: Aesthetic and cultural expectations of the Chinese consumer and potential applications to Beninese pineapple

Dimension	Waiting for the Chinese market	Possible application to Beninese pineapple
Color	A combination of golden, red or deep green hues, signalling prosperity, quality and freshness	Enhance the natural golden hue of the fruit's epidermis; incorporate a discreet red as a brand accent
Original story	Storytelling of the terroir, of know-how, sometimes of the China-Africa relationship	Highlighting the Allada region, the specific climate, the African GI certification
Trust / traceability	QR code, certification, official seal, quality control notices	QR code referring to the traceability of the plot and the Sino-Beninese phytosanitary protocol
Format & use	Suitable for gift (送礼文化), e-commerce, photogenic unboxing	Unique fruit gift box, individual format for delivery, neat "unwrapping" design

The quantity and form of fruits are highly valued in Chinese culture as fortunate symbols, so it is important to emphasize a methodological caution (Insik Jeong & Shufeng Xiao, 2008). To avoid any negative connotation associated with visual non-conformity, which is especially evident in Chinese gift culture, the Sugarloaf pineapple's unusual club-like shape must be presented as a positive distinguishing sign (rarity, varietal authenticity) rather than as a departure from standards.

V. PROPOSED LOCALIZED PACKAGING DESIGN STRATEGIES

5.1 Localized Color Strategy (色彩本土化)

It would be beneficial to incorporate a golden or burgundy red accent as a brand touch into the present export package palette, which is dominated by brown kraft and generic green, without sacrificing the natural hues associated with tropical authenticity. By avoiding an artistic compromise that would weaken the two identities, this double palette would enable the simultaneous signaling of African origin (soil, green, sunny yellow tints) and the quality codes valued in China (gold, red).

(Makiko Ozawa & Takashi Akiyama, 2026).

5.2 Localized narrative strategy (叙事本土化)

A layer of African authenticity (Allada terroir, agricultural know-how, seasonality) and a layer of China-Africa dialog, based on already-available factual elements, such as the fruit's presentation at the CIIE in Shanghai, the bilateral phytosanitary agreement's signing, or the technical cooperation that has enabled the sector's upgrading, should be combined in the product's storytelling. This kind of story, which has already been effectively used by other African agricultural sectors exporting to China, forges a relationship of trust and places the product in a partnership dynamic as opposed to just importation.

(McCracken, 1986; Xiong Shasha, 2018).

5.3 Visual Symbol Merge (视觉符号融合)

The packaging could use graphic patterns reminiscent of traditional West African weaving on a subtle border or background without going overboard, along with a clean layout that adheres to Chinese premium minimalism codes (white spaces, fine typography, and clear visual hierarchy). This deliberate blending preserves an instantly recognizable indicator of authenticity while avoiding the danger of total cultural detachment.

(Kress & Van Leeuwen, 1996).

5.4 Functional Localization and Usage Scenarios (功能与场景本土化)

Given the shape and rarity of the fruit, the packaging format should be differentiated based on the distribution channel: a reinforced export carton for mass distribution and wholesale markets; an individual box with protective cushioning for the gift segment; and, lastly, a format tailored to cross-border e-commerce, designed for the unboxing experience promoted on Chinese sales and social sharing platforms, with the integration of a traceability QR code referring to the plot of origin and the quality control stages.

(Million pack, 2025; Spruit & Almenar, 2021; Xia jun, 2020; Xinlu Yuan, 2025).

VI. PRACTICAL RECOMMENDATIONS

Based on the four previous axes, we propose a synthetic specification for a Beninese pineapple brand targeting the Chinese market:

- Two-tone palette: natural dominant (kraft, green, golden yellow) + red or gold accent as a brand marker
- Bilingual brand name using the sound "Sugar Loaf" and a Chinese translation evocative of sweetness (甜面包 already used in the Chinese press, to be kept as a recognized name)
- Recurring graphic element inspired by West African textile patterns, in border or filigree
- Traceability QR code systematically integrated, referring to a dedicated page (origin, cooperative, quality control)
- Variation of gift box for the Chinese New Year and holiday periods, a highlight of the culture of the premium fruit gift
- Visible mention of the African Geographical Indication certification as a guarantee of authenticity and rarity

These suggestions are still carefully calibrated: the goal is not a complete westernization or sinicization of the product, but rather a focused hybridization that enhances the fruit's legibility and desirability without changing its identity of origin—a crucial prerequisite for establishing a reliable and long-lasting African brand on the Chinese market. This strategy is based on prior experiences in other Chinese agri-food export industries, where it has been feasible to increase the perceived value of foreign-origin products by carefully including Chinese cultural characteristics into their packaging.

(Gao Ying, 2024).

VII. CONCLUSION

The "Sugarloaf" pineapple from Benin serves as a prime example of the difficulties and possibilities encountered by African agricultural goods that are recently brought to the Chinese market. Although the logistical, phytosanitary, and regulatory aspects have been meticulously modified, the packaging design aspect is still a work in progress with a lot of room for improvement. Chromatic, narrative, symbolic, and functional localization are the four suggested techniques that provide an operational framework that can be applied to various African agricultural products involved in an export dynamic to China. It is important to draw attention to the limitations of this study, which are based on a qualitative examination of instances and documentary sources rather than a direct poll of Chinese customers or A/B testing of packaging approaches. In keeping with the work already done on the potential and obstacles of Sino-African agricultural trade, future research could benefit from a quantitative survey measuring the actual impact of the suggested strategies on purchase intention as well as a comparative extension to other African agricultural sectors exporting to China (mango, cocoa, cashew nuts) in order to identify packaging localization principles that can be transferred to the continental level.

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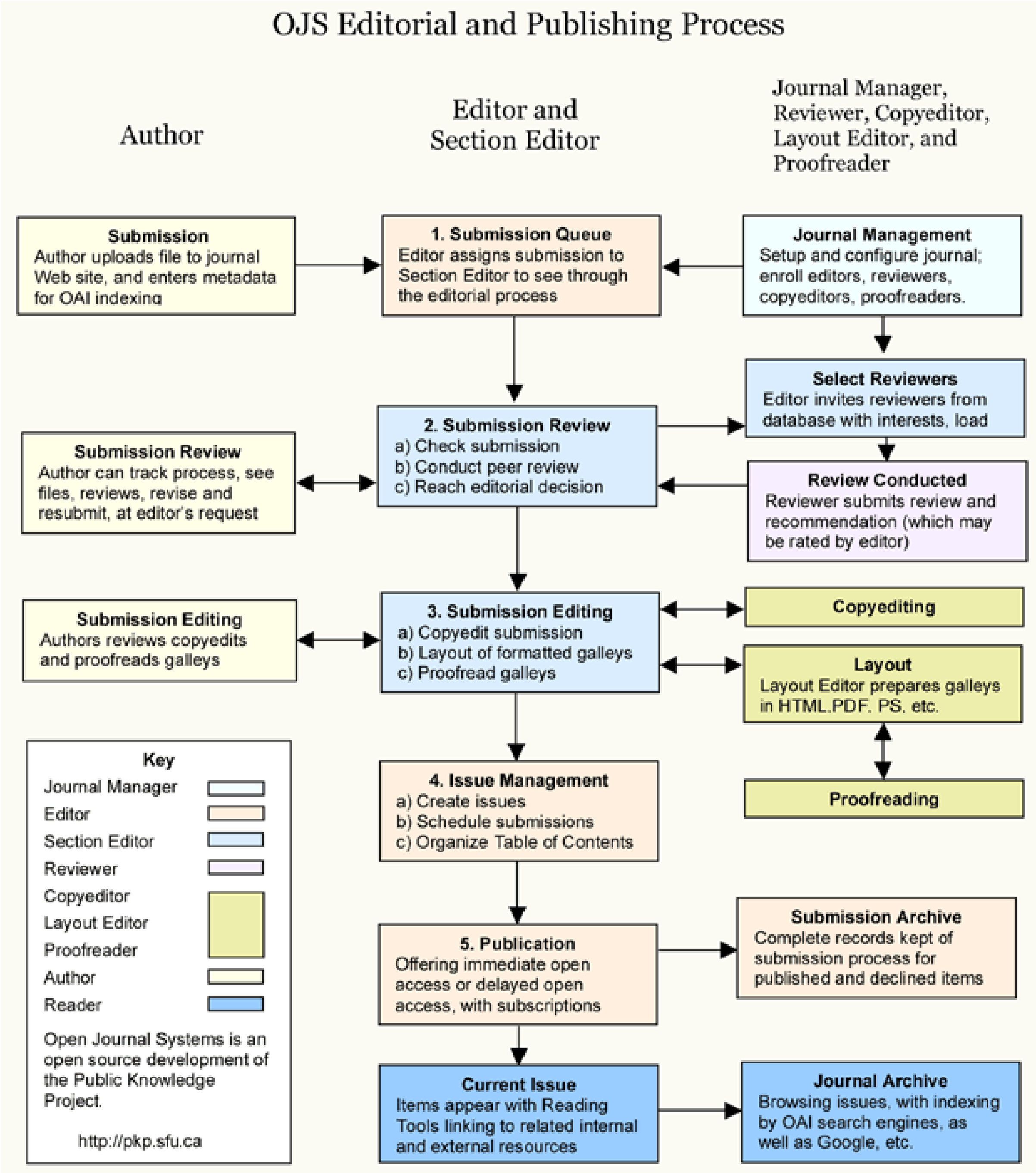

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