

Sustainable Livelihood Index and Relative Importance of Regional Factors: A Study with Special Reference to Blocks of Undivided Midnapur District of West Bengal

Jagabandhu Mandal^{1*}, Rajib Kumar Dolai², Pinaki Das³, Debasish Mondal⁴

¹Assistant Professor, Subarnarekha Mahavidyalaya, Gopiballabpur, India

²Assistant Professor, Tamralipta Mahavidyalaya, Tamluk, India

³Professor, Vidyasagar University, Midnapore, India

⁴Ret. Professor, Vidyasagar University, Midnapore, India

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*Corresponding author e-mail: jagabandhu.eco@gmail.com

ABSTRACT

The concept of 'sustainable livelihoods' is an increasingly important word in today's agenda on the developmental debate about rural development. This paper describes the Sustainable Livelihoods Index (SLI) as a useful tool in assessing the livelihood elements of the three rural regions at the blocks level of Undivided Midnapur Districts of West Bengal. We use suitable unequal methodology like Fuzzy Set Analysis to calculate SLI consist of four groups of assets namely physical, cultural, social, and economic assets. The data sets for this study are census 2001, 2011 and different round of Districts Statistical hand books. The Sustainable Livelihood Index (SLI) significantly different among the blocks and three separate regions namely Jhargram, Paschim Midnapur and Purba Midnapur. The relative importance of factors in SLI has been assessed using the True Relative Importance methodology. This approach combines statistical logic, axioms, and theorems from various correlation measures, including squared orthopartial, semi-orthopartial, and simple correlations. Six factors were selected for analysis: student teacher ratio (STR), social factors like percentage of SC/ST people (PCSCST), cooperative attitude factors like ratio of member of cooperative and numbers of cooperatives (RCOPA), health related factors (BEDPINT) and percentage of indoor treatment out of total patients (POIND), economic factor like per capita small saving (PCSS) and time (TIME), to demonstrate how they contribute to sustainable livelihood. In the presence of multicollinearity, factors can exhibit positive or negative overlapping, depending on the absence or presence of enhancement synergism. The relatively most important factor is STR, while the least influential factor is POIND. STR appears as the most important factor because education directly strengthens skills, awareness, and opportunities, which strongly improve sustainable livelihood outcomes. Squared marginal correlations sometimes

overestimate or underestimate the true importance of variables because they do not separate unique effects from overlapping influences.

KEYWORDS: Fuzzy Set Analysis; Sustainable Livelihood Index; Orthopartial Correlation; Multicollinearity; True Relative Importance

1. INTRODUCTION

The sustainable livelihoods (SL) framework (Scoones, 1998, Carney, 1998) has been widely adopted by governments and donor agencies to improve the way rural peoples' lives are understood. It places people, particularly rural poor people, at the center of a web of inter-related influences that affect how these people create a livelihood for themselves and their households. The *livelihood assets* include natural resources, technologies, their skills, knowledge and capacity, their health, access to education, sources of credit, or their networks of social support. The extent of their access to these assets is strongly influenced by their *vulnerability context*, which takes account of trends (for example, economic, political, technological), shocks (for example, epidemics, natural disasters, civil strife) and seasonality (for example, prices, production, employment opportunities). Access to these assets is also influenced by the prevailing social, institutional and political environment, which affects the ways in which people combine and use their assets to achieve their goals. These are their livelihood strategies.

Livelihood is defined as “the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base” (Chambers and Conway, 1992). The livelihood framework theoretically describes employment activities and vulnerability management strategies (Pfluger, 2000).

The sustainable livelihood framework can be used as a qualitative analytical framework to identify and assess internal and external factors to the region and households that affect its socio-economic survival. It looks into livelihood strategies in a given vulnerable context. Livelihood strategies differ with regard to whether people have to deal with gradual changes or sudden shocks and crises.

As regards the livelihood strategy of the vulnerable section of the people, there are a numbers of deficiencies like low productivity, low income, high consumption share, no savings, lack of health and education, lower caste, gender inequality etc. However, what is really needed is an objective, to measure livelihood, calculated from a small number of specific dimensions of how assets-based capital impacts on people's livelihoods. While such a measure has yet to be agreed upon, it is hoped that study such as this will help to guide discussions toward a consensus on how such a measure may be derived.

This study is entirely based on the secondary data. The 54 blocks of Undivided Midnapur districts are purposely chosen for the present study. The data is based on Census 2001 and 2011 and districts statistical hand book of different year.

The Sustainable Livelihood Index (SLI) offers a composite framework to assess how multiple socio-economic and institutional factors interact to shape overall livelihood outcomes. Yet, identifying the relative importance of these factors is challenging, particularly when explanatory variables overlap through multicollinearity or synergistic effects. Traditional measures, such as simple or marginal correlations, often fail to provide an accurate decomposition of explanatory power, as they either overestimate or underestimate the true

contribution of a factor. As highlighted in empirical studies, reliance solely on marginal measures can lead to misleading conclusions when factors are interdependent or influenced by shared structural determinants.

To address this challenge, the True Relative Importance (TRI) methodology provides a statistically sound approach for evaluating the actual contribution of each factor by integrating squared orthopartial, semi-orthopartial, and simple correlations. This method corrects for overlaps, enhancement-synergism, and sign changes, yielding a clearer and more reliable decomposition of explanatory power. Applying this methodology allows a comprehensive assessment of how different dimensions, education, social structure, cooperativeness, economic stability, and health infrastructure, collectively shape sustainable livelihood outcomes.

Recent research on agricultural performance, factor importance, and modelling precision provides a strong methodological foundation for assessing regional determinants of sustainable livelihoods. Dolai et al. (2025) demonstrated that the True Relative Importance (TRI) method more accurately captures the contribution of agricultural factors, showing that irrigation and fertilizer use were the dominant drivers of India's agricultural growth from 1960–61 to 2019–20, while rainfall contributed minimally due to its uneven distribution; their work also highlights the limitations of relying on marginal correlations, which can misrepresent actual factor effects. Similarly, Dolai et al. (2023) found that across six agricultural sub-periods, irrigation, cropping intensity, and fertilizer use remained the most influential variables, reinforcing the centrality of controlled inputs over climate-dependent factors for regional development. Methodological improvements are further supported by Mondal et al. (2024), who showed that incorporating structural breaks significantly enhances the accuracy of time-series curve-fitting models for agricultural GDP, demonstrating that break-adjusted models outperform traditional approaches and better capture policy- and climate-induced fluctuations relevant to livelihood dynamics. Beyond production-related factors, Pradhan et al. (2023) revealed that India's economic openness exerts a greater influence on GDP growth than crude oil prices, and their introduction of the TRI approach effectively resolves multicollinearity issues inherent in the BAD method—an insight valuable for understanding macroeconomic contexts that shape livelihood opportunities. Complementing these studies, Dolai et al. (2025) applied fuzzy logic modelling to assess soil properties and found that pH and nutrient levels critically affect rice yield, with fuzzy models outperforming traditional predictive methods, thereby offering valuable tools for livelihood assessments in agrarian regions such as undivided Midnapur where soil variability influences household resilience.

Scope and Innovativeness of the Present Study

The scope of this research encompasses on the analysis of sustainable livelihood of the rural regions of undivided Midnapur and further to compare this status among the three considered districts of undivided Midnapur. For this purpose, we have constructed an index i.e., sustainability livelihood index (SLI). In this regard, Fuzzy methodology has been used. It is based on unequal weightage and have used the non-linear logarithm Fuzzy Membership Function to construct the aggregate index. Several researchers have considered the later methodology as appropriate to address the variability of the data. The analysis is important because these is wide regional variation in the un-divided Midnapur which can be unearthed using the Fuzzy Membership Function. This analysis can help and improve the block and districts level planning. Further, the effectiveness of the factors influencing it is also explored for achieving sustainability.

The present study offers a comprehensive and multidimensional assessment of the determinants of the Sustainable Livelihood Index (SLI) by examining six critical factors—Student–Teacher Ratio (STR), Percentage of SC/ST population (PCSCST), Cooperative Attitude (RCOPA), Beds per Institution (BEDPINT), Percentage of Indoor Treatment (POIND), Per Capita Small Savings (PCSS), and Time (TIME)—within a unified analytical framework. Its key innovation lies in the application of the True Relative Importance (TRI) methodology, which decomposes the explained variance into unique and overlapping components using squared orthopartial, semi-orthopartial, and simple correlations. Unlike conventional approaches that rely on marginal or simple correlations and often misrepresent contributions due to multicollinearity, the TRI method accounts for enhancement-synergism, sign changes, and variable overlaps, providing a more accurate and theoretically sound evaluation of each factor's true impact. By identifying which dimensions exert dominant, moderate, or minimal influence on livelihood sustainability, the study not only advances methodological rigor but also generates nuanced insights that can support evidence-based policy interventions aimed at strengthening sustainable livelihoods.

2. DATABASE AND METHODOLOGY

The database and methodology section provides a detailed roadmap of the analytical framework employed to dissect the impact of factors on Sustainable livelihood Index using unequal weights in case of 54 blocks of Undivided Midnapur in 2001 and 2011. Undivided Midnapur of West Bengal divided into three regional districts separated on January 1, 2002, it divided into Paschim Midnapur and Purba Midnapur and on April 2017 and further Paschim Midnapur divided into two parts Paschim Midnapur and Jhargram. Two secondary data sets, census and census amenities 2001 and 2011 and different round (2002-03, 2011-12, 2012-13) of districts statistical hand book are used for the study.

The methodology section is divided into various analytical stages, each employing specific econometric and statistical tools to analyze the data comprehensively. For the construction of the Sustainable Livelihood Index (SLI), four types of assets has been considered as dimensions and under that seven indicators have been taken. The dimensions and indicators are as follows: *Physical Assets (PHYASTI)*: Per capita land area, *Cultural Assets (CULTASTI)*: Percentage of total literacy and female literacy. *Social Assets (SOCASTI)*: sex ratio and worker population ratio, *Economic Asset*: Aman rice productivity and Percentage of main worker. The notation, specification and source of the indicators used for the construction of the SLI is given in Table 1.

Measures of Livelihood by using Fuzzy Analysis

Assume $i \in [1, n]$ respondent, $j \in [1, M]$ indicators related to livelihood. Consider $X^j = \left\{ X_{j/j=1,2,3,\dots,M} \right\}$ vectors of indicators respectively as capital assets. The variable X_j^i is the values taken by indicators j for the i -th respondent. For the formulation of Membership Function in respect of degree of effective achievement for each indicator, let us assume that μ_j^i provides the degree of effective achievement of the i -th respondent relative to the indicator j . When ranking values of j by increasing order (i.e., higher the value of a given indicator, higher is the degree of effective achievement), function μ_j^i is defined as follows:

$$\mu_j^i = \begin{cases} 1, & \text{If, } X_j^{max} \leq X_j^i \\ \frac{X_j^i - X_j^{min}}{X_j^{max} - X_j^{min}}, & \text{If, } X_j^{min} \leq X_j^i \leq X_j^{max} \\ 0 & \text{If, } X_j^i \leq X_j^{min} \end{cases}$$

Where, X_j^{min} and X_j^{max} are the lower and upper bound of the system. It is to be noted that the functions are increasingly linearly between zero and one according to the degree of effective achievement. If it is closer to one, it is an indication of high degree of achievements and if it is closer to zero, it is an indication of low degree of achievement.

The higher degree of achievement means higher level of livelihood. In order to obtain the composite index of 'livelihood' for each respondent block, different degrees of effective achievement are obtained for each respondent and indicator need to be summarized. Following Cerioli and Zani (1990), composite index is calculated by taking the weighted arithmetic mean of the membership functions, obtained from the respective indicators. Mathematically, it is represented as:

$$\mu_{LH}(i) = \sum_{j=1}^M W_j \mu_j^i \quad (i) \quad \dots\dots\dots (2)$$

Where W_j is the weight attributed to the respective indicators (j). The weight must be positive and its sum must be equal to one. That is

$$W_j \geq 0 \text{ and } \sum_{j=1}^M W_j = 1 \quad \dots\dots\dots (3)$$

The weights of each indicator are calculated as follows:

$$W_j = \log(1/\bar{\mu}_j) / \sum_{j=1}^M \log(1/\bar{\mu}_j) \quad \dots\dots\dots (4)$$

$$\text{Where, } \bar{\mu}_j = 1/N \sum_{j=1}^N \mu_j^i \quad \dots\dots\dots (5)$$

The weight W_j is the inverse function of the mean effective achievement level relative to the indicator j . Since livelihood does not vary in a linear way, the logarithmic curve function has been used into the weighting system. In this way a more important weight has been given to the indicators those are more widespread among the respondents. The composite index SLI with high numbers indicates favorable conditions. The high value of sustainable livelihood index indicates high level of livelihood while low value indicates low level of livelihood.

Notation Specification and their corresponding indicators, time period and data sources of the variable are given in the Table 1.

Table 1 Notation, Specification of the dimensions and indicators used in construction and analysis of Sustainable Livelihood Index

Notation	Specification	Source
Physical Asset Index (PHYASTI)	Per capita land area (in Hectare), 2003-04, 2011-12	DSH*
Cultural Asset Index (CULTASTI)	Percentage of Total Literacy rate, 2001,2011	Census
	Percentage of Female Literacy rate, 2001, 2011	Census
Social Asset Index (SOCASTI)	Sex ratio, 2001, 2011	Census
	Work Participation Rate, 2001, 2011	Census
Economical Asset Index (ECOACTI)	Aman Rice Productivity, 2003-04, 2012-13	DSH
	Percentage of Main Worker, 2001, 2011	Census

<i>Factors that Influence Sustainable Livelihood of the Region</i>		
Educational Factor (STR)	Student Teacher Ratio, 2003-04, 2012-13	DSH
Social Factor (PCSCST)	Percentage of SC/ST, 2001, 2011	Census
Cooperativeness Factor (RCOPA)	Ratio of Member of Cooperative and Number of Cooperative (Cooperative Attitude)	DSH
Health Factor (BEDPINT)	Bed per Institution, 2003-04,2012-13	DSH
Health Factor (POIND)	Percentage of Indore Treatment out of total Penitents, 2003-04,2012-13	DSH
Economical Factor (PCSS)	Per capital Small Saving,2003-04, 2012-13	DSH

Note: *DSH-District Statistical Hand Book.

Theoretical Background of Relative Importance

We use Ordinary Least Squares (OLS) specifications to analyse the data and estimate several critical measures, including marginal correlation, simple correlation, ortho correlation, and the relative relevance of the explanatory factors. Using these analytical tools, we may determine the magnitude and direction of connections between variables and acquire a better understanding of their relative importance in shaping the Livelihood Index. The following is our empirical specification:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + U$$

The Sustainable Livelihood Index (Y) is considered as the dependent variable, while several socio-economic and institutional factors are taken as independent variables to assess their influence on livelihood sustainability. These include: X_1 , the Social factor (PCSCST), representing the percentage of Scheduled Castes and Scheduled Tribes in 2001 and 2011; X_2 , the Health Factor (BEDPINT), indicating the number of beds per institution during 2003–04 and 2012–13; X_3 , another Health Factor (POIND), representing the percentage of indoor treatment out of total patients for the years 2003–04 and 2012–13; X_4 , the Economic Factor (PCSS), which denotes per capita small savings during 2003–04 and 2012–13; X_5 , the Educational Factor (STR), measured as the student–teacher ratio for the same years; and X_6 , the Cooperativeness Factor (RCOPA), defined as the ratio of cooperative members to the total number of cooperatives, reflecting the cooperative attitude within the community.

U is the random error term, and β_i is the coefficient of X_i , which represents the amount of change in Y for one unit change in X_i while keeping all other explanatory variables constant. This coefficient is also known as the partial regression coefficient.

The regression coefficient has two distinct interpretations, although the term partial regression coefficient applies to only one of them (see Mondal, 2008).

- (i) It may represent the change in that specific portion of the dependent variable Y that is not influenced by the other independent variables, resulting from a one-unit change in the corresponding portion of X that is itself independent of the remaining predictors.
- (ii) Alternatively, it may denote the change in Y that is attributable to a one-unit change in X , specifically in the component of X that cannot be explained by the other independent variables included in the model.

In the first type of regression, the resulting correlation is conventionally referred to as a partial correlation in the literature, although it does not reflect the true partial effect. The true partial

correlation arises only from the second regression. To resolve this inconsistency, Mondal (2008) introduced the term orthopartial correlation (with ortho signifying “correct”) to designate the correlation produced by the second regression, which accurately captures the true partial relationship.

The marginal explanatory power of an independent variable X_i can be expressed as:

$$\text{Marginal Explanatory Power}_{X_i}(r^2) = \frac{t^2_{X_i}}{t^2_{X_i} + \text{degree of freedom}}$$

where the degrees of freedom are defined as:

$$\text{degree of freedom} = n - (k + 1)$$

Here,

n = total number of observations,

k = number of independent variables in the model.

The partial or orthopartial explanatory power of an explanatory variable X_i may be expressed as follows:

$$\text{Partial / Orthopartial Explanatory Power}_{X_i}(r_i^2) = R_1^2(Y \text{ on } X_k) - R_2^2(Y \text{ on } X_{k-i}), \\ i = 1, 2, 3, \dots, k-1, k$$

Here,

$R^2(Y \text{ on } X_k)$ denotes the coefficient of determination after adding the explanatory variable whose orthopartial contribution is being evaluated, and

$R^2(Y \text{ on } X_{k-i})$ represents the coefficient of determination before the inclusion of that explanatory variable.

Mondal (2008) proposed that this measure is more appropriately termed orthopartial significance, because it reflects the true partial contribution of a variable after isolating the unique component of its explanatory power. This contrasts with conventional partial correlations, which are often influenced by multicollinearity and therefore do not yield a correct decomposition of explanatory effects.

The relative importance of an explanatory variable is obtained by combining its squared orthopartial correlation with a sequence of squared semi-orthopartial correlations, each weighted according to its contribution. Mondal (2008) addressed longstanding gaps in econometric theory by demonstrating a statistically valid method for decomposing the total R^2 into additive components attributable to each explanatory variable. Based on this formulation, five distinct theoretical cases arise, each requiring a specific approach to averaging orthopartial correlations:

Case I. No theoretical multicollinearity, no theoretical enhancement–synergism, and no theoretical change in sign.

Case II. Theoretical multicollinearity exists, but no enhancement–synergism and no change in sign.

Case III. Theoretical multicollinearity and enhancement–synergism exist, but no change in sign.

Case IV. Theoretical multicollinearity and a change in sign exist, but no enhancement–synergism.

Case V. Theoretical multicollinearity, enhancement–synergism, and change in sign all exist.

For a typical model with six explanatory variables— X_1, X_2, X_3, X_4, X_5 & X_6 — the schematic representation illustrates that these variables may be either partially or jointly interrelated. Such interdependence indicates the possible presence of multicollinearity, enhancement–synergism, or sign-reversal effects within the model. Consequently, the variance of Y explained by these six predictors is not mutually exclusive; rather, it consists of overlapping contributions arising from shared linear relationships among the variables. This overlap aligns with the structure of partial linear dependencies, typically represented schematically by intersecting regions, where each explanatory variable contributes both unique and common portions to the total explanatory power.

In a six-variable regression model, each explanatory factor produces 120 distinct paths $(6-1)!$ connecting its squared orthopartial correlation to its squared simple correlation. Along each path, six sequential points are generated: the first point represents the squared orthopartial correlation; the second point corresponds to the up-to-two-joint semi-orthopartial contribution; the third point reflects the up-to-three-joint contribution; the fourth point indicates the up-to-four-joint contribution; the fifth point represents the up-to-five-joint contribution; and the sixth point denotes the up-to-six-joint or simple explanatory power. Across these ordered contributions, three types of behavioural patterns may arise: change-in-sign (CS), no-change-in-sign (NCS), and enhancement–synergism (ES).

The relative importance of an explanatory variable can be evaluated in three forms: unsigned average, signed average, and adjusted signed average. Under the unsigned average, all joint contributions are taken in absolute terms, effectively assuming positive overlap among the variables. The signed average, by contrast, incorporates the usual pattern of positive and negative overlaps observed along the joint contributions. The adjusted signed average further refines this by correcting for sign-reversal behaviour: when a variable changes sign at any point, overlaps along all meaningful paths are adjusted accordingly (for example, if the signed average is negative, any positive joint contributions are treated as sign-change points, and vice versa). However, in the present case, such adjustment is unnecessary because the overall multiple regression explanatory power (R^2) and the aggregated contributions of all variables do not differ significantly in sign, eliminating the need for adjusted corrections.

The unsigned-average relative importance of the explanatory variable x_i is given by:

$$x_i = \left| \frac{\delta_1}{n} \right| + \left| \frac{\delta_{21} + \delta_{22} + \dots + \delta_{2(n-1)}}{n * (n-1)} \right| + \left| \frac{\delta_{31} + \delta_{32} + \dots + \delta_{3 \frac{(n-1)(n-2)}{2}}}{n * \frac{(n-1)(n-2)}{2}} \right|$$

$$+ \left| \frac{\delta_{41} + \delta_{42} + \dots + \delta_{4 \frac{(n-1)(n-2)(n-3)}{3*2}}}{n * \frac{(n-1)(n-2)(n-3)}{3*2}} \right| + \dots$$

$$+ \left| \frac{\delta_{k1} + \delta_{k2} + \dots + \delta_{kn-1c_{k-1}}}{n * n - 1c_{k-1}} \right| + \dots + \left| \frac{Simple}{n} \right|$$

Where,

n = total number of explanatory variables.

δ_1 = squared orthopartial contribution.

δ_{2j} = squared semi-orthopartial contribution for all “up-to-two-joint” combinations.

δ_{3j} = semi-orthopartial contributions for “up-to-three-joint” combinations.

δ_{kj} = semi-orthopartial contributions for “up-to-k-joint” combinations.

$(n - 1 \ k - 1)$ = number of possible joint-combination paths at level k .

“Simple” = squared simple correlation of X_i .

Absolute values ensure the unsigned nature of the measure (i.e., all overlaps assumed positive).

3. RESULTS AND DISCUSSIONS

Sustainable Livelihood Index in the Rural Undivided Midnapur

SLI for the studied in districts of undivided Midnapur is constructed on the basis of four assets as dimensions (Physical, Cultural, Social and Economic) with seven indicators (per capita land area, total literacy rate, female literacy rate, sex ratio, work participation rate, Aman rice productivity and percentage of non-marginal workers to total population). The SLI based on fuzzy measurement SLIFZ and is present in Table 2. The districts are considered the indices i.e., SLIFZ presents the scenario where Jhargram performed relatively better than Paschim Midnapur and Purba Midnapur. The values of SLIFZ of all the 54 blocks of undivided Midnapur are given in Table A1.

Table 2 Sustainable livelihood Index and its Rank based on measures Fuzzy index of Three Districts of Undivided Midnapur

Name	No. of Block	2011		2001	
		SLIFZ	Rank	SLIFZ	Rank
Regi Jhargram	8	0.606	1	0.526	1
on/D Paschim Midnapur	21	0.469	2	0.371	2
istic Purba Midnapur	25	0.318	3	0.314	3
t					
Undivided Midnapur	54	0.419	--	0.367	--

Sources: Authors' Calculation

It can be noted that Purba Midnapur is in a relatively better condition followed by Paschim Midnapur and Jhargram as regards to economic development of the society (Mandal 2021). But in the context of sustainable livelihood an opposite scenario is revealed where Jhargram performs relatively better followed by Paschim Midnapur and Purba Midnapur. The reason behind this variation can be unearthed if we consider the dimension-wise status of the districts. Table 3 presents the weighted dimensional index and their ranks based on Fuzzy Analysis. In respect of physical asset index, considering the three districts, Jhargram performed relatively better followed by Paschim Midnapur and Purba Midnapur. This was mainly due to high per capital land holding resulting in higher weight of physical assets as compared to other assets. The weight assigned to physical asset was 39.1 per cent while to cultural asset, social asset and economic asset are 14.1 per cent, 28.3 per cent and 18.5 per cent respectively as per analysis for all 54 blocks taken as Undivided Midnapur (Appendix Table A2). Based on cultural asset index, among the three districts, Purba Midnapur districts was comparatively in a better position followed by Paschim Midnapur and Jhargram Districts. This better performance of Purba Midnapur in the cultural asset index was mainly due to its better

performance in education. In case of social assets, this was mainly due to their higher sex ratio, Jhargram districts was comparatively in a better position followed by Paschim Medinipur and Purba Medinipur. In case of economical assets higher productivity of Aman rice and and higher percentage of non-marginal workers to total population as compared to other blocks. In 2001, all the three districts had the same position as in 2011 in case of physical, cultural and social asset. However, in case of economic asset the position of Paschim Medinipur and Purba Medinipur was interchanged.

Table 3 Dimensional Index and their Rank based on Fuzzy Analysis of the three Districts of Undivided Midnapur in 2011, 2001

		PHYA STI	Ra nk	CULA STI	Ran k	SOC ASTI	Rank	ECO ASTI	Ran k
2011									
Dis tric t	Jhargram Districts	0.289	1	0.031	3	0.177	1	0.109	2
	Paschim Midnapur	0.126	2	0.076	2	0.131	2	0.136	1
	Purba Midnapur	0.044	3	0.120	1	0.081	3	0.072	3
	Undivided Midnapur	0.112	–	0.090	–	0.115	–	0.102	–
2001									
Dis tric ts	Jhargram Districts	0.249	1	0.027	3	0.145	1	0.105	1
	Paschim Midnapur	0.107	2	0.064	2	0.108	2	0.091	3
	Purba Midnapur	0.036	3	0.105	1	0.073	3	0.099	2
	Undivided Midnapur	0.095	–	0.078	–	0.097	–	0.097	– o

Sources: Autor's' Calculation

Relative Importance of the factors

Although a wide range of factors can influence the Sustainable Livelihood Index, their relative importance in a multivariate framework can be difficult to determine, as many of these factors overlap and interact in both positive and negative ways. In this analysis, six factors, the Social Factor (PCSCST), Health Factors (BEDPINT and POIND), the Economic Factor (PCSS), the Educational Factor (STR), and the Cooperativeness Factor (RCOPA), collectively explain 41.6342% of the variation in the Livelihood Index. Among these, overlaps among the six factors account for 186 portions of explanatory power, indicating substantial shared influence that may operate either positively or negatively. Beyond these overlaps, only 6 portions of the total explanatory power arise from the factors acting independently or orthopartially.

From squared orthopartial to squared simple correlations, each factor generates 120 paths. A comparison between squared simple and squared orthopartial correlations shows that, for all variables except POIND, the squared simple correlations are higher than their corresponding orthopartial values. The presence of multicollinearity among the predictors, driven mainly by positive overlapping rather than any synergistic enhancement. As a result, squared simple correlations tend to overestimate the actual explanatory power of each factor.

In contrast, squared orthopartial correlations underestimate relative importance for all variables except POIND, which behaves inversely.

Table 4 Results from pooled regression of Sustainable livelihood Index on its factors

R Square	0.416342	Adjusted R Square		0.381669				
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>sq. marginal correla.</i>	<i>sq. simple correla.</i>	<i>sq. ortho correla.</i>	relative importance
Intercept	0.579666	0.033441	17.33389	4.95E-32				
STR	-0.00265	0.000602	-4.40495	2.64E-05	0.161154	0.2764	0.11213	0.178382
PCSCST	0.001036	0.00039	2.657895	0.009143	0.065372	0.118175	0.040824	0.07043
RCOPA	-0.00015	4.56E-05	-3.30815	0.001302	0.097762	0.12194	0.06324	0.084103
BEDPINT	-4.5E-05	0.000765	-0.05944	0.952718	3.5E-05	0.088932	2E-05	0.031719
POIND	-0.00118	0.00153	-0.77266	0.441526	0.005876	0.000505	0.00345	0.001691
PCSS	-0.03288	0.01893	-1.73697	0.085441	0.029006	0.10223	0.01744	0.050016
Total					0.359205	0.708183	0.2371	0.416342

The assessment of relative importance using squared marginal, simple, and orthopartial correlations reveals meaningful insights into how different socio-economic and institutional factors shape livelihood sustainability. Among the six variables, the Student–Teacher Ratio (STR) stands out as the most influential determinant, with the highest relative importance value of 0.178. This strong contribution reflects the crucial role of educational infrastructure in strengthening human capital. A favourable STR enhances the quality of education, improves learning outcomes, and broadens skill development, all of which translate into better employment opportunities, higher productivity, and greater adaptive capacity in rural and semi-urban settings. As education strongly influences multiple dimensions of livelihood, its dominant statistical weight corresponds well with its real-world impact.

Following STR, the Cooperative Attitude (RCOPA) and the Percentage of SC/ST population (PCSCST) exhibit moderate yet meaningful importance, with relative contributions of 0.084 and 0.070. RCOPA's influence highlights the value of community cooperation, mutual support systems, and collective economic activities in improving livelihood conditions. Cooperative institutions often enable shared access to credit, inputs, and information, making communities more resilient and economically stable. Meanwhile, PCSCST reflects the socio-

demographic composition of the region. Areas with higher SC/ST populations often face structural disadvantages, limited access to resources, and socio-economic vulnerabilities, making this factor moderately influential in explaining variations in livelihood sustainability.

Per capita small savings (PCSS), with a relative importance of 0.050, also shows moderate significance. Savings represent financial security, economic stability, and the ability to cope with shocks. Households with higher savings capacity tend to have better resilience against livelihood risks, improved investment potential, and more stable income patterns. Therefore, its moderate explanatory power aligns with its practical role in enhancing economic well-being.

In contrast, the health-related variables, Beds per Institution (BEDPINT) and Percentage of Indoor Treatment (POIND), account for relatively minor portions of the explanatory power, with values of 0.031 and 0.001, respectively. Although health is a fundamental component of human development, these particular indicators capture narrow and specific dimensions of the health system. BEDPINT reflects health infrastructure availability but does not necessarily indicate utilization, accessibility, or quality of care. POIND, representing indoor treatment rates, captures only inpatient services and often fails to reflect overall population health, especially in regions where outpatient care or informal treatment is more common. Furthermore, both variables share considerable overlap with other factors and exhibit weaker independent effects, thereby reducing their relative importance in the multivariate framework.

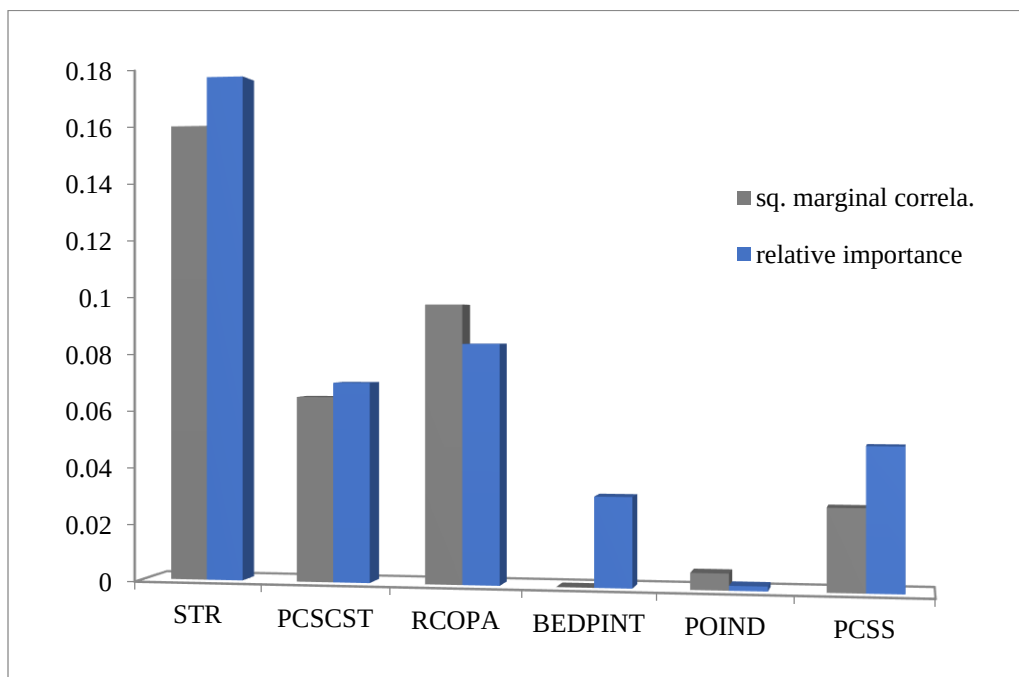


Figure-1: Comparison of Squared Marginal Correlations and True Relative Importance

When squared marginal correlations are used to measure each factor's explanatory power, they sometimes overestimate or underestimate the true importance of the variables because they do not separate unique effects from overlapping influences. In this case, the marginal correlations underestimate the real importance of STR, PCSCST, BEDPINT, and PCSS, while they overestimate the importance of RCOPA and POIND.

4. CONCLUSION

To construct a suitable composite Sustainable Livelihood Index, we have used unequal weight methodology popularly Fuzzy methodology to address that the variability for the construction of sustainable livelihood index. Since, there is wide regional variation in the undivided Midnapur. Considering three regions or districts of Undivided districts, the Purba Midnapur is in a relatively better condition followed by Paschim Midnapur and Jhargram as regards to economic development of the society (Mandal 2021). But in the context of sustainable livelihood an opposite scenario is revealed where Jhargram performs relatively better followed by Paschim Midnapur and Purba Midnapur.

The relative importance of factors influencing the Sustainable Livelihood Index (SLI) has been evaluated using the True Relative Importance methodology, which integrates statistical logic, axioms, and theorems derived from squared orthopartial, semi-orthopartial, and simple correlations. Six key factors, Student–Teacher Ratio (STR), social composition (PCSCST), cooperative attitude (RCOPA), health-related indicators (BEDPINT and POIND), economic security through per capita small savings (PCSS), and time (TIME)—were analyzed to understand their contributions to sustainable livelihoods. In the presence of multicollinearity, these factors display both positive and negative overlaps, shaped by the presence or absence of enhancement synergism. The analysis identifies STR as the most influential factor and POIND as the least impactful. STR emerges as the strongest driver because education enhances skills, awareness, and opportunities, thereby improving livelihood outcomes. Additionally, squared marginal correlations may either overestimate or underestimate true factor importance, as they do not distinguish unique contributions from overlapping effects.

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Appendix Table

Table A1 Block wise Component Index of Sustainable Livelihood Index based on Fuzzy Analysis and Aggregate Index and Rank of both Measures Fuzzy (SLIFZ) and Dimensional Index (SLIDI) in 2011

Sub-Division	Blocks/Districts	PHYA STI	Ra nk	CULA STI	Ra nk	SOCA STI	Ra nk	EOCA STI	Ra nk	SLI FZ	Ra nk
Jhargra m	Jhargram	0.33	3	0.04	47	0.19	6	0.12	25	0.67	5
	Binpur-I	0.23	9	0.03	52	0.18	8	0.11	27	0.55	8
	Binpur-II	0.39	1	0.03	51	0.22	2	0.07	42	0.72	2
	Jamboni	0.30	5	0.04	48	0.15	14	0.08	36	0.58	7
	Nayagram	0.39	2	0.00	54	0.23	1	0.12	23	0.73	1
	Sankrail	0.24	8	0.05	44	0.19	5	0.13	16	0.62	6
	Gopiballav pur-I	0.26	7	0.01	53	0.11	22	0.12	20	0.51	12
	Gopiballav pur-II	0.17	12	0.04	49	0.14	16	0.13	18	0.47	17
	Jhargram	0.29	1	0.03	8	0.18	1	0.11	4	0.61	
Sadar	Salboni	0.31	4	0.06	42	0.19	4	0.15	7	0.71	3
	Keshpur	0.12	18	0.07	36	0.10	30	0.14	10	0.43	22
	Garbeta-I	0.14	15	0.05	46	0.11	23	0.15	3	0.45	19
	Garbeta-II	0.28	6	0.06	41	0.18	10	0.16	1	0.68	4
	Garbeta-III	0.17	11	0.05	43	0.15	13	0.15	6	0.53	9
	Medinipur	0.15	13	0.04	50	0.14	17	0.15	4	0.47	16
	Sadar	0.20	2	0.06	7	0.14	2	0.15	1	0.55	
Kharag pur	Debra	0.09	24	0.09	31	0.20	3	0.15	5	0.53	10
	Pingla	0.09	26	0.10	27	0.15	15	0.14	15	0.47	18
	Keshiary	0.19	10	0.07	39	0.17	11	0.10	31	0.52	11
	Dantan-I	0.13	16	0.05	45	0.11	24	0.12	21	0.40	25
	Dantan-II	0.09	23	0.10	30	0.07	45	0.12	19	0.38	31
	Narayangar h	0.15	14	0.07	35	0.17	12	0.11	28	0.50	13
	Mohanpur	0.09	20	0.09	33	0.05	52	0.14	8	0.37	32
	Sabong	0.08	27	0.12	13	0.18	7	0.12	24	0.50	14
	Kharagpur-I	0.09	22	0.07	38	0.12	21	0.16	2	0.44	20
	Kharagpur-II	0.12	17	0.06	40	0.18	9	0.11	26	0.48	15
	Khargrapur	0.11	3	0.08	6	0.14	3	0.13	3	0.46	
Ghatal	Chandrakona-I	0.12	19	0.08	34	0.09	36	0.14	11	0.43	23

	Chandrakon a-II	0.09	21	0.07	37	0.09	34	0.14	14	0.39	29
	Ghatal	0.06	34	0.09	32	0.07	47	0.14	9	0.36	35
	Daspur-I	0.04	43	0.10	26	0.13	18	0.14	13	0.42	24
	Daspur-II	0.03	47	0.11	24	0.11	26	0.14	12	0.38	30
	Ghatal	0.07	4	0.09	5	0.10	5	0.14	2	0.39	
	Paschim Midnapur	0.13	2	0.08	2	0.13	2	0.14	1	0.47	
Tamluk	Tamluk	0.01	52	0.12	11	0.09	35	0.09	34	0.30	45
	Sahid Matangini	0.00	54	0.12	12	0.05	53	0.08	39	0.24	51
	Panskura-I	0.05	40	0.10	28	0.13	20	0.08	37	0.36	36
	Kolaghat	0.00	53	0.11	25	0.07	46	0.09	32	0.27	49
	Moyna	0.02	48	0.12	16	0.03	54	0.05	49	0.23	54
	Nandakuma r	0.02	51	0.11	20	0.08	38	0.07	41	0.28	48
	Chandipur	0.03	45	0.13	8	0.06	49	0.02	54	0.24	52
	Tamluk	0.02	8	0.12	3	0.07	8	0.07	6	0.27	
Haldia	Mahishadal	0.03	46	0.12	15	0.08	41	0.07	45	0.29	47
	Nandigram- I	0.05	39	0.11	22	0.08	42	0.06	47	0.30	46
	Nandigram- II	0.05	41	0.13	3	0.10	28	0.06	48	0.34	38
	Sutahata	0.02	50	0.11	21	0.05	51	0.05	52	0.23	53
	Haldia	0.02	49	0.12	17	0.07	43	0.06	46	0.27	50
	Haldia	0.03	7	0.12	2	0.08	7	0.06	8	0.28	
Egra	Potashpur-I	0.06	32	0.11	19	0.11	25	0.11	29	0.39	27
	Potashpur- II	0.08	28	0.12	14	0.08	40	0.10	30	0.37	33
	Bhagawanp ur-I	0.03	44	0.13	9	0.10	29	0.05	51	0.31	44
	Egra-I	0.09	25	0.10	29	0.13	19	0.12	22	0.43	21
	Egra-II	0.07	30	0.12	18	0.08	37	0.13	17	0.40	26
	Egra	0.07	4	0.11	4	0.10	5	0.10	4	0.38	
Contai	Khejuri-I	0.06	35	0.13	4	0.08	39	0.05	50	0.33	41
	Khejuri-II	0.06	33	0.11	23	0.06	48	0.07	43	0.31	43
	Bhagawanp ur-II	0.06	37	0.14	1	0.10	27	0.03	53	0.33	40
	Ramnagar-I	0.04	42	0.12	10	0.09	33	0.09	35	0.34	37
	Ramnagar- II	0.07	29	0.13	6	0.10	32	0.07	40	0.37	34
	Contai-I	0.05	38	0.13	5	0.07	44	0.08	38	0.34	39
	Deshapran	0.06	36	0.13	7	0.06	50	0.07	44	0.31	42
	Contai-III	0.07	31	0.14	2	0.10	31	0.09	33	0.39	28
	Contai	0.06	6	0.13	1	0.08	7	0.07	7	0.34	
	Purba Midnapur	0.04	3	0.12	1	0.08	3	0.07	2	0.32	

Table A2 Dimensional Index and weight for Construction of SLIFZ in Jhargram, Paschim Midnapur and Purba Midnapur Districts of Undivided Midnapur, 2011

	Blocks	PHYA STI	Wei ght	CULA STI	Wei ght	SOCA STI	Wei ght	ECOA STI	Wei ght	SLI FZ	Ra nk
	Jhargram	0.83	0.39	0.31	0.14	0.66	0.28	0.62	0.19	0.67	5

Jhargra m	Binpur-I	0.59	0.39	0.21	0.14	0.65	0.28	0.60	0.19	0.55	8
	Binpur-II	1.00	0.39	0.23	0.14	0.79	0.28	0.37	0.19	0.72	2
	Jamboni	0.76	0.39	0.31	0.14	0.54	0.28	0.44	0.19	0.58	7
	Nayagram	0.99	0.39	0.00	0.14	0.80	0.28	0.63	0.19	0.73	1
	Sankrail	0.62	0.39	0.36	0.14	0.68	0.28	0.72	0.19	0.62	6
	Gopiballa vpur-I	0.67	0.39	0.06	0.14	0.40	0.28	0.67	0.19	0.51	12
	Gopiballa vpur-II	0.44	0.39	0.27	0.14	0.48	0.28	0.68	0.19	0.47	17
Sadar	Salboni	0.80	0.39	0.41	0.14	0.68	0.28	0.78	0.19	0.71	3
	Keshpur	0.31	0.39	0.52	0.14	0.34	0.28	0.77	0.19	0.43	22
	Garbeta-I	0.36	0.39	0.34	0.14	0.39	0.28	0.83	0.19	0.45	19
	Garbeta-II	0.70	0.39	0.44	0.14	0.63	0.28	0.88	0.19	0.68	4
	Garbeta- III	0.44	0.39	0.38	0.14	0.54	0.28	0.79	0.19	0.53	9
	Medinipur	0.39	0.39	0.26	0.14	0.48	0.28	0.80	0.19	0.47	16
Kharag pur	Debra	0.23	0.39	0.67	0.14	0.69	0.28	0.80	0.19	0.53	10
	Pingla	0.22	0.39	0.72	0.14	0.51	0.28	0.73	0.19	0.47	18
	Keshiary	0.48	0.39	0.48	0.14	0.61	0.28	0.51	0.19	0.52	11
	Dantan-I	0.33	0.39	0.36	0.14	0.39	0.28	0.63	0.19	0.40	25
	Dantan-II	0.23	0.39	0.68	0.14	0.24	0.28	0.67	0.19	0.38	31
	Narayang arh	0.38	0.39	0.52	0.14	0.61	0.28	0.58	0.19	0.50	13
	Mohanpur	0.24	0.39	0.61	0.14	0.17	0.28	0.78	0.19	0.37	32
	Sabong	0.21	0.39	0.83	0.14	0.65	0.28	0.62	0.19	0.50	14
	Kharagpur -I	0.24	0.39	0.49	0.14	0.44	0.28	0.84	0.19	0.44	20
	Kharagpur -II	0.31	0.39	0.45	0.14	0.64	0.28	0.62	0.19	0.48	15
Ghatal	Chandrak ona-I	0.31	0.39	0.57	0.14	0.30	0.28	0.76	0.19	0.42	23
	Chandrak ona-II	0.24	0.39	0.50	0.14	0.31	0.28	0.74	0.19	0.39	29
	Ghatal	0.16	0.39	0.62	0.14	0.23	0.28	0.78	0.19	0.36	35
	Daspur-I	0.11	0.39	0.73	0.14	0.47	0.28	0.75	0.19	0.42	24
	Daspur-II	0.07	0.39	0.80	0.14	0.37	0.28	0.75	0.19	0.38	30
Tamlu k	Tamluk	0.02	0.39	0.85	0.14	0.30	0.28	0.48	0.19	0.30	45
	Sahid Matangini	0.00	0.39	0.84	0.14	0.16	0.28	0.42	0.19	0.24	51
	Panskura- I	0.12	0.39	0.72	0.14	0.44	0.28	0.44	0.19	0.36	36
	Kolaghat	0.01	0.39	0.77	0.14	0.24	0.28	0.50	0.19	0.27	49
	Moyna	0.06	0.39	0.82	0.14	0.12	0.28	0.29	0.19	0.23	54
	Nandaku mar	0.05	0.39	0.81	0.14	0.29	0.28	0.38	0.19	0.28	48
	Chandipur	0.08	0.39	0.89	0.14	0.22	0.28	0.10	0.19	0.24	52
Haldia	Mahishad al	0.07	0.39	0.83	0.14	0.27	0.28	0.35	0.19	0.29	47
	Nandigra m-I	0.13	0.39	0.80	0.14	0.27	0.28	0.31	0.19	0.30	46
	Nandigra m-II	0.12	0.39	0.95	0.14	0.36	0.28	0.30	0.19	0.34	38
	Sutahata	0.05	0.39	0.80	0.14	0.18	0.28	0.24	0.19	0.23	53
	Haldia	0.06	0.39	0.82	0.14	0.25	0.28	0.33	0.19	0.27	50

Egra	Potashpur-I	0.16	0.39	0.81	0.14	0.38	0.28	0.57	0.19	0.39	27
	Potashpur-II	0.20	0.39	0.83	0.14	0.28	0.28	0.52	0.19	0.37	33
	Bhagawanpur-I	0.08	0.39	0.89	0.14	0.35	0.28	0.26	0.19	0.31	44
	Egra-I	0.23	0.39	0.69	0.14	0.47	0.28	0.63	0.19	0.43	21
	Egra-II	0.18	0.39	0.81	0.14	0.30	0.28	0.70	0.19	0.40	26
Contai	Khejuri-I	0.16	0.39	0.93	0.14	0.28	0.28	0.28	0.19	0.33	41
	Khejuri-II	0.16	0.39	0.80	0.14	0.22	0.28	0.36	0.19	0.31	43
	Bhagawanpur-II	0.15	0.39	1.00	0.14	0.36	0.28	0.14	0.19	0.33	40
	Ramnagar-I	0.11	0.39	0.87	0.14	0.32	0.28	0.46	0.19	0.34	37
	Ramnagar-II	0.18	0.39	0.93	0.14	0.33	0.28	0.39	0.19	0.37	34
	Contai-I	0.14	0.39	0.93	0.14	0.24	0.28	0.44	0.19	0.34	39
	Deshapran	0.16	0.39	0.90	0.14	0.21	0.28	0.36	0.19	0.31	42
	Contai-III	0.17	0.39	0.96	0.14	0.34	0.28	0.49	0.19	0.39	28
	Un Divided Midnapur	0.29	0.39	0.64	0.14	0.41	0.28	0.55	0.19	0.42	
	Percentage of Weight	--	39.1	--	14.1	--	28.3	--	18.5	100	--

Crisis, Volatility, and Market Resilience: Evidence from GARCH Modelling of the BSE Sensex

Dipankar Pradhan^{1*}, Binota Reang²

¹Assistant Professor, ICAI University, Tripura

²M. Com Student, ICAI University, Tripura

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*Corresponding author e-mail: pradhandipankar10@gmail.com

ABSTRACT

This study examines the volatility behaviour of the Indian stock market by analysing the BSE Sensex during the pre-COVID and COVID periods. The COVID-19 pandemic introduced unprecedented uncertainty into global financial markets, significantly influencing investor behaviour, market risk, and overall stability. Against this background, the study aims to compare market performance and volatility dynamics across normal and crisis periods, with a specific focus on volatility persistence and clustering. The analysis is based on secondary daily time-series data of the BSE Sensex. Stock returns are computed using continuously compounded log returns. Descriptive statistical measures are employed to examine the basic characteristics of the return series, while the Augmented Dickey–Fuller (ADF) test is used to confirm stationarity. Market volatility and risk are modelled using the GARCH (1,1) framework, which is widely used to capture time-varying volatility and the persistence of market shocks. The empirical results indicate that the BSE Sensex exhibited relatively stable volatility during the pre-COVID period, whereas volatility increased sharply during the COVID-19 phase, confirming the presence of strong volatility clustering and persistence. The GARCH estimates show that shocks during the pandemic had a significant and long-lasting impact on market volatility. Overall, the findings confirm that COVID-19 had a substantial effect on stock market risk and stability. The study contributes to the existing literature by providing a focused GARCH-based analysis of volatility behaviour during crisis conditions, offering valuable insights for investors, policymakers, and risk managers in emerging markets.

KEYWORDS: BSE Sensex; Stock Market Volatility; COVID-19 Pandemic; GARCH Model; Financial Crisis; Market Risk; Emerging Markets

1. INTRODUCTION

Financial markets have been instrumental in the economic well-being of a nation, as it facilitates resource allocation, transmission of information, and the control of investor expectation. Stock exchanges are one of such markets that are particularly sensitive to the economic shocks, policy changes and world uncertainties. Financial crises, geopolitical conflicts, or health-related crises are examples of unexpected outside factors that tend to interfere with the normal operations of the market, causing price changes and increasing volatility. It is thus the understanding of the behaviour of stock market during such extreme events that is crucial to the investors, policy makers and financial regulators.

The new coronavirus crisis that started at the beginning of 2020 is one of the most significant shocks in the history of the modern economy in the world. What started as a national health crisis quickly turned into an economic crisis all over the world, and at the same time, it touched upon production, trade, employment, and financial systems. The effect of lockdown, travel restrictions, disruption of supply chains, and widespread uncertainty greatly changed the investor sentiment of global financial markets. Fear, panic and the sudden fluctuations of expectations caused stock markets to respond with a volatility, steep downfalls, and abrupt turns that had never been experienced before.

There was severe turbulence in the stock market in India in the period of the pandemic. The BSE Sensex a major benchmark index of the performance of leading Indian firms experienced sharp falls in the first stage of COVID-19 especially in March 2020. Such movements were spurred by local conditions including countrywide lockdowns and shrinking economies, and international ones including capital flight, international demand breakdown, and risk-aversion. Nevertheless, as the government stimulus packages were implemented, the monetary policy was accommodative, the vaccination campaigns were launched and the economy gradually opened, the market started to recover and reached a new level. This dynamic reaction of large-scale crises on stock markets is emphasised by this contrasting behaviour.

Conventional financial theories tend to believe in market efficiency and predictable trends in risks, but when crisis periods arise, these beliefs are put into question. In case of extreme events such as COVID-19, stock markets are prone to volatility clustering, shock persistence, and risk that varies over time. Simple linear models cannot adequately model such characteristics. Higher-order econometric models, especially the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model, are thus far and large utilised to examine time-changing volatility and risk persistence in financial markets.

Whereas a substantial literature has been used to investigate the effect of COVID-19 on financial markets, a lot of the available literature has dwelled either on immediate effects or individual stages of the pandemic. Empirical data on the comparative volatility behaviour in normal (pre-COVID) and crisis (COVID) regimes under a common econometric model is not available, particularly on emerging markets such as India.

It is against this background that the current research study is being conducted to examine the volatility behaviour of the BSE Sensex both in the pre-COVID and COVID eras through the application of descriptive statistics, unit root testing and GARCH modelling. The paper aims to offer a more insight into market risk and market stability in times of crisis conditions by examining volatility dynamics and persistence to help address the gaps in existing literature on financial market behaviour and provide practical implications to investors and policymakers.

Background of The Study

Economic shocks are extremely sensitive to the financial markets and the volatility of the stock markets is more likely to indicate the shifts in investor sentiment and uncertainty in an economy. COVID-19 pandemic was a global crisis that affected the economic activity and financial systems of the entire world. The COVID-19 outbreak in India and the ensuing nationwide lockdowns resulted in drastic drops and utter unpredictability of the stock market and specifically to the BSE Sensex that is a prime indicator of the stock market performance in general. The initial stages of the pandemic escalated market risk due to panic selling, capital movements and unpredictability on economic recovery. Nevertheless, the policy interventions, easing of monetary policy, and vaccination programmes slowly reinstated investor confidence, which resulted in robust recovery in the market later. These opposite market behaviours point to the dynamic character of volatility in normal and crisis times. These changes are impossible to understand without sophisticated econometric methods that would be able to capture time-varying risk and volatility persistence. Thus, the analysis of the pre-COVID and COVID periods of the BSE Sensex is important in terms of stability of the markets, dynamics of risks, and the stability of the new financial markets.

2. LITERATURE REVIEW

COVID-19 pandemic has spawned a plethora of scholarly interest in the manner in which it affects financial markets and financial markets especially stock market volatility and investor behaviour. According to financial theory, unforeseen external shocks enhance uncertainty, and therefore create volatility, structural breaks and non-normal market behaviour. The pandemic was a special environment to put these theoretical hypotheses to the test in developed and developing markets.

Preliminary empirical data prove that COVID-19 was a great enhancer of stock market volatility across the globe. Chaudhary, Bakhshi, and Gupta (2020a, 2020b) contrasted the economic situation in developed and developing countries and observed the devastating impacts on the markets during the first outbreak and the slower recovery of economic growth in emerging markets because of the insufficient institutional preparedness. In the same manner, Sarwar et al. (2020) and Baig et al. (2020) have shown that the news of the pandemic caused a substantial growing volatility and liquidity stress in global markets and reinforced crisis-response and investor-behaviour theories.

A number of studies in the Indian setting note spikes in volatility in the middle of the pandemic. Madheswaran, Lingararajan, and Duraisamy (2023) utilized GARCH-based econometric models as the analysis of BSE Sensex and found a relatively stable behaviour pre-COVID-19 and extremely volatile behaviour during the COVID-19 wave. Their results emphasize the existence of volatility persistence and augmented risk in the market when conditions are of crisis. In line with this, Dhanjal and Raman (2022) noted that in March 2020, the market collapsed dramatically and then recovered slowly with the intervention of the policy and lack of restrictions.

Asymmetric pandemic impacts are also indicated by sectoral studies. Nitha, Sivakumari, and Suraj (2021) have demonstrated that IT and pharmaceutical industries have been faster recovering, whereas tourism and real estate recovery was long-lasting. The study by Mahajan (2025) showed that the transmission of volatility was uneven across sectors, and diversification is crucial in managing the market risk.

Other than volatility modelling, behavioural and informational factors have also been studied. According to the study by Pandey (2021), the correlations between COVID-19 case statistics and the BSE Sensex were strong, indicating that investor sentiment was more affected by the reported outcomes, rather than the real-time risks to health. Tripathi (2022) emphasized

the impact of misinformation and ineffective communication during the COVID-19 that led to heightened fear and ambiguity, which have indirect influence on financial confidence.

On methodological grounds, the recent literature is dominated by advanced econometric volatility models. Silva (2022) implemented the asymmetric EGARCH regimes in both emerging and developed markets and demonstrated that negative news were more effective in volatility compared to positive news. The research studies that predict on short-term basis by Ghosh (2022) proved that time-series models can still be used to predict even upon the instability brought about by a crisis.

On the whole, the literature confirms that COVID-19 was a systemic shock (Bhullar et al., 2022; Subburayan, 2024; Manogna & Singh, 2025), which heightened volatility and changed the dynamics of returns and market efficiency, which was tested. Nonetheless, an overwhelming majority of studies are limited by the time scope or individual modelling techniques and do not perform GARCH-based volatility analysis on a broader level over a long period of time, especially with respect to emerging markets such as India.

Research Gap

Despite the large amount of literature on the effects of COVID-19 on stock markets, there are still some gaps. The majority of research is devoted to one stage in the pandemic or considers a limited time frame, which prevents comparing the behaviour of the market before and during COVID-19. Moreover, the current literature tends to base their results on short-term studies or sector-specific results, with little to no focus on long-term persistence of volatility. The empirical research using GARCH models to investigate time-varying volatility of BSE Sensex during normal and event-based periods with the use of consistent daily data are relatively few. This paper will aim to close these gaps by offering a dedicated GARCH-based dynamic volatility analysis of the Indian stock market.

Objectives of The Study

The main aim of my research will be to examine the volatility behaviour of BSE Sensex in the pre-COVID and COVID periods. In particular, the research will seek to analyse the dynamics of stock market returns and risk in the normal and crisis conditions. It aims at determining the existence of volatility clustering and persistence based on GARCH (1,1) model. The other goal is to evaluate the effects of market shocks during the COVID-19 pandemic on the dynamics of volatility and the market stability in general. The research also seeks to give empirical evidence on risk behaviour in the Indian stock market when the uncertainty is at its highest levels.

Hypotheses

The hypotheses guiding the study are the following testable hypotheses:

H₀₁: The difference in the behaviour of the BSE Sensex in terms of its returns in the pre-COVID and COVID period is insignificant.

H₁₁: The return behaviour of the BSE Sensex is significantly different between the pre-COVID and the COVID period.

H₀₂: The volatility of the BSE Sensex stock market does not materially differ in the COVID-19 era.

H₁₂: The stock market volatility of the BSE Sensex is significantly greater at the COVID-19 period.

Data and Methodology

The current research is purely based on secondary data, which are suitable to the study of the stock market behaviour and history of volatility. To make sure the results are accurate and consistent, the BSE Sensex data on the form of daily closing prices have been gathered out of valid and publicly available financial databases. The research will cover the time frame of April 2010 to March 2025, so that it is possible to compare the market behaviour prior to the period of the COVID-19 pandemic and during it. To be analytic, the dataset will be split into three sub-periods: the pre-COVID period (April 2010 to February 2020), the COVID period (March 2020 to February 2021) and the post COVID period (March 2021 to March 2025). This classification includes the normal market dynamics and those brought about by crises.

Daily stock returns are computed using the continuously compounded log-return formula, which is widely used in financial econometrics due to its desirable statistical properties and suitability for volatility modelling: $R_t = \ln \left(\frac{P_t}{P_{t-1}} \right) \dots (1)$

where R_t denotes the return at time t , P_t represents the closing price at time t , and P_{t-1} is the closing price at time $t - 1$.

Descriptive statistics are employed to summarise the basic characteristics of the return series. Measures such as mean, standard deviation, skewness, and kurtosis are calculated to assess average returns, market risk, asymmetry, and the presence of extreme observations. These statistics provide preliminary insights into market behaviour and help identify changes in volatility and distributional properties across the pre-COVID and COVID periods.

Before applying volatility models, it is essential to examine whether the return series is stationary. The Augmented Dickey–Fuller (ADF) unit root test is applied to test the null hypothesis of non-stationarity. Stationarity is a necessary condition for GARCH modelling and ensures valid statistical inference. The test is conducted under different specifications, including with constant, with constant and trend, and without both, to confirm robustness.

To test whether the return series is stationary, the Augmented Dickey–Fuller (ADF) test is employed.

$$\text{ADF Equation: } \Delta Y_t = \alpha + \beta Y_{t-1} + \sum_{i=1}^k \gamma_i \Delta Y_{t-i} + \varepsilon_t \dots (2)$$

Where ΔY_t = First difference of the series, α = Constant, β = Coefficient for unit root testing, γ_i denotes lagged difference coefficients, ε_t = Error term

To analyse time-varying volatility and risk persistence, the study employs the Generalized Autoregressive Conditional Heteroskedasticity (GARCH (1,1)) model. The GARCH framework is particularly suitable for capturing volatility clustering, a common feature of financial return series during crisis periods. The mean and variance equations are specified as follows: $R_t = \mu + \varepsilon_t \dots (3)$

$$\sigma_t^2 = \omega + \alpha \varepsilon_{t-1}^2 + \beta \sigma_{t-1}^2 \dots (4)$$

where σ_t^2 denotes the conditional variance, α captures the short-term impact of past shocks (ARCH effect), and β measures volatility persistence (GARCH effect). A value of $\alpha + \beta$ close to unity indicates high volatility persistence, which is commonly observed during crisis periods such as the COVID-19 pandemic.

All statistical and econometric analyses are carried out using standard econometric software packages. The combined application of descriptive statistics, unit root testing, and GARCH modelling ensures a comprehensive examination of market volatility and risk behaviour during normal and crisis periods.

3. RESULTS

This paragraph gives the empirical results acquired after the descriptive analysis and GARCH-driven volatility modelling of the BSE Sensex. The findings are presented in a chronological manner to shed light on the market behaviour, price trend, and volatility trends both during the pre-COVID and COVID eras. The graphical and statistical outputs are employed to present undistorted evidence of how Indian stock market reacted to the shock caused by the pandemic.

Figure 1. Demonstrates the trend of the BSE Sensex closing stock prices throughout the period of study, showing the long-term trends and the trends of the volatility. The index has a definite growth tendency, which suggests the continued growth of the Indian stock market with time. The Sensex was steadily growing with comparatively average variation in the pre-COVID phase indicating economic stability and confidence of investors. A drastic and steep drop is seen around the beginning of 2020 and this is when the COVID-19 pandemic broke out, the economy was severely disrupted with extreme market disruption. This stage is defined by strong volatility and sudden price changes. The index has a robust recovery in the post-COVID period with growth to new heights following this decline. Nevertheless, the changes observed in the recovery period are more numerous and acute as compared to the pre-COVID period. This trend shows that volatility clustering exists and high volatility is followed by high volatility and the uncertainty has not yet been removed even though market has recovered.

Figure 1. Trend of BSE Sensex Closing Prices During Pre-COVID, COVID, and Post-COVID Periods



Source: own calculation based on secondary data

The table 1 shows the descriptive statistics of BSE Sensex closing stock prices in the period of conducting the study. The average level that the Sensex traded was 37,409.15. The large standard deviation of 18,682.31 indicates a high level of price changes indicating high risks of the market and its volatility, especially in times of uncertainty like during COVID-19. The skewness value of 0.84 is positive which means that more often high price values were obtained compared to low ones indicating that the market is growing up. The value of kurtosis of -0.46 shows that the distribution is flatter, which means that there are no frequent extreme price movements. On the whole, these findings can be validated as the results show that the

BSE Sensex was volatile, but the price movement was more stable and had a long-term expansionary trend.

Table 1. Descriptive Statistics of BSE Sensex Closing Prices

BSE closing stock price	
Mean	37409.1535
Standard Deviation	18682.3073
Skewness	0.8362
Kurtosis	-0.4583

Source: own calculation based on secondary data

Table 2 indicates the Augmented Dickey-Fuller (ADF) unit root test result of the BSE Sensex Returns. In the level form, the test statistics are large in absolute magnitude and statistically significant with the values of -60.8017, -60.7996, and -60.7251 being under specifications with constant, constant and trend and without both respectively. The associated probability values are near to zero which means that it is significant at the 1% level. This causes null hypothesis of unit root to be rejected indicating that the series of returns is at level stationary. The t-statistics are very significant at the first difference with the t-statistics being close to -24.30 and probability value of zero in all the model specifications. These findings are very much affirmative in the fact that there are no unit root issues in the series of returns. As such, the data meet the prerequisite of being stationary, which makes them acceptable to undergo additional econometric analysis including the GARCH volatility modelling.

Table 2: Augmented Dickey–Fuller (ADF) Unit Root Test Results for BSE Sensex Returns

Test Specification	t-Statistic	p-value	Decision
At Level (RETURN)			
With Constant	-60.8017	0.0001	Stationary***
With Constant and Trend	-60.7996	0.000	Stationary***
Without Constant and Trend	-60.7251	0.0001	Stationary***
At First Difference (ΔRETURN)			
With Constant	-24.3027	0.000	Stationary***
With Constant and Trend	-24.2994	0.000	Stationary***
Without Constant and Trend	-24.3059	0.000	Stationary***
Notes: *** denotes significance at the 1% level. Lag length selected based on Schwarz Information Criterion (SIC). p-values are based on MacKinnon (1996) one-sided critical values.			

Source: own calculation based on secondary data

GARCH (1,1) model is estimated to analyse the volatility behaviour of the BSE Sensex in the long-term perspective of 2010-2025. The findings on Table 3 and Figure 2 clearly show that stock market volatility is time-varying and extremely persistent, which confirms that volatility clustering exists in the Indian stock market. The constant ($C = 0.0679$) in the mean equation is positive and statistically significant at 1 percent indicating that the BSE Sensex produced positive average returns during the study period. This shows a long-term growth in the market notwithstanding the periods of instability. This low R-squared figure is anticipated in the financial models that are based on returns and does not discredit the viability of volatility estimation. There is good evidence of conditional heteroskedasticity in the variance equation. The ARCH name, modelled by $\text{RESID}(-1)^2 = 0.0842$, is positive and significantly significant, which means that shocks of the past or unexpected news directly affect the current market

volatility. This does testify to the fact that abrupt price fluctuations in the past period augment short-term risk in the stock market. More to the point, the GARCH term $\text{GARCH}(1) = 0.8948$ is big and statistically significant which shows the presence of high volatility persistence. It implies that when volatility increases, it is likely to stay high over a long time.

The total of the ARCH and GARCH coefficients ($0.0842 + 0.8948 \approx 0.979$) are close to unity, indicating that there is a high level of volatility persistence. This behaviour is common in economic crisis and structure uncertainty times, such as the COVID-19 pandemic. This observation confirms that volatility shocks in the BSE Sensex do not correct at a fast rate to their normal levels but fade away progressively with time.

These results are also backed up by the conditional variance plot. The volatility is rather low and stable throughout the majority of pre-COVID years and is the normal condition in the market. Nevertheless, there is a very sharp spike at the period of 2020, which was associated with the outbreak of COVID-19 and the ensuing market panic. Though the volatility decreases after this point, it does not revert to the pre-crisis levels at once, which means that doubt in the post-pandemic era will persist.

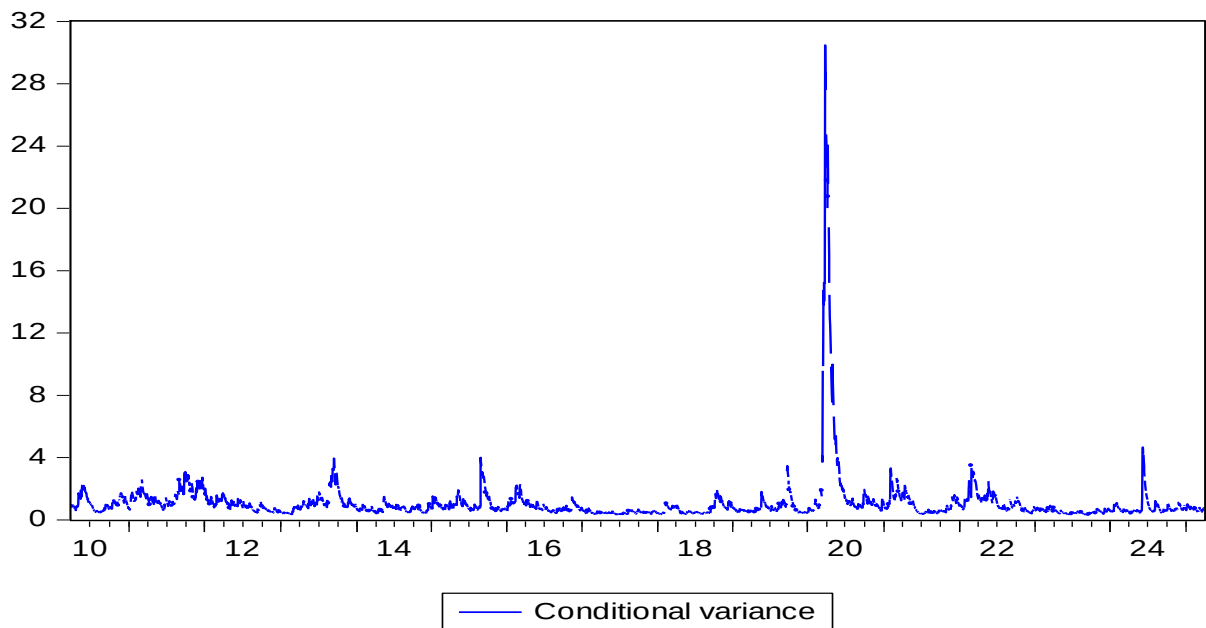
On the whole, ARCH-GARCH findings are that the BSE Sensex has a high volatility clustering and long-run volatility of the market. The model is quite effective in capturing the effect of significant economic shocks, especially the COVID-19, and the increased and protracted risk of investors during crisis periods. This implies that GARCH-type models should be employed when analysing and predicting the risk in stock markets in emerging economies such as India.

Table 3. GARCH (1,1) Estimation Results for BSE Sensex Returns

Mean Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (C)	0.0679	0.0134	5.0627	0.00
Variance Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (ω)	0.0222	0.004	5.5316	0.00
ARCH (α): $\text{RESID}(-1)^2$	0.0842	0.0058	14.4989	0.00
GARCH (β): $\sigma^2(-1)$	0.8948	0.0084	107.1186	0.00
Model Diagnostics				
Statistic				Value
R-squared				-0.0007
Adjusted R-squared				-0.0007
S.E. of regression				1.0504
Sum of squared residuals				4105.803
Log-likelihood				-4976.148
Akaike Information Criterion (AIC)				2.6761
Schwarz Criterion (SC)				2.6827
Hannan–Quinn Criterion (HQ)				2.6784
Durbin–Watson statistic				1.9917

Source: own calculation based on secondary data

Figure 2. GARCH (1,1) Estimated Conditional Volatility of BSE Sensex Returns (2010–2025)



Source: own calculation based on secondary data

The GARCH (1,1) is estimated to analyse stock market volatility in the normal conditions of the economy before the COVID-19 (2010-2020). The Table 4 results show that the value of the mean return of the BSE Sensex is positive and statistically significant ($C = 0.0598$, $p = 0.0005$), indicating the market growth to be steady and consistent throughout the pre-pandemic period. This is an indication of comparatively good investor confidence and macroeconomic environment prior to the outbreak of COVID-19.

The equation of variance gives valuable information on the behaviour of volatility. The ARCH term ($\text{RESID}(-1)^2 = 0.0605$) is positive and very significant which means that the short-term market shocks affected the current volatility. Nonetheless, the size of such coefficient is moderate, which indicates that only temporary volatility increases were caused by sudden news or unexpected events. The value of the GARCH term ($\text{GARCH}(-1) = 0.9252$) is large and statistically significant which means high volatility persistence. This implies that when volatility was high, it was likely to persist in the near future, which is a common characteristic of financial markets in the normal state.

The sum of the ARCH and GARCH coefficients is nearly equal to unity (0.9857), which verifies the existence of volatility clustering, where there are high-volatility and high-volatility periods followed by low-volatility and low-volatility periods respectively. In spite of this carry-over, the conditional variance graph Figure 3 indicates that the volatility spikes in the pre-COVID period were relative and short-lived. Following every rise, volatility slowly went back to lesser levels which means that the market was in a position to absorb shocks and stabilise with time.

In general, the pre-COVID findings indicate that the BSE Sensex had volatility clustering and persistence as well as the market risk was rather contained. Lack of extreme and protracted volatility shows the presence of a stable and strong stock market environment before the COVID-19 crisis.

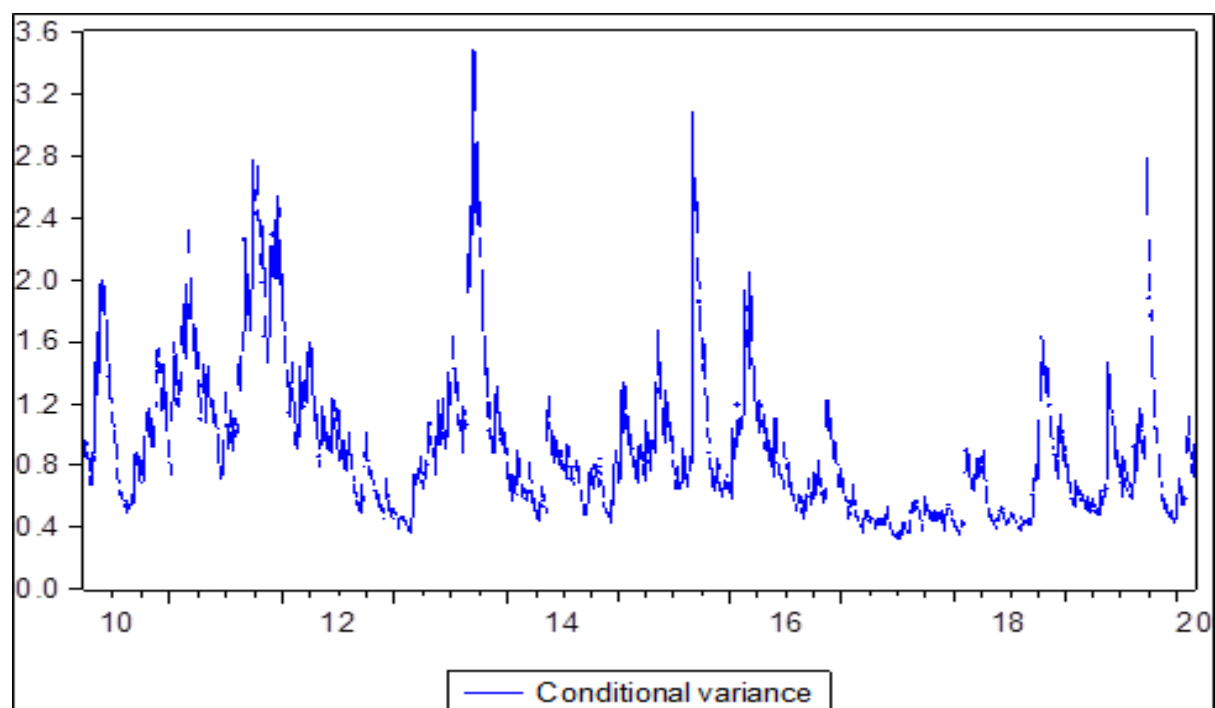
Table 4. GARCH (1,1) Estimation Results for BSE Sensex Returns (Pre-COVID Period)

Mean Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (C)	0.0598	0.0171	3.4889	0.0005

Variance Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (ω)	0.0145	0.0041	3.5736	0.0004
ARCH (α): RESID (-1) ²	0.0605	0.0085	7.0857	0
GARCH (β): σ^2 (-1)	0.9252	0.011	84.0891	0
Model Diagnostics				
Statistic				Value
R-squared				-0.0009
Adjusted R-squared				-0.0009
S.E. of regression				0.9537
Sum of squared residuals				2236.614
Log-likelihood				-3253.831
Akaike Information Criterion (AIC)				2.6486
Schwarz Criterion (SC)				2.6581
Hannan–Quinn Criterion (HQ)				2.6521
Durbin–Watson statistic				1.8629

Source: own calculation based on secondary data

Figure 3. GARCH (1,1) Estimated Conditional Volatility of BSE Sensex Returns (2010–2020)



Source: own calculation based on secondary data

The GARCH (1,1) model that was estimated using the data on the Indian stock market in the period between March 2020 and February 2021 captures the volatility behaviour of the Indian stock market throughout the first wave of the pandemic. According to the mean equation results given in Table 5, the constant term is positive and statistically significant ($C = 0.0019$, $p = 0.0279$). Though the returns are small, this value indicates that average returns slightly stabilised during the larger COVID, which was a partial recovery and adaptation of investors after the first shock of the market.

The equation of the variance shows good indicators of increased and continuous volatility. The ARCH term ($\text{RESID}(-1)^2 = 0.1145$, $p < 0.01$) is both positive and significant, which means that new shocks during the pandemic influenced the volatility of the market

significantly on the short run. This is indicative of the sensitivity of the market to the pandemic-related developments including lockdown policies, infection rates, and announcements. The volatility persistence is high and significant as the GARCH term ($\text{GARCH}(-1) = 0.8458$, $p < 0.01$) is large. The ARCH and GARCH are near to each other and as a result, the volatility shocks that occurred in the initial wave of COVID-19 did not dissipate quickly and persisted in affecting market risk throughout time.

These findings are also upheld by the conditional variance plot. The volatility is extremely high in the initial months of 2020, which is associated with the beginning of COVID-19 and country-wide lockdowns. The volatility decreases gradually as the year goes by meaning that the market is gradually adjusting and gaining investor confidence after the policy interventions and economic support measures. At the beginning of 2021, the volatility is low and stable, but there are still minor spikes, and it is likely that some uncertainty will remain.

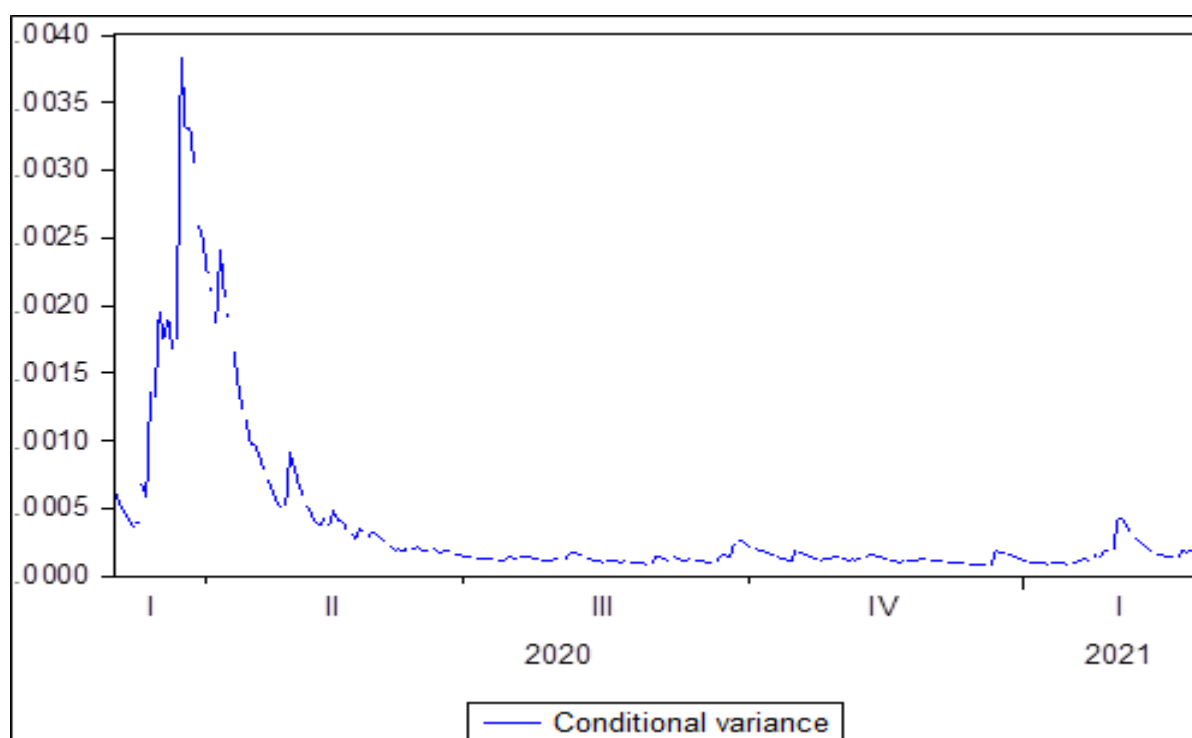
On the whole, the findings suggest that though COVID-19 has caused serious instability on the market, the Indian stock market has been resilient throughout the first wave of the situation, and volatility has stabilised instead of being consistently high.

Table 5. GARCH (1,1) Estimation Results for BSE Sensex Returns during Covid-19 ((March 2020– February 2021))

Mean Equation				
Sample Period: March 2020 – February 2021				
Estimation Method: Maximum Likelihood (Normal Distribution)				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (C)	0.0019	0.0009	2.1989	0.0279
Variance Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (ω)	8.83E-06	3.00E-06	2.9417	0.0033
ARCH (α): RESID (-1) ²	0.1145	0.0291	3.9357	0.0001
GARCH (β): $\sigma^2(-1)$	0.8458	0.0359	23.5504	0.000
Model Diagnostics				
Statistic				Value
R-squared				–0.0019
Adjusted R-squared				–0.0019
S.E. of regression				0.0209
Sum of squared residuals				0.1079
Log-likelihood				694.4373
Akaike Information Criterion (AIC)				–5.5457
Schwarz Criterion (SC)				–5.4892
Hannan–Quinn Criterion (HQ)				–5.5229
Durbin–Watson statistic				2.2183

Source: own calculation based on secondary data

Figure 4. Conditional Volatility of BSE Sensex During COVID-19 Market Shock (March 2020– February 2021)



Source: own calculation based on secondary data

Estimates of the GARCH (1,1)-model using data in the post-COVID period (March 2021-March 2025) are also useful in understanding the volatility behaviour of the Indian stock market during the recovery and normalisation stage after the pandemic shock. As can be seen, the mean equation results, as given in Table 6, indicate that the constant term is positive and statistically significant ($C = 0.0007$, $p = 0.004$), which means that the BSE Sensex produced stable and positive average returns during the post-COVID period. Their scale of returns is quite small but has a high level of statistical significance because they are associated with enhanced investor confidence, economic reopening, and a more predictable market environment than the period of the crisis.

The stable but continuous volatility structure is pointed out in the variance equation. The ARCH term $(\text{RESID}(-1))^2 = 0.0997$, $p < 0.01$ is a positive one, but the value is very significant so the new information and unexpected shocks still affect short-term volatility. The middle-range value of this coefficient, however, presupposes that the short-term effect of shocks is not very impressive in comparison with the COVID period. The GARCH value ($\text{GARCH}(-1) = 0.8530$, $p = 0.01$) is big and significant and attests to high volatility self-correlation. Notably, the total of the ARCH and GARCH coefficients is less than one, which means that it is mean-reverting and volatility is non-explosive, which is a critical sign of the stability of a market.

These findings are also supported by the conditional variance plot presented in Figure 5. The level of volatility in the post-COVID period is significantly low and more stable compared to the pandemic peak. Although there are some cases where there are spikes especially when there are world or national events, the spikes are one-time and after that, the shock normalises. This trend is indicative of the existence of a strong market structure that can absorb shocks effectively.

In general, the post-COVID outcomes indicate that the Indian stock market has not been severely affected by the pandemic-related disruption. Despite volatility, the volatility is always regulated and is foreseeable, and is the effectiveness of the policy interventions, better market

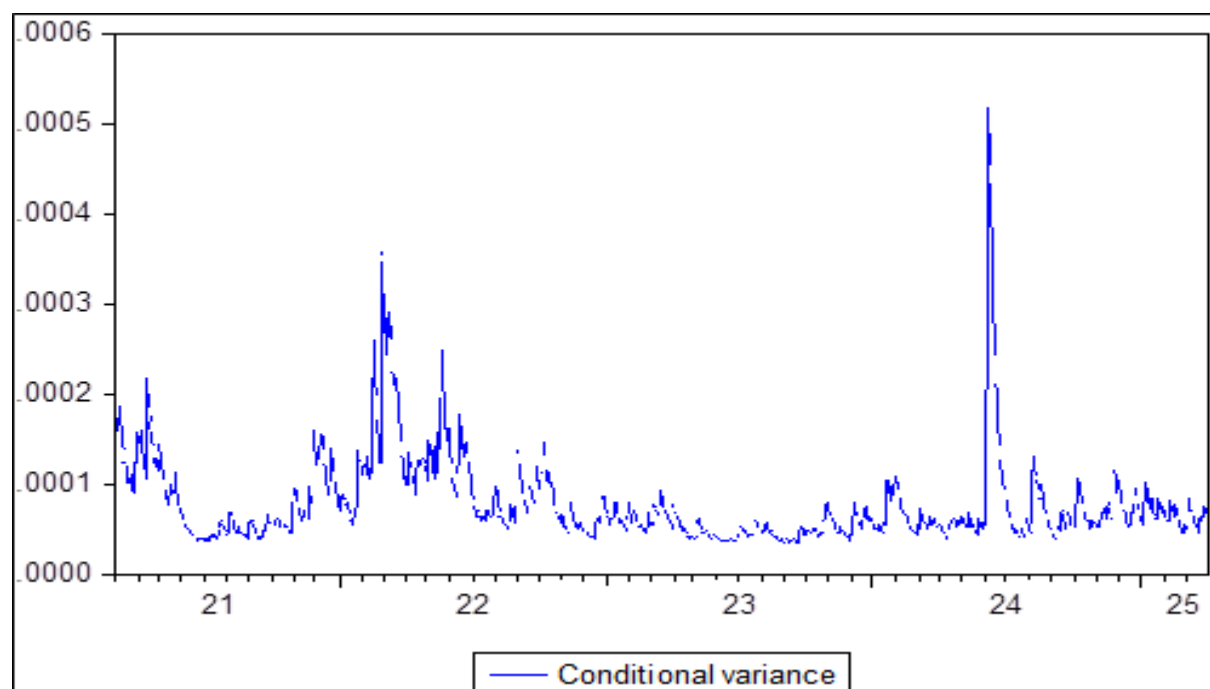
mechanisms, and adaptive investor behaviour that have enabled long-term market stability to be restored.

Table 6. GARCH (1,1) Estimation Results for BSE Sensex Returns During Post-COVID Recovery Period (2021–2025)

Mean Equation				
Sample Period: March 2021 – March 2025				
Estimation Method: Maximum Likelihood (Normal Distribution)				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (C)	0.0007	0.0002	2.878	0.004
Variance Equation				
Variable	Coefficient	Std. Error	z-Statistic	p-value
Constant (ω)	3.71E–06	8.83E–07	4.1973	0.000
ARCH (α): RESID (–1) ²	0.0997	0.0122	8.1754	0.000
GARCH (β): σ^2 (–1)	0.853	0.018	47.457	0.000
Model Diagnostics				
Statistic				Value
R-squared				–0.0082
Adjusted R-squared				–0.0082
S.E. of regression				0.0088
Sum of squared residuals				0.0791
Log-likelihood				3411.088
Akaike Information Criterion (AIC)				–6.7267
Schwarz Criterion (SC)				–6.7073
Hannan–Quinn Criterion (HQ)				–6.7194
Durbin–Watson statistic				1.9947

Source: own calculation based on secondary data

Figure 5. Conditional Volatility Dynamics of BSE Sensex in the Post-COVID Recovery Period (2021–2025)



Source: own calculation based on secondary data

4. DISCUSSION

The empirical results of this paper give complete evidence on how the COVID-19 pandemic changed the volatility structure and risk dynamics of the Indian stock market, as modelled by BSE Sensex. Through a uniform GARCH structure, the analysis of the market behaviour in the pre-COVID, COVID (first wave) and post-COVID regimes indicates the obvious regime volatility persistence, shock transmission and market stability.

According to the descriptive statistics and price trend analysis, although the BSE Sensex has an upward tendency over a long period, the market had significant fluctuations especially when the market was full of uncertainty. The sudden fall at the very beginning of the COVID-19 period is the panic selling and sudden re-reading of the risks, whereas the recovery after that point demonstrates the adaptive power of the market. Nevertheless, the fact that there still were frequent fluctuations during the recovery phase points to the fact that the uncertainty did not vanish instantly, which is congruent with the volatility clustering behaviour that is typical of the recovery period following significant crises.

The return series are stationary, as the Augmented Dickey Fuller test indicates, and this fact justifies the use of GARCH modelling in the analysis of volatility. Lack of unit root problems would guarantee that the market volatility trends are not caused by spurious trends but instead the real pattern.

The entire sample GARCH (2010-2025) outcomes indicate that volatility within the Indian stock market is a time-varying and persistent volatility. The big and significant GARCH coefficient proves that volatility shocks are long-term effects, which is enhanced during times of structural stress when the COVID-19 pandemic happens. Close to unity of the ARCH-GARCH sum implies that the shocks dissipate slowly hence the necessity to model volatility dynamically as opposed to the case when variance is kept constant.

A sub-period volatility behaviour comparison provides some meaningful differences in volatility behaviour. In the pre-COVID phase, volatility clustering, as well as volatility persistence, existed, but those volatility spikes were rather moderate and short-term. This implies that the market could absorb shocks effectively when market is operating under normal economic conditions and there is support through the stable macroeconomic fundamentals and investor confidence.

However, in contrast to this, the first wave of the COVID (March 2020-February 2021) has very different dynamics. The large ARCH effect suggests that volatility was strongly impacted in the short-run by new information and pandemic-related shocks, and represents the increased sensitivity to uncertainty around lockdowns, infection rates, and policy responses. The large GARCH coefficient also suggests that these shocks were long-lived, and one would have had high risk. Nevertheless, the decreasing trend in conditional variance at the end of this period indicates that there was a learning and adjustment process where investors were reacting to the policy interventions and better information.

The evidence of market recovery and stabilisation represents the post-COVID period. Although the volatility persistence is statistically significant, the ARCH effect is relatively moderate and the aggregate of ARCH and GARCH coefficients is less than one, which is a sign of a mean-reversing volatility. This indicates a more developed and resilient market situation, in which shocks are absorbed without causing the long-term instability. Sentimental volatility that is experienced during this period is temporary, as it is related to certain global or local events as opposed to systemic stress.

Altogether, the results prove the COVID-19 as a strong systemic shock that temporarily impaired market efficiency and increased risk. The post-COVID evidence however demonstrates the resilience of the Indian stock market which was supported by effective policy

measures and improved market mechanisms as well as adaptive investor behaviour. The experiment supports the applicability of the GARCH models to explain the volatility processes in the emerging markets especially in crisis and recovery periods.

5. CONCLUSION

This paper was an analysis of volatility behaviour of the Indian stock market by the BSE Sensex during the pre-COVID, COVID (first wave) and post-COVID regimes using a GARCH (1,1) model. Empirical findings indicate that the market volatility varies with time, and it is very persistent especially in the time of crisis. Although the pre-COVID period was marked by relatively stable and short-term volatility, the COVID era was marked by intense volatility increases and increased risk-prone to greater uncertainty and information shocks. On the contrary, post-COVID shows slow market stabilisation, accompanied by the mean-reverting volatility, which implies recovery and resilience. In general, the results support the notion that COVID-19 had a severe effect on the stability of the markets, and successful policy reactions and adjusting investor behaviour helped to overcome the crisis.

The implications of the results to the policymakers and players in the market are significant. The fiscal and monetary measures are very essential in curbing severe volatility during emergencies. The market transparency, liquidity support and communication between investors can be improved to minimize panic-driven trading. Volatility clustering and volatility persistence can remind investors and portfolio managers that dynamic risk management and diversification can be valuable in making informed decisions with the help of volatility-based forecasting models like GARCH, particularly when uncertainty is elevated.

The study is limited in some ways despite the contributions it has made. The discussion is limited to the BSE Sensex, which might not be reflective of the dynamics in a specific sector or the firm heterogeneity. Additionally, the research uses a conventional GARCH (1,1) model with normal errors distribution, which might be incapable of capturing the asymmetric effect or extreme tail risks that are present during crisis.

Further studies can be done by extending this analysis to other market indices or sectoral indices in order to have more in depth information about the varying volatility behaviour. Asymmetric GARCH models or models with structural breaks would also be a significant addition to the knowledge. Cross-comparative research on various crises in the world can also assist in determining how strong the market resilience is in new economies.

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Evolving Market Dynamics and Consumer Behavior in the Era of Quick Commerce

Rajeev Kumar^{1*}

¹Associate Professor, Doon University-Dehradun, India

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***Corresponding author e-mail:** ranjanrajeev87@gail.com

ABSTRACT

The concept of quick commerce (Q-commerce) characterized by fast delivery and technological infrastructure-based retail solutions is redefining consumer behavior and market forms in the developing world economies. This chapter discusses the impact of digital platforms, analytics and innovation on purchasing decisions where consumers are increasingly demanding speed, convenience and personal experience. These changes have brought about impulse purchases and on-demand services that are hyperlocal. Competition, strategic alliances, and changing value chains at the market level emphasize the significance of delivery speed and reliability of the services. The chapter also talks about the key behavioral changes, such as a shorter decision cycle, an increased level of online trust and the increased sustainability awareness of urban consumers. In reaction, companies are embracing the use of flexible supply chains, predictive systems, and customer centric strategies. On the whole, the chapter places Q-commerce not only as the logistics innovation, but as the general change in the consumer culture and in the relations within the retail. It underlines the importance of business models that would be effective in balancing speed, customer satisfaction and sustainability in a fast-changing retail environment.

KEYWORDS: Quick Commerce, Consumer Behavior, Digital Retail Transformation, Hyperlocal Delivery, Market Dynamics

1. INTRODUCTION

The retail landscape has been evolving dramatically in the last couple of years, mainly because of increasing use of digital technologies, evolving consumer demands, and new business models. Among the most striking changes in this change is the emergence of Quick Commerce (Q-Commerce), which is quickly changing how consumers buy and get access to

everyday goods. Characterized by very high delivery timetables, Q-Commerce transcends the e-commerce and even on-demand services by championing the urgency and convenience. Blinkit, Zepto, Swiggy Instamart, Dunzo, and Big Basket in India show such a change, as international competitors like Getir and Gorillas prove its applicability worldwide. Collectively, these platforms bring out the role of speed, convenience and technological integration that are redefining consumer behaviors and competitive market structures. The formation of Q-Commerce is directly connected to the creation of a powerful digital ecosystem in the past 10 years. The high use of smartphones, the increased availability of the internet, and the growth of digital payment systems have led to the situation when instant service is not just a possibility, but a necessity. Consumers are becoming more demanding of convenient, one-to-one and time-saving shopping experiences that can fit into their hectic schedules.

The shift has facilitated the impulse purchasing and spontaneous purchasing, rather than the planned purchasing. This has also been reflected in businesses re-considering how they create demand, supply chain management and retention of customers. To ensure they keep pace with this fast-changing environment, more advanced technologies, such as artificial intelligence, data analytics, and demand forecasting, are already implemented and integrated into micro-warehousing strategies. Q-Commerce is operationally on the intersection logistics, technology and consumer behavior. It discontinues the previous retailing model, and it focuses on the localized inventory forms, particularly through the implementation of dark stores or micro-fulfillment hubs inside and around densely populated communities. These facilities offer faster order processing and delivery.

This system is further enhanced by real-time data and machine learning tools that can monitor consumer preferences, purchase trends, and delivery efficiency. Simultaneously, the competitive environment is changing as well as the traditional firms are diversifying their services in product lines; new entrants seek to differentiate themselves via pricing, product diversification and by delivering their products accurately. The COVID-19 pandemic has been instrumental in making the use of Q-Commerce more of a reality. The mobility limitations and safety concerns drove consumers towards online shopping of necessities. What started as a need, slowly turned into a favorite way of shopping and some time even became a norm. The pandemic showed that not only can ultra-fast delivery models be implemented, but they are also appreciated by consumers, with many ready to spend more money to ensure speed and reliability. Consequently, Q-Commerce has evolved into a small city-centered idea into a large-scale retail model, particularly in densely populated and digitally linked areas, including India, China, and Southeast Asia.

Q-Commerce is experiencing a fast growth, but has a number of issues. Speed may strain the operational efficiency and profitability. Repeated shipments with small order quantities might be costly and be environmentally questionable. Moreover, the use of gig workers, the strongest competition in prices, and the necessity to operate 24/7 complicate the process of scaling these models successfully.

The other weakness is customer retention in a market where customers can easily switch platforms and offerings in the market are similar in service offerings. It is thus paramount to understand how consumer behavior would be interplaying with market forces to determine the sustainability of Q-Commerce in the long run. In the light of the consumer behavior, Q-Commerce has promoted the culture of instant consumption. The customers have become demanding in terms of speed, instant access and smooth service delivery. The ease of fast delivery usually results in more impulse purchases and repurchasing, especially among young consumers.

Nevertheless, the considerations like privacy of data, concern of environmental protection, and trust in online platforms still play a role in decision-making. This brings a complicated tradeoff between convenience, ethical consideration, and personalized experiences in the Q-Commerce ecosystem. Q-Commerce has opportunities and challenges in the emerging markets such as India. Its growth is supported by a young society, an increasing urbanization, and the increase in income levels. Meanwhile, there are challenges of infrastructure constraints, logistics, and regional diversities. The preferences of consumers are

very different in different places and businesses must be able to implement localization in terms of prices, product choices and communication. Firms like Zepto and Blinkit have reacted with hyperlocal and data-driven models to differentiate their products according to the demand on a neighborhood scale. The above strategies emphasize the need to comprehend local consumer behavior in order to gain a competitive edge.

In both scholarly and business terms, Q-Commerce poses very significant questions concerning the future of retail. There are long-term profitability, customer relationship, worker welfare and regulatory framework issues which require careful consideration. To deal with these issues, various fields should be considered, such as marketing, logistics, behavioral science, and digital innovation. Summing up, Q-Commerce signifies a radical change in the retail industry, where expediency and experience have taken the center stage in the value generation. With the ongoing advancement in technology and the maturity of markets, this model is bound to have an additional impact on consumer expectations and competition. These changes are necessary to understand by both businesses and researchers, as Q-Commerce will determine the next step of the digital retail, especially in developing economies.

2. REVIEW OF LITERATURE

Much has been written about digital retail and consumer behaviours, from early research on e-commerce and mobile commerce to recent studies on quick commerce. The early research done by Kotler and Keller (2016), identified convenience and value as key factors in consumer decision making. Recent research by (Gupta & Singh, 2023) implies that speed and customization are key consumer expectations. Theoretical models such as Technology Acceptance Model (Davis, 1989) and Unified Theory of Acceptance and Use of Technology (Davis, 1989) describe technology adoption.

But the growth of quick commerce brings in new variables like speed of delivery, reliability of service and the dynamic environment of making decisions. Social and economic development and prevailing urban culture and prevalent usage of mobile phones has given rise to quick commerce in markets like India and south Asia. The rise has been complemented by improvements in online payment technologies. Previous studies suggest factors like trust, platform convenience and social factors play a crucial role in consumer participation in online retail.

The concept of quick commerce, with delivery times typically ranging from 10 to 30 minutes, has started to transform traditional retail business models. In India, companies such as Blinkit, Zepto and Swiggy Instamart have deployed micro-fulfilment centers, data analytics and predictive analytics to address the need for speedy services. The sector is highly competitive with significant infrastructure investments made. As per Bhati et al. (2025), a few players dominate the market, resulting in an oligopolistic market structure with intense price competition through discounts and promotional activities to attract and retain customers.

Despite its expansion, the sector faces ongoing challenges. Profitability remains uncertain due to high operational costs associated with maintaining fast delivery networks. The dependence on gig-based delivery personnel has also raised concerns regarding job security and working conditions. Additionally, the environmental implications of frequent deliveries and increased packaging waste are becoming more prominent in both academic and policy discussions. Consumer behaviour within the quick commerce ecosystem is shaped by multiple factors, including convenience, delivery speed, price awareness, and trust. Research shows that quick delivery is a key driver, especially in urban areas where time is a critical factor. For example, the study Saleem (2025) by on Zepto suggests that customers may be willing to trade-off price for time efficiency. At the same time, consumers have high expectations of product availability and quality. Sparse product selection or quality issues may impact consumer satisfaction and retention. Any shortfall in this regard can lead to consumers seeking out other options, as there are low barriers to switching providers in this industry. Quick commerce is enabled by technology.

The use of artificial intelligence and machine learning helps with demand prediction, route planning and recommendations. Mukhopadhyay (2024) offers a fuzzy cognitive mapping

model to understand the factors driving adoption, and identifies the perceived usefulness, ease of use, and social influence as key factors. In practice, the implementation of dark stores and micro-fulfilment hubs offers companies greater efficiency in delivery, especially in highly urbanized areas with a high density of demand. However, there are questions surrounding the sustainability of the quick commerce model. Frequent delivery, intense operations, and packaging waste are a concern. Regulation, too, is on the agenda.

In India, regulators like the Competition Commission have started to scrutinize pricing, particularly with regard to dominance and anti-competitive practices. The future will require more work to explore the sustainability of quick commerce, regulatory issues, and evolving consumer expectations in the online retail environment. It is deduced the literature points out that although quick commerce has apparent advantages like as swiftness and accessibility, it also poses challenges such as feasibility, cost-effectiveness and governance.

Ongoing research will be crucial in informing policy and strategy in this emerging area. In conclusion, the current literature shows that quick commerce is changing retail consumer expectations and competition. Although convenience and speed are key to the adoption, the mention of sustainability, profitability and regulatory challenges suggest that the concept is still in development. The review figures out a scarcity of research work in the area of consumer retention, ethical contemplations and business suppleness. So, future research needs to take a more holistic approach to understand the interplay between technological advancements, market dynamics, and consumer behavior in shaping the scalability and sustainability of quick commerce in emerging markets.

Table 1 : Summary of Key Theoretical Frameworks Applied to Quick Commerce

Theory/Model	Developed by	Core Idea	Application to Q-Commerce	Key Constructs
Technology Acceptance Model (TAM)	Davis (1989)	Explains user acceptance of new technology based on perceived usefulness (PU) and perceived ease of use (PEOU).	TAM helps in understanding how consumers adopt Q-Commerce platforms like Blinkit, Zepto, or Swiggy Instamart. If users find the apps easy to use and beneficial for saving time, their intention to use increases.	• Perceived Usefulness (PU) • Perceived Ease of Use (PEOU) • Attitude Toward Use • Behavioral Intention

Unified Theory of Acceptance and Use of Technology (UTAUT)	Venkatesh et al. (2003)	Integrates several technology adoption theories to explain behavioral intention and usage behavior.	UTAUT helps in understanding the drivers influencing consumer intention to use Q-Commerce platforms, including performance expectancy (speed and convenience), effort expectancy (ease of use), social influence (peer recommendations), and facilitating conditions (internet access and app reliability).	• Performance Expectancy • Effort Expectancy • Social Influence • Facilitating Conditions
Consumer Decision-Making Theory	John Dewey 1910	Outlines the stages consumers follow before making a purchase decision: problem recognition, information search, evaluation, purchase, and post-purchase behavior.	Applied to understand how impulse & convenience-driven purchases shape consumer behavior. Q-Commerce modifies decision-making process by compressing time and emphasizing instant gratification.	• Problem Recognition • Information Search • Evaluation of Alternatives • Purchase Decision • Post-Purchase Evaluation
Theory of Planned Behavior (TPB)	Ajzen (1991)	Behavior is guided by intentions, which are influenced by attitudes, subjective norms, and perceived	TPB is applied to examine how attitudes (e.g., trust in delivery), social norms (peer and family influence), and perceived control (availability of resources like	• Attitude toward Behavior • Subjective Norms • Perceived Behavioral Control

		behavioral control.	smartphones and internet) affect the decision to engage in Q-Commerce purchases.	• Behavioral Intention
Diffusion of Innovation (DOI) Theory	Rogers (1962)	Explains how innovations spread through populations over time.	DOI theory is useful for analyzing the adoption stages of Q-Commerce among consumers — from innovators to laggards. Early adopters are often tech-savvy urban consumers who influence the mass market through word-of-mouth and social media.	• Innovation • Communication Channels • Time • Social System
Expectation–Confirmation Theory (ECT)	Bhattacharjee (2001)	Consumer satisfaction and continued usage depend on the confirmation of pre-purchase expectations.	Used to assess customer satisfaction with delivery speed, product freshness, and reliability. If expectations are met or exceeded, it leads to customer loyalty and repeated app use.	• Expectation • Perceived Performance • Confirmation • Satisfaction • Continuance Intention
Service-Dominant (S-D) Logic	Vargo & Lusch (2004)	Focuses on service as the basis of all economic exchange and emphasizes co-creation of value between firms and	In Q-Commerce, customers and platforms co-create value through interactive apps, feedback systems, and personalized delivery services. The service experience, rather	• Value Co-Creation • Service Exchange • Customer Engagement

		consumers.	than just product delivery, defines consumer satisfaction and loyalty.	
Resource-Based View (RBV)	Barney (1991)	A firm's competitive advantage arises from valuable, rare, inimitable, and non-substitutable (VRIN) resources.	RBV explains how platforms leverage technology infrastructure, data analytics, and hyperlocal delivery networks as strategic resources to gain market advantage over competitors.	• Valuable Resources • Rare Resources • Inimitable Resources • Non-Substitutable Resources

3. MARKET DYNAMICS OF Q-COMMERCE

The technological innovation, urban infrastructure, and the changing consumer priorities have a impact in market dynamics in quick commerce. By 2025, the Q-commerce market in India is projected to be over USD 5 billion, thanks to such platforms as Blinkit, Zepto, and Swiggy Instamart. These companies use micro-fulfilment centres and data analysis to forecast the local demand and best delivery paths.

The challenge of competition has increased and alliances have been made among retailers, logistics companies and fintech companies. In the new Asian markets, like Indonesia, Malaysia, Vietnam and the Philippines, Q-commerce can be tailored to fit local market frameworks, where affordability and trust-building is made with the cash-on-delivery option. The market development proves a shift towards hybrid forms of digital plus tangible retail, also known as phygital commerce.

4. CONSUMER BEHAVIOR SHIFT

The emergence of Q-commerce has changed the preconception of consumers, allowing them to be satiable due to convenience to immediate fulfilment. In urban India, especially among millennials and Gen Z customers, platforms that offer delivery times within minutes are preferred. This immediacy has reshaped the loyalty consumers who now have a multi-platform consumption behavior, where speed, price, and reliability are put at the forefront, over brand attachment.

In addition, online credibility and quality assurance are also significant factors in repeat purchase behavior. Impulse buying has risen in prominence, with Q-commerce making the time interval between want and purchase shorter. As an illustration, the 10-minute model offered by Zepto is aimed at young professionals who want to spend less time, whereas Swiggy Instamart employs predictive analytics to forecast the needs of its users.

Q-commerce is confronted with a number of challenges in spite of its rapid growth. The viability of ultra-fast delivery models is being questioned based on the operational costs, labour-intensive characteristics, and environmental issues. The continuity of the product quality and dependability during time constraints in delivery is complex. Privacy concerns regarding the gathering and algorithmic targeting of data are becoming a concern on the consumer side.

Nevertheless, personalization, artificially intelligent inventory management, and green logistics are promising opportunities. Companies that embrace ethical and sustainable behaviors can have long term loyalty and differentiation. Brand equity can be strengthened further by partnerships with local suppliers and establishing renewable energy systems into delivery networks. Future studies on Q-commerce can be devoted to the speed-to-sustainability balance.

Theoretically, a combination of behavioral economics and digital consumer models can give a deeper understanding of micro-decision-making. In the emerging markets, the long-term viability of Q-commerce will be dictated by inclusiveness to consumers who have lower income levels and to non-metro regions. The sector will be influenced by technological development like drone delivery, customer prediction based on AI and hyper-localized marketing. It is also the role of policymakers to regulate the practice of gig labour in order to create social sustainability as well as allow innovation.

5.CONCLUSION

The emergence of fast commerce is a major shift in the world of retailing, which is the convergence of technology, changing consumerism, and responsive market practices. In most emerging Asian economies this is more than just an increase in faster delivery schedules; it is a more fundamental change in the consumption habits, where accessibility is becoming a more important value than ownership and impulse buying is becoming an increasingly popular trend. The consumers are no longer a passive consumer but they are the ones who shape the availability of products, services design and supply chain. The identification of these changes is crucial to businesses and policymakers because they adapt to the needs of a digitally-driven marketplace. Quick commerce is a unique stage of retail development, changing the way markets operate and consumers engage with brands. It leaves behind the traditional e-commerce and traditional retail format being defined by speedy delivery, localized distribution systems, and digitally enabled operations. Examples of how technological integration, logistics innovation, and data-driven decision-making can be used to meet the increasing demand of speed and convenience include platforms like Blinkit, Zepto, and Swiggy Instamart in India.

With predictive solutions and strategically placed fulfilment centres, these platforms have established new benchmarks of efficiency and sometimes deliver goods within minutes. In market perspective, fast commerce has amped up rivalry and urged companies to reconsider pricing and inventory control and structure their supply chain. Despite the presence of some large players in the sector, it is very dynamic with new entrants seeking ways of differentiating themselves based on the quality of their delivery performance, assortment and service quality. Meanwhile, maintaining profitability on a cost-intensive model remains a problem. Matters pertaining to workforce management, development of infrastructure and environmental impact are issues that need long term and strategic consideration. The increasing demand to be now and here and now is captured in consumer behaviour. The consideration of speed, accessibility, and reliability has become a focus in the purchase decision-making process.

Younger digital-savvy urban populations are likely to be more inclined to adopt the product, but trust, transparency, and the quality of the product on a regular basis are the key factors to establishing long-term relationships. With the ever-changing expectations, companies have to keep on being innovative so as to remain relevant and loyal to customers. Along with its benefits, quick commerce also has some significant issues. Smaller, more frequent orders are also associated with increased costs of operation and environmental impact, and reliance on the gig-based labour model has led to discussions on job security and working conditions.

The fact that it is becoming more and more regulated compounds the issue of doing business in this space. The balance between speed, efficiency, personalization and responsible business practices should be maintained to guarantee sustainable growth in companies. All in all, quick commerce is not just a hyperbole of logistics, but a larger shift in the retail sector, which is characterized by consumer requirements informing value generation and time is an essential asset. Academics, practitioners, and policymakers need to gain a better understanding of the market trends, behavioral changes, and other challenges. With the sector keeping on

changing, research and dynamic strategies will be instrumental in establishing the long-term effects of the sector on the retailing systems in India and other emerging economies.

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People, Personalisation, Engagement: Bridging Traditional and Digital Marketing in a New Era

Monika Shegal^{1*}

¹Assistant Professor, MERI College of Engineering and Technology, Delhi

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***Corresponding author e-mail:** monikasehgal34@gmail.com

ABSTRACT

Market Landscape revolutionized due to digital era. The fast adoption of digital technologies has reshaped the connection between brands and customers. Customer retention is a daunting challenge for e-commerce businesses in today's competitive landscape. As e-commerce sprouts in the digital era, e-commerce companies must strategically plan membership models to attract and retain customers. This article reconnoiters the role of membership models in e-commerce, with a focus on customer retention and happiness. The research explores how companies integrate personalisation and engagement to maintain a strong customer base. This study also endeavours to explore customer motivations and expectations towards membership marketing models (both free and paid) in E-commerce. Pearson correlation and regression are employed in the data. The data suggested most respondents chose memberships on e-commerce platforms. The study emphasizes the long-term effects of pricing and information access through membership marketing models on customer retention. The findings of this research align to provide e-commerce businesses with valuable insights into the effectiveness of free and paid membership models for customer acquisition, retention, and satisfaction.

KEYWORDS: Membership marketing, Customer Motivation, Customer Retention, E-commerce.

1. INTRODUCTION

The concept of membership is antiquated in marketing; nonetheless, there is an expansion in these models due to rapid advances in the e-commerce sector. Membership has been consumed since ancient times to establish a loyal customer base for large and small

businesses (Gary, 1993). Marketers are now embracing digital media to enrich brand visibility; therefore, injecting a membership model in the digital domain is vital. With the shift towards digital platforms, membership marketing has become essential for enhancing brand visibility and customer engagement. In today's digital economy, customer acquisition through traditional marketing methods is costly, making membership models a cost-effective and sustainable approach to acquiring and retaining customers. Membership marketing is an astute strategic technique that contrives traditional customer acquisition and retention tactics on digital platforms. Membership marketing converts not only visitors but also casual customers into brand advocates. This stratagem is cost-effective in the long run, requiring less investment to acquire and retain customers. In membership marketing, customers become members when they obtain perks, prizes, or privileges that non-members do not have. Membership models free as well as paid, becomes fruitful for the customers as they provide customization, convenience and credibility. E-commerce industry etched a transactional benefits from the membership programs and also provide entertainment with retail in subscription services. To achieve brand loyalty, target more revenue, gain long term brand loyalty and various benefits modules (Gruen, 1994)

Amazon, Nykaa, Flipkart, and Meesho, and many more e-commerce sector offer memberships such as Amazon prime membership, Nykaa prime members, Flipkart Plus member, Meesho gold member to magnetize the customers. Customers not only get attracted but also sensing the belongingness and recognition which is essential for implementing membership programs (M. Webster, 2013). E-commerce strategize the membership programs in this way that they provide exclusive discounts, personalized offers, and tailored experiences to the customers (Famiyeh, 2015). This strategically shift signifies a customer-centric approach where main focus on delivering value, not just transactions (Budi Jaya Sugiato, 2023). (George M. a., 2018) also states that through creation of a sense of belonging e-commerce companies can get repeat purchases, brand advocacy, and achieve a higher customer retention rate.

Companies always survive and can win by getting higher customer retention (Gao, 2021). Companies with lower acquisition customer cost always having highest competitive advantage (Pfeifer, 2005). Customer retention is not one day activity but companies have to deliver quality of products, reasonable price, exclusive discounts, 24*7 customer support, personal selling, convenience (Chen, 2017), (Ndubisi, 2007). Exclusive discounts in memberships are the main contributor to attracts and motivates customer and leads to higher retention (Tebelika, 2023).

The study examines how membership models can incentivize retention, engagement in e-commerce sector. This paper also has goals to achieve valuable insights for e-commerce and their free and paid membership models for customer acquisition and retention.

Need for this study

It is no surprise that customers are increasingly value-conscious and seek experiences over one-off purchases making membership models significant. This study is required because client acquisition costs are high and there is intense competition in the digital economy. Membership models are a more sustainable approach than continuously bringing in new customers since they promote loyalty and repeat business. Platforms for online shopping gather a ton of consumer data. By using this data to tailor offers and recommendations, membership models increase customer satisfaction and engagement. The paper will therefore be intended to detect various membership marketing models, analyzing their potential benefits and drawbacks in driving customer retention and also exploring customer motivations for joining a particular membership model, their expectations, and the perceived value derived from the membership.

Background of the study

Table 1: Meta analysis of Literature

Scholars	IDV	DV	Insights
(Iyengar, 2022)	Subscription leads	Customer buying decision	Profitable, the subscription program leads to customer purchases.
(George M. W., 2018)	Admission-based membership services	Customer commitment and loyalty	Customers gradually used admission-based membership services on the grounds of commitment.
(Patricia Rich, 2016)	Prospects is a membership program in the digital age	Perceived value of membership programs	Potentials membership program upshot on the Perceived value of membership programs
(M. Webster, 2013)	Satisfaction, confidence in the association's expertise	Customer retention and brand advocacy	Members who are gratified and confident in the association's expertise are more retained.
(Mitchell, 2011)	The social tribe behavior on individual consumption	Perceived usefulness of membership programs	The social tribe perceived usefulness of memberships
(Wirtz, 2000)	Disparate Membership programs	Organizational objective, consumer value	Membership programs expressively enhance consumer lifetime value which leads to achieving organizational objectives.
(Gruen T. W., 2000)	Examine professional associations'	Membership's commitment, Customer loyalty	Carefully chosen relationship-building efforts on member participation

	relationship-building efforts		enhance customer loyalty.
(Bhattacharya, 1998)	Paid membership contexts	Customer lifetime value, customer retention rate.	Members who customary their membership as a gift are more likely to retain.

The topic of membership marketing in the digital age has not received much scholarly attention, despite the large number of articles that are listed above. Minimal research, but membership marketing is thought of as a type of customer loyalty in the long run that maximizes profits. (Barlow, Relationship marketing - the ultimate in customer services, 1992) Since customers became members in exchange for benefits, membership models are more closely tied to the exchange theory and social identity theory. (Cropanzano, 2005), (Gruen T. W., 1994). Exchange theory in marketing utters that the value of membership models is value exchanged for value (Houston, 1987) and according to social identity theory, a consumer chooses how well they can spot the potential individualism provided by group affiliations. (Lutz, 2003), (Gruen T. W., 1994), (Tajfel, 1985).

The success or failure of certain membership programs is largely determined by the discounts and incentives offered. (Varadarajan, 1988). Membership modalities must be applied by the company while keeping corporate goals and client acquisition and retention costs in mind. The minimal customer acquisition cost results in the highest return on investment. (Pfeifer, 2005). Additionally, situational elements have been considered when analyzing how membership models in digital marketing affect client retention (Wirtz, 2000), (Stryker, 1980).

The review for this study divulges the vitality of membership marketing in driving customer loyalty and repeat purchases. Various studies have highlighted the positive impact of membership programs on customer commitment, loyalty, and brand advocacy. Since there isn't much information on how membership models affect customer retention, it's evident that not everyone who tries their hand at membership programs succeeds. For this reason, this research enhancing the previous literature on the topic of membership model effects in multiple ways. To the best of our knowledge, this research will first aid in understanding the significance of all (free as well as paid) membership models and then investigate the role that membership marketing play in customer retention.

Research Objectives

1. To study the benefits of membership marketing models in the e-commerce sector.
2. To explore the customer motivations and expectations towards membership marketing in e-commerce.

Research Methods

Research objectives are achieved through a structured questionnaire method. A questionnaire was filled out via Google Forms. The direct contact method is used to collect data from the respondents to prove the conceptual framework. Due to time constraints, sample size consist 150 and only 100 authenticate responses was selected. Even though the sample is tiny, it includes a variety of responders to minimize the possibility of error when the results are generalized.

Conceptual framework

In membership models, the membership engagement cycle begins with the introduction pack and progresses to user engagement activities such as discounts, newsletters, catalogs,

gifts, unanticipated content, and renewal packs. Through membership, customers get open access to information, less pricing, convenience, and a platform of recognition via user engagement activities. These aspects were considered, and customers were asked questions.

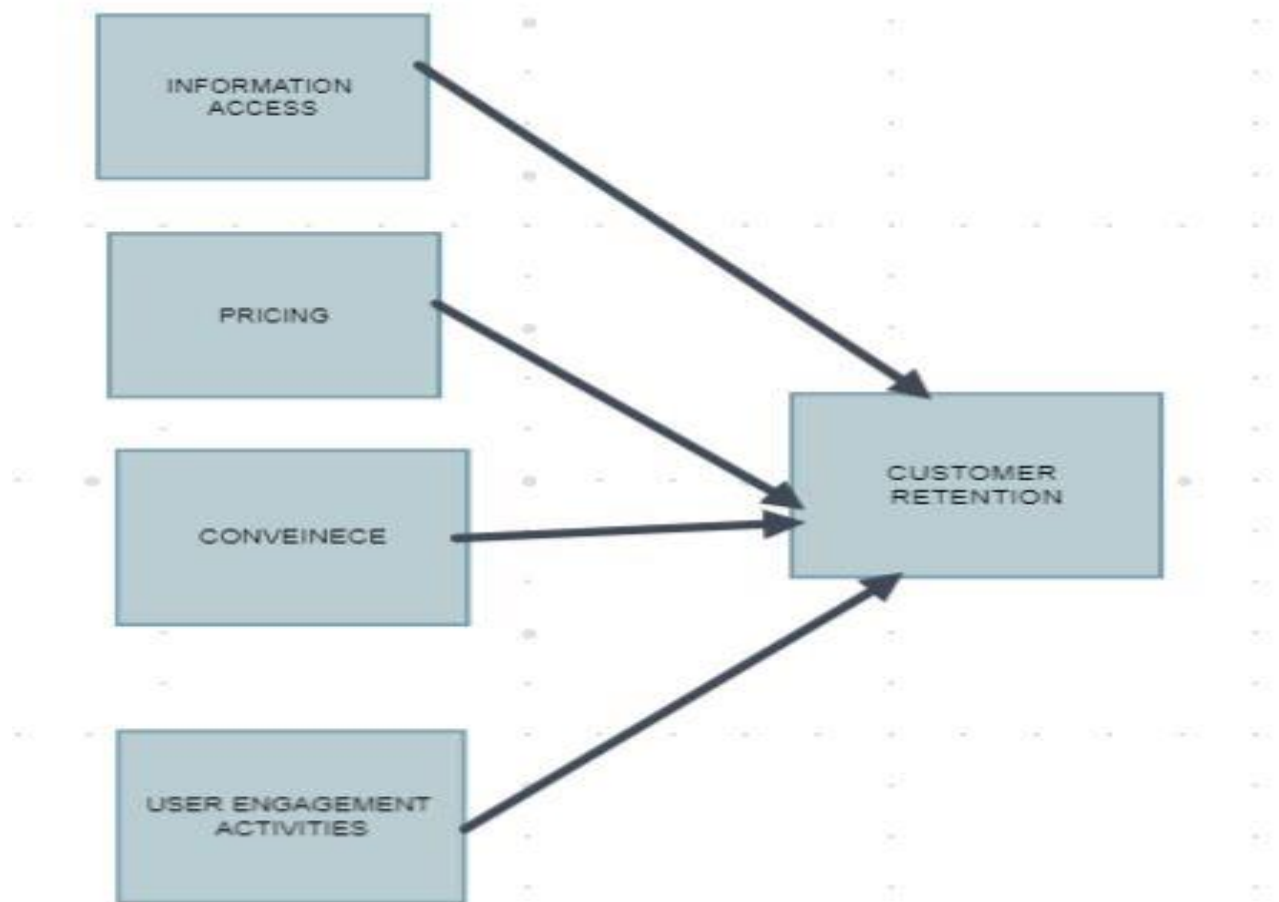


Figure 1: Conceptual Framework
Source: The Author

2. DATA ANALYSIS AND INTERPRETATIONS



Figure 2: Results reflect descriptive data for percentages of members.

Out of 100 respondents, 72% are members of e-commerce websites. It shows that the majority of respondents favor memberships on e-commerce websites. 28% of respondents are nonmembers of E-commerce. It indicates that customer prefer memberships in E-commerce.



Figure 3: Results showing the satisfaction percentage of having memberships.

Out of 102 respondents, 63% are satisfied with having free as well as paid memberships on e-commerce, and 37% respondents are not satisfied with having memberships on e-commerce. This indicates that the customers are satisfied with having memberships on e-commerce.

Table 2: Correlation between customer retention and various influencing factors of membership marketing

Customer Retention	Correlation (r)	Customer Retention	Information access	Pricing	Convenience	User engagement activities
		1	.869	.873	.840	.840
	Sig 2 tailed		.056	.053	.075	.075
	N	100	100	100	100	100

The data in table 2, we can interpret that practically all of the variables have weight and contribute significantly to the association with customer retention. Pricing has much impact on the customer retention yield correlational value of 0.873 with a significant value of .053 followed by Information access yield .869 correlational value at a significant value of 0.56. It indicates that 'pricing' and 'Information accesses' are the variables that retain customers in the long run.

Table 3: Regression analysis

Particular	R square	F
Information Access	.815	152.16
Pricing	.826	85.67
Convenience	.729	41.25
User engagement activities	.639	35.14

According to the regression study, pricing considerations have a significant relation with customer retention, Having R square value of 0.826. Information access (r-square= 0.815) has a significantly higher impact on customer retention. User engagement activities have little

effect on customer retention, as evidenced by the convenience factor's r square value of 0.729 and yield of 0.639 when compared to other factors.

3. FINDINGS

Main Findings of this study suggest that membership models in ecommerce sector became fruitful and proved a good source of customer retention, cost effectiveness, higher engagement rates. Membership models can help in getting repeat purchases, positive word of mouth and brand loyalty, as it provides customized experiences, exclusive discounts, and personalized offers. Membership models also enhances the feeling of community, sense of belongingness, enduring bonds with prior customer base as well as with prospects. E-commerce companies through memberships get repeat business, loyal customer base, strong competitive advantage, customer happiness, higher engagement rates and value propositions. Ultimately, it can be said in conclusion that this strategy promotes a solid brand affinity and helps long-term company expansion.

Thorough literature review and the data congregated from the sample of 100 respondents, the researchers were able to accomplish the second goal. The researchers discovered that a variety of factors, including distinct benefits, customized experiences, community and recognition, convenience, perceived value, customer experience, trust, and transparency-all influence customers' motivation to choose memberships in e-commerce after reading the literature from various websites (listed below) or several research papers/ blogs, etc. In addition, a membership program that fosters a sense of community and provides speedy shipping, easy returns, and seamless shopping experiences can also be alluring. E-commerce businesses may design membership programs that complement customer interests, increase motivation, and promote long-term engagement and loyalty. The terms "pricing," "information access," "convenience," and "user-generated activities" are used by researchers to explain their effects on customer retention while drafting conceptual frameworks.

A large number of respondents signed up for membership programs provided by e-commerce enterprises, according to the data (Table 1). It shows that customers are responding favorably to membership marketing, free as well as paid membership models.

The majority of respondents are happy with the membership provided by e-commerce sectors, according to the results (table 2). It suggests that customers prefer memberships.

The findings indicate (in Table 3) that there is a strong association between the dynamics of membership marketing programs and customer retention, particularly when it comes to pricing.

Table 4 presents the results, which suggest that membership models' price and information access strategies are effective in retaining customers. The study's findings imply that customers prefer memberships because they receive lower-priced products than non-members. If customers find membership models convenient, they will select membership models based on a cost-benefit analysis. Customer happiness leads to retention and engagement, if through membership's customers became happy, so it can become a successful long-term strategy for e-commerce. Ultimately, this paper suggest that membership models proved that it can be winning strategy to compete in fast changing marketing world because it offers value , exclusive discounts, convenience, easy payment solutions, 24*7 customer support and many more. E-commerce companies that focus on spanning client relationships through membership programs are more likely to achieve long-term success and customer loyalty.

4. CONCLUSION

In digital marketing era, transformation became fast, customers are not stay at one platform as the products are just one click away, It is imperative to get retention in this era. Enlisting the new customer as well as retain the previous ones are became more complex. For long term success, strong customer base is the necessity. Particularly in e-commerce sector, where competition is cut throat as products and brands are more and easily available, attracting and maintaining strong customer base is crucial for long term survival in the Industry. E-commerce has to strategically launch the membership models free as well as paid to not only attract, acquire but retain and engage also. Strong perks attract customers, exclusive discounts boost retention rates, and entertainment segment also helps in getting engagement. Membership model is cost effective yet powerful tool to get competitive advantage, higher profits and long term success.

Customers attract and engage in that platform where customers are undoubtedly informed about the value proposition in exchange of membership premium fee. Membership model works on transparency in getting trust, fair deal with customers, conveniently supply goods and services to the members. Information accessibility, personalization, convenience makes membership more profitable. It also guarantees that customers remain engaged and loyal towards them.

In digital era, customers became value conscious, having low attractions, short attention spans and e-commerce make strategies to cope with these challenges. They offer membership, sponsorship models but there is no evidence whether it is a good strategy or not. Lack of previous study focuses on this aspect. Necessity of this study is need of an hour. This study signifies that e-commerce company that unify the efficient customer acquisition with retention can build a loyal base that serves as the cornerstone for long term success in digital era.

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Current Landscape and Future Predictions of Technological Innovations in Cultural Tourism: Promotion and Preservation

Deepjyoti Borah¹, Dr. Pradip Kumar²

¹Research Scholar, Assam University, Silchar, Assam

²Assistant Professor, Assam University, Silchar, Assam

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*Corresponding author e-mail: deepjyotib36@gmail.com

ABSTRACT

This research study explores the transformative potential of technological advancements for promoting and protecting cultural tourism. Critical to the global tourism industry, the cultural heritage tourism sector provides unique insights into the nation's historical, artistic, and cultural fabric worldwide. This study employs a qualitative, exploratory research design to investigate the role of emerging technologies in cultural tourism, focusing on the balance between promotion and preservation. The study shed light on how current and future applications of augmented reality (AR), virtual reality (VR), artificial intelligence (AI), blockchain, and advanced data analytics can transform visitor engagement, site management, and preservation efforts. The study assesses global trends and compares them to changes in India, a country rich in cultural legacy yet constrained by infrastructural constraints. Key objectives include examining the impact of these technologies on visitor experience, accessibility, and sustainability, as well as making strategic recommendations to stakeholders. The study emphasizes AI's role in personalizing tourist experiences, using VR to make cultural sites accessible to remote audiences, and blockchain's potential for assuring artifact authenticity. Furthermore, it investigates how modern data analytics might improve visitor flow and maintenance procedures, thereby helping the long-term development of cultural heritage tourism. This comprehensive review provides a forward-thinking view on implementing technologies into cultural heritage tourism, with significant insights for heritage site managers, tourism marketers, policymakers, and technology developers. The findings highlight the importance of strategically utilizing these technologies to improve the preservation, accessibility, and overall experience of cultural tourism, assuring its continued enrichment for future generations.

KEYWORDS: Cultural Tourism, Heritage, AI, AR, VR, Blockchain, Promotions, Preservations, Sustainability

1. INTRODUCTION

The United Nations World Tourism Organization (UNWTO) defines cultural tourism as a tourism activity whereby visitors have the inbuilt motivation to learn, discover, experience, and consume both tangible and intangible cultural attractions/products at a tourism destination. Such a form of tourist activity brings about the incorporation of identity, possible history, and creative expressions into the destination, differentiating it from recreational or leisure tourism. These attractions include, but are not limited to:

- Cultural Heritage (eg, Monuments, archaeological sites, museums)
- Living Cultures (eg, Traditions, festivals, rituals)
- Arts (eg, Visual arts, music, theatre, crafts)

Cultural tourism primarily caters to attractions and experiences that typically include monuments and sites of architectural interest, festivals, and cultural organizations. There is somewhat of a shift from an elite niche toward a broader market in that it attracts people of middle age, higher education, and medium income levels. Cultural tourists are characterized by the fact that they travel long distances, prefer destinations with outstanding cultural sites, and are less sensitive to variations in weather. The scholars have found it challenging to define "cultural tourists" and understand the motivation and behaviour of these tourists (Bertocchi et al., 2021). To enhance cultural tourism, inclusive design and digital storytelling can be employed to increase visitor motivation and diversity. Sustainable cultural tourism development requires careful analysis of various categories, such as monuments, festivals, and digitization.

Cultural tourism, encompassing travel centred around heritage sites, museums, festivals, and local traditions, is a cornerstone of the global tourism industry. According to the World Travel & Tourism Council (WTTC, 2022), it generates over 40% of global tourism revenue, highlighting its critical role in economic systems worldwide. This form of tourism is a vital economic engine, fostering job creation, infrastructure, and cultural preservation. However, balancing growth with sustainability is crucial to avoid degradation and ensure long-term benefits. Collaborative efforts of governments, businesses, and communities are key to maximizing their positive impact while safeguarding cultural assets for future generations.

Technology serves a dual purpose of enhancing accessibility while simultaneously inviting unwanted consequences of commodification, highlighted by Richards (2018). It can improve access by erasing physical, geographical, and economic barriers. Technology, therefore, creates a more inclusive and equitable experience, thereby aligning with the public good. Ultimately, creating a structure to negotiate a balance requires sustained funding, an ethical framework, and critical engagement, ensuring that technology is a venue for access and not a tool for increased inequity.

The objective of the research is to determine how new technologies such as artificial intelligence (AI), virtual reality (VR), and blockchain can contribute to the evolution of cultural tourism. This study will look at the current uses as well as potential future applications of these technologies in cultural tourism, and will attempt to make predictions related to those uses and their balance between economic growth (having new and exciting ways to market and develop visitor experiences) and preservation (protecting the sustainability of cultural heritage). The study will identify the opportunities for integration of technology in cultural tourism, address the challenges of technology ethical concerns, and the practical implications of implementing

such technologies, and develop recommendations for how stakeholders can responsibly employ these technologies.

2. RESEARCH METHODOLOGY

The current research adopts a qualitative approach towards adopting an exploratory research design to explore emerging technologies and cultural tourism, weighing promotion against preservation. The research design was undertaken to meet the dual aims of the paper: the exploration of technological innovations (AI, AR, blockchain), and assessing future trends while considering sustainability and ethics. Secondary data was selected from peer-reviewed journals, industry reports, case studies, and government policy documents. This approach is appropriate to assist with the synthesis of pre-existing knowledge and trends without undertaking possible lengthy processes associated with gathering primary data. The databases that were searched include JSTOR, Elsevier, and Google Scholar, with keywords relating to the following: AI in cultural tourism, blockchain in preservation, smart tourism, digital marketing, and promotion as means of engagement in cultural tourism. Publications from the years 2015 to 2024 were included for the study to maintain relevance, focusing specifically on the elements of technology, sustainability, and cultural tourism.

3. TECHNOLOGICAL INNOVATIONS IN CULTURAL TOURISM: CURRENT LANDSCAPE

3.1 Digitalization of Cultural Heritage

Digital technologies, including virtual reality (VR), are changing museums, providing new avenues for archiving, accessibility, and engagement. By using VR for online archiving processes, museums can combat the shortcomings of the impact of physical spaces and technology on visitors and become part of the emerging metaverse culture (Gao & Braud, 2023). As an alternative use of VR, Google Arts & Culture offers virtual tours by developing a database of images for mass digitization (Wasielewski, 2022). The British Museum has experimented with soundscapes to enhance immersive exhibits in VR a more traditional experience. The use of foley-style soundscapes has proven to increase engagement with visitors (Williams et al., 2023). Digital platforms, including Google Arts & Culture, Europeana, and others, create value by mediating these interests and adding cultural ecosystems together (Pesce et al., 2019). All digital experiences and digital transformation are, to a certain extent, driven by the acceleration of expectations following the COVID-19 pandemic (Wasielewski, 2022; Williams et al., 2023).

The increased popularity of virtual reality (VR) in contextualizing exhibits in museums has been to create a more valuable visitor experience. Research indicates that VR is likely to produce favourable visitor satisfaction and visitor intentions to revisit museums, particularly when it adopts a sense of presence and authenticity (Choi & Nam, 2024). The introduction of gamified experiences via VR in digital twin environments in museums will significantly enhance visitors' motivation and engagement, although the learning outcomes, possibly spatially, may be deleterious (Chernbumroong et al., 2024).

3.2 Smart Tourism and IoT

Recent investigations have highlighted the significant impact of IoT technologies on traveller satisfaction at city destinations. As technology is necessary for IoT-enabled smart tourism ecosystems, tourism management has the potential to improve operational efficiency

and traveller experiences through smart sensors, mobile applications, and personalized recommendation systems (Rosário & Dias, 2024).

Smart city initiatives in Barcelona embed cultural heritage in IoT technologies to enhance tourism experiences and manage visitor patterns. These examples provided or embedded in government policies have a clear focus on social inclusion and sustainability (Noori et al., 2020; Vardopoulos et al., 2023) i.e., immersing unheeded historical resources or improving advanced on-site virtual experiences at important cultural heritage sites extended by IoT sensors (Garau, 2014). The second stream of technology, or IoT, would involve experiential innovations improving real-time visitor monitoring that would assist city management in addressing problems related to overtourism at historic centres (Zubiaga et al., 2019). Nevertheless, most smart tourism initiatives will succeed or fail based on community involvement and local government support (Vardopoulos et al., 2023).

3.3 AI and Big Data

Chatbots have shown potential for enhancing history education and overall museum experiences, with embodied and reflective models demonstrating superiority (Noh & Hong, 2021). AI chatbots can effectively support Content and Language Integrated Learning, enabling students to learn cultural content in foreign languages simultaneously (Mageira et al., 2022). However, research indicates a gap in measuring visitor experience with museum chatbots, highlighting the need for more comprehensive evaluation methods (Štekerová, 2022). Ongoing efforts to implement AI chatbot platforms for museums, such as MuBot, aim to provide interactive, human-centred experiences that allow visitors to engage with exhibits through natural language conversations. These platforms utilize advanced AI technologies like Machine Learning, Natural Language Processing, and Semantic Web to create intelligent, continuously learning chatbots that can answer visitor questions and enhance the overall museum experience (Varitimiadis et al., 2020). However, this technology also presents challenges that need to be carefully considered.

Big data analytics offers promising tools for predicting and managing tourist flows in urban destinations, potentially mitigating overcrowding issues. By analysing social media data, such as geotagged photos from Flickr, researchers can identify popular tourist locations and predict behavioural patterns (Miah et al., 2017). Similarly, data from platforms like Panoramio can help differentiate overcrowded areas from those with growth potential (Encalada et al., 2017). Big data analytics enables destination management organizations to better define boundaries, understand tourist needs, and manage stakeholders more effectively (Gajdošík, 2019).

3.4 Social Media and Digital Marketing

The transformative prospects in digital marketing in tourism and the changing paradigms associated with the growing focus on SMM (Social Media Marketing) in existing and emerging markets. It should be noted that the effect of SMM on tourist satisfaction, engagement, and loyalty is significant and reported in emerging destinations such as Vietnam (Tam et al., 2024). Likewise, the relevance of digital marketing and the willingness to adopt it have also been observed in the tourism and hospitality sectors in regions that historically may have avoided it. Digital marketing strategies are more effective than traditional marketing in situations when focused on price, flexibility, consistency, and data (Cooper et al., 2021). Evidence of research has already emerged in the tourism environment of Thailand, showing that the efficacy of digital marketing is directly linked to tourists' perceptions of sustainable tourism services, service quality, and eventually, tourists' satisfaction and behavioural intention (Sharafuddin et al., 2024).

Instagram is a powerful tool for marketing cultural heritage sites and sustainable tourism sites. Instagram travel influencers play an important role in how people view

sustainable destinations, but geo-location data does not always make tourists go to the places more (Kilipiri et al., 2023). In South Africa, cultural and heritage tourism is viewed as an important part of the economy. The VisitSouthAfrica campaign effectively advertises cultural heritage sites through Instagram influencers using visual content, engaging strategies, and trust establishment with the target audience. Nevertheless, tourist guides perceive poor governance and management of heritage sites and poor preservation and marketing efforts as hindering the development of cultural tourism in the country (Van Der Merwe, 2016).

4. FUTURE PREDICTIONS FOR TECHNOLOGICAL INNOVATIONS

4.1 Immersive Technologies

Virtual technology and holography are growing as tools for cultural heritage documentation and communication, allowing for a more rich, immersive, and three-dimensional experiences to connect to and appreciate heritage sites. Additionally, authentic holograms, like true-color OptoClones™, represent the incredible ability to document and exhibit artifacts in an ultra-realistic manner, even if the original artifacts are not readily available (Sarakinos & Lembessis, 2019). 3D digital copies of artifacts offer a new aspect of preservation and investigation. Still, they also present challenges for understanding the authenticity of the copies and the subjective nature behind their creation (Galeazzi, 2018). Although these challenges will need to be considered and addressed, immersive VR and AR experiences, along with museums and historical institutions, are embracing the use of holography to preserve events in time and enable telling stories in exciting ways. The continued advancement of professional VR/AR capabilities allows us to create sustainable cultural heritage conservation and engaging experiences to help the public connect to places and objects of the historic past.

Mixed reality (MR) technology is changing the way people engage with cultural experiences in many dimensions. MR interactivity and vividness have been shown to enhance visitors' degree of perceived immersion, enjoyment, and brand loyalty in cultural attractions (Bae et al., 2020). MR can create contextual relationships with users, the virtual content, and cultural context, with a focus on collaborative engagement (Bekele & Champion, 2019). MR apps that integrate literary traditions and in-form aesthetic experiences can add presence, embodiment, and personal valuation of heritage, creating experiences for users that shift away from passive readership and toward a social tripartite involvement (Bertrand et al., 2021). In hybrid virtual and augmented reality settings, aspects like object interactivity, generation of user content, and avatar closeness impact engagement levels (Li et al., 2023). These mechanisms all shape a more immersive, interactive, and personally meaningful cultural experience, leading to higher levels of audience engagement and appreciation of cultural heritage.

4.2 AI and Machine Learning

The tourism industry is also being transformed in a way that incorporates AI-enabled personalization with customizable experiences, along with the future of AI automating travel arrangements. In cultural tourism, AI has been identified as part of enhancing the experience ability to create engagement with users, or to form and reinforce community connectedness (Orea-Giner et al., 2022). For example, AI tools such as ChatGPT are being frequently used by consumers to help plan personalized trips. Recent studies show that these tools increase tourists' trust toward service providers with a positive effect on their behavioural intentions. AI can enhance tourism services, but it could never replace the human experience that is essential to experiential tourism.

Machine learning algorithms are important contributors to developing more personalized travel recommendations, including recommendations on online tourism platforms. In the context of personalized recommendations, machine learning will typically utilize deep learning approaches, including Convolutional Neural Networks (CNN) and Deep Neural Networks (DNN), to classify user reviews and tourism product factual information (Wang, 2020). The creation of a data-driven approach using machine learning methods with personalized recommender algorithms produces recommendations that are more personal and optimal than current levels of recommender systems (Shrestha et al., 2024). The empirical context of a thematic travel planner that employs hybrid recommendation models, makes use of human-centred and location-aware recommendations encoded into multiplicity data sources for recommendations encoded by human-user perspectives and location-aware assignment of recommendations using methods and techniques like Naive Bayes classifications, deep-learned CNN, and sentiment analysis (Asaithambi et al., 2023). Feature selection methods based on machine learning using the relevant data from search queries allow for improved accuracy in tourism forecasting, further minimizing overfitting, where model performance could be interpreted as variance in the prediction of tourist arrivals and related hotel occupancy, which outperformed benchmark models (Li et al., 2023).

4.3 Blockchain and Digital Trust

Blockchain can help provide provenance tracking and increased due diligence, but its usefulness will always be limited by both legal and technical issues (Giannoulis & Kapellakou, 2023). Much of the provenance work being done by museums relies on the notion of improved documentation, and any inadequate documentation could still allow museums to acquire looted artifacts (Gerstenblith, 2019). As we can see, there are innovative approaches that hold promise and may be better options than the traditional approach of acquisition. However, it is difficult to assess whether either of these two methodologies will help reduce looting in the archaeological context in the future. Implementing these methods also has challenges that focus on the issue of legal harmonization.

NFTs (Non-fungible Tokens) have implications for changing our perceptions of digital ownership and value concerning cultural artifacts. NFTs create a sense of artificial scarcity and authenticity of the object, thus creating a new way of deciding parameters for collecting digital objects (Fortagne & Lis, 2024). The perceived intent of buying an NFT can take a variety of different forms, from utility to limited-edition artificial scarcity to aesthetic experience, and, more fundamentally, assurance of ownership by the underlying blockchain (Fortagne & Lis, 2024). Value-making ownership experiences can arise from even non-transferrable NFTs by building identity through a form of possession, albeit a unique digital one (Elsden et al., 2024). NFTs represent a new techno-economic configuration converting digital files into assets, making us question what the practices, devices, relations, and rights are in the construction of ownership (Miroshnichenko & Birch, 2024).

4.4 Sustainable Technologies

Putting solar power technologies in heritage sites involves opportunities and challenges. Renewable energy sources are a means of reducing environmental impacts and energy costs (Lucchi, 2023); however, the integration of these sources must be carefully weighed against preservation to avoid detracting from heritage values or traditional appearances. In a mixed economic-environmental context, World Heritage designation can cultivate tourism revenue on the one side, while on the other, it can increase the cost of living and non-biodegradable waste. The power dynamics of various stakeholders in the management of heritage sites have implications for conservation, as is the case in the Honghe Hani Rice Terraces, where inequalities of power led to unexpected degradation of the site in protection legalities (Hua et al., 2022).

4.5 Hyper-Personalization and Gamification

The increased participation of visitors and learning in cultural heritage sites through augmented reality (AR) and gamification exhibits impressive potential. Firstly, applications in augmented reality enhance learning through creating associations with artifacts and personalizing the learning experience (Tom Dieck et al., 2018). Furthermore, by gamifying the environment, such as CompARe, inquiry-based learning during field trips can also be managed by addressing such paradoxes as students' distraction, responsibility, and motivation (Souropetsis & Kyza, 2025). However, a great deal of this has to do with immersion and presence because most games, such as Pokémon GO, distract from the physical environment. Locative game mechanics and narrative techniques also have to be carefully designed to nurture the reconciliation between these transitions, keeping the well-architected experiences of most users aware of the heritage site (Haahr, 2017).

5. PROMOTION OF CULTURAL TOURISM THROUGH TECHNOLOGY

5.1 Digital Marketing Strategies

Latest research unveils the suitability of 360-degree video and the virtual reality (VR) paradigm for the purpose of tourism marketing and education. Some findings indicated that 360-degree VR videos can provide experiences as immersive and enjoyable as real visits, resulting in superior spatial presence and emotional engagement (Wagler & Hanus, 2018). This technology has also been effectively used in the marketing of tourist villages by modifying visitors' behavioural intentions through experience marketing variables (Yunikawati, 2023). In terms of tourism education, 360-degree VR video works effectively on experiential learning, thus closing the gap between theory taught in classrooms and the real world (Vaishnavi & Ajit, 2024). It includes such elements as viral marketing mixed with cutting-edge new technology tools, which are beneficial in getting tourism and hospitality businesses.

5.2 Social Media and Influencers

Instagram influencers are the game changers in travel decision making and the promotion of tourism destinations among the sustainable modes of travel (W. K. Chen et al., 2023; Kilipiri et al., 2023). Their attractiveness, similarity, and expertise help build trust and parasocial relationships with their audience, intending to influence travel intentions (W. K. Chen et al., 2023). Content and follower engagement and ratio of social media influencers become crucial determinants toward the travel decision, with trust as the mediating variable (Saini et al., 2023). Geolocation data by influencers does not guarantee a traveller's intention for sustainable destinations (Kilipiri et al., 2023). Cultural distance from the influencers to the followers determines the engagement levels, the deeper level occurring when they are close culturally (Bentley et al., 2021).

5.3 Translation technologies

Domain-specific translation tools could work better than general-purpose ones in emergency response situations (Turner et al., 2019). Nevertheless, the translation of cultural words and concepts in tourism texts is still a challenge (S. Chen et al., 2023). Notably, beyond translation, tourists need to develop intercultural competence with responsibility, understanding, appreciation, and action, important attributes for developing memorable cultural experiences and stimulating active engagement in cultural exchanges (Fan et al., 2021). In general, this highlights the advantages and disadvantages translation technologies carry in the context of tourism while calling for development and evaluation in these areas.

6. PRESERVATION OF CULTURAL HERITAGE THROUGH TECHNOLOGY

6.1 Digital Preservation Techniques

Recent studies have shown that 3D laser scanning and photogrammetry can help protect architectural heritage sites. The fires in Notre Dame make an ultimate case for an extensive digitization policy that includes state-of-the-art approaches, ranging from deep learning to advanced ones such as 3D Gaussian Splatting (Comte et al., 2024). The studies show that laser scanning is good at documenting small details, while drone photogrammetry has the advantage of relatively fast surveying of large areas (Gado et al., 2024). The synergy of these methods allows for improved documentation quality and efficiency (Gado et al., 2024). The 3D scanning of heritage sites allows the digital reconstruction of the damaged works and the crafting of replicas using additive technologies. This has found successful applications in the reconstruction of destroyed sculptures and monuments (Parfenov et al., 2022). For sites of cultural heritage threatened by several risks, the ultimate choice will rely on accessibility and dimensions, and automated photogrammetry and UAVs provide sustainable solutions for complete and accurate 3D digitization (Leon et al., 2020).

6.2 Sustainable Tourism Practices

Ever-increasingly, the use of IoT sensors is becoming a major strategy toward sustainable tourism management. One of the most common uses for these technologies is the well-known real-time monitoring of visitor flows that helps prevent overtourism and manage carrying capacity in historic centres (Zubiaga et al., 2019). In addition, IoT solutions were able to prove their value for stakeholder expectations concerning the implementation of sustainable energy management at tourism destinations (Tiwari et al., 2022). In tourist attractions, intelligent sensing networks could optimize the node deployment, improve monitoring area coverage, and increase data processing efficiency (Hu, 2022). For example, more high-end hotels are likely to adopt IoT technology for sustainability, such as energy savings, belong to international groups, consider sustainability important for customers, cater to business travellers, have five-star ratings, or serve guests from Northern Europe or North America (Eslerod et al., 2019). Such applications of IoT in tourism show how the technology could be used to sustain management practice in segmenting sustainability across different sectors of the industry.

6.3 Community Engagements

The role of digital technologies is seen as key in the preservation of indigenous cultural heritage and as an opportunity for fostering community participation. Examples such as virtual reality and online exhibitions are fostering public engagement and educational awareness about intangible cultural heritage (ICH). Innovative approaches such as synchronized laser triangulation can digitally preserve intricate cultural objects. In contrast, community museums are now increasingly benefiting from 3D and spherical technologies that strengthen the connection between museums, collections, and communities (Cassidy et al., 2019). Digital interventions for cultural heritage communication in Indonesia are being used by stakeholders, including websites and mobile applications for UNESCO World Heritage Sites and intangible cultural heritage (ICH) (Permatasari et al., 2020). The platforms promote cultural values and cultural identity awareness, especially among the youth. However, there must be careful consideration that ICH preservation requires actual ties with communities and faces the danger of commoditization through digital platforms (Permatasari et al., 2020).

7. CHALLENGES AND ETHICAL CONSIDERATIONS

7.1 Over-Tourism

Social media and online platforms, together with smart technologies, have completely changed how tourists experience places, as well as destination marketing (El Archi et al., 2023; Sinanan & Ritter, 2024). Benefits linked to these technologies include more ecosystem sustainability and analytic capabilities, but they can also pose challenges, including privacy issues and increased digital divide (El Archi et al., 2023). Thus, rising city tourism, accompanied by an experience travel-based shift and cheap air travel, are additional reasons behind overtourism. Furthermore, the platformization of tourist destinations and algorithmic governance raises potential concerns for inequalities and geopolitical issues (Frenzel et al., 2022; Sinanan & Ritter, 2024).

7.2 Data Privacy

Digital technologies impact the tourism sector by providing avenues for sustainable development and raising other issues. Therefore, smart technologies, data analytics, and social media are being applied to enhance sustainability at tourist destinations (El Archi et al., 2023). In return, questions are raised concerning inequalities, data privacy, and the digital divide with the introduction of digital infrastructures and algorithmic governance into tourism (Frenzel et al., 2022; Sinanan & Ritter, 2024). The COVID-19 pandemic exacerbated the rapid adoption of digital technology in tourism, leading to a call for research on its effects (Frenzel et al., 2022). Trends that stand out include AI, IoT, circular economy, big data, and augmented/virtual reality (Loureiro & Nascimento, 2021).

7.3 Digital Divide

The most significant potential virtual reality (VR) technology, as far as developing tourism experiences is concerned, is regarding the way it helps improve tourism as a visitor-attracting phenomenon. Unfortunately, adoption levels are substantially low among many societies due to socioeconomic and infrastructural barriers. These include the general lack of knowledge about VR by the tourism sector, the idea that it is of no use, and the unwillingness to invest in the costs of buying such technological equipment (Sousa et al., 2024). Financial constraints, unsatisfactory technological infrastructure, and the association of real experiences with virtual experiences can also detract from the use of VR (Ray Octafian et al., 2024). Sociocultural factors, content limitations, affordability issues, supply-chain and supply problems, and equal design concerns present further challenges in increasing acceptance rates of VR usage (Pimentel et al., 2021).

7.4 Algorithmic Bias and Discrimination

AI algorithmic biases concerning recommendation systems may generate unfair outcomes and discrimination among different user demographics on online tourism platforms. So far, research has shown that these are unfair as they favour popular items and dominant user groups, creating stereotypes, biases, and miscalibrations (Ahn et al., 2022). Public bias is the most critical factor in miscalibration, particularly for users who are not interacting much with popular items (Abdollahpouri et al., 2020). Hence, researchers call for the consideration of different stakeholder perspectives, like environmental effects and over- or under-disturbance impacts. Oversampling underrepresented groups has proven effective in reducing stereotypes while improving recommendation quality (Ahn et al., 2022).

7.5 Employment and Job Displacement

While digital transformation in tourism provides a plethora of opportunities for employees in various functions, the flip side is that it can lead to a few challenges. It could lead to creating opportunities for employment with diversified choices, but with the flip side are situations of job loss and dislocating workers, especially workers with a lower skill set (Aynalem et al., 2016; Rydzik & Kissoon, 2022). Workers' perceptions of digital transformation change over time, thus making the application of a social exchange perspective

in managing the process quite pertinent (Van Der Schaft et al., 2024). Other challenges in the domain include poor working conditions, discrimination, and seasonality (Aynalem et al., 2016). Intelligent automation and digital surveillance may worsen the inequalities and diminish worker agency (Rydzik & Kissoon, 2022). The journey to digital transformation should include changes in strategy, leadership, and organizational culture.

8. CONCLUSION AND SUGGESTIONS

Technology adoption in tourism is undergoing tremendous transformation with advanced technologies like AI enabling operational efficiency, along with personalization, and enhancing customer experiences. Some key trends are artificial intelligence, Internet of Things, big data, and augmented/virtual reality. In cruise tourism, intelligent technologies like robotic bartenders, digital signage, and facial recognition are increasingly being used. However, there are ethical concerns in the construction of tourism; hence, such issues should be tackled for responsible growth. This response elaborates on the chief ethical concerns around technological adoption in tourism by drawing on various studies and paves the way for ways to avert this problem. Digital technologies are significant in enhancing cultural heritage and promoting sustainable tourism in developing countries. They can document, survey, and preserve cultural assets, thereby making them more accessible to tourists. The implementation of digital technologies in sustainable tourism destinations has increased steadily, with Europe, Asia, and North America at the forefront of research. Nonetheless, there are challenges, especially in developing countries, where technological infrastructure and legal frameworks require strengthening.

We can project that in the coming ten years, several technological innovations will improve cultural tourist experiences in the emerging digital economies. Virtual and augmented reality technologies are likely to enhance user immersion and interaction with cultural heritage attractions significantly. Gamification and digital learning technologies are becoming critical tools for grasping cultural tourism knowledge and support. Further increased accessibility to cultural heritage is brought about through the creation of databases of cultural relics, online repositories, and dynamic exhibitions. The process is also confronted with issues, especially with aging populations whose elderly members will likely experience inconvenience in embracing digitalized cultural tourism services. Future studies need to balance heritage preservation and technological innovation and work towards standardizing methods for digital cultural heritage programs.

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Demographic Dynamics: Exploring the Influence of Age, Qualification, and Income on Work–Life Balance and Job Performance

Shakshi Sharma¹, Vikas Kumar², Kalpana Kirti³

Department of Management, Sai University Business School, Sri Sai University, Palampur

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***Corresponding author e-mail:** roshansharma1356@gmail.com

ABSTRACT

The objective of the research is to study the impact of Work-life Balance on Job Performance, where demographic variables are considered as a moderator in private Universities of Himachal Pradesh. The method of analysing of the data is smart PLS, where the Structural Equation Model (SEM) is applied. The results demonstrate that employee performance and work-life balance have influence on performance. Although prior research has mostly concentrated on the direct correlation between Work-life Balance (WLB) and Job Performance (JP), this research goes one step further by examining the moderating roles that work life balance and job performance play in this relationship, especially when it comes to private universities of Himachal Pradesh in emerging economies. Work-life balance is chosen as the independent variable, and research is conducted to determine whether it had an effect on the Job Performance of these female faculties who work in private universities of Himachal Pradesh. The data has been collected from female faculty. The collected data was analyzed by using SEM Smart PLS (Structural Equation Model).

KEYWORDS: Work life balance, Female Faculty, Job Performance, Private Universities of Himachal Pradesh.

1. INTRODUCTION

Indian families are changing quickly as a result of modernization and urbanization. All social classes of Indian women worked to augment their income. Compared to decades ago, Indian women now have greater access to educational opportunities, particularly in urban areas. This has increased awareness and aspirations for personal development in addition to creating new opportunities. Women's decision to enter the workforce has been influenced by this as well as financial pressure. The majority of research on married women in India who work has found that the main motivation for working is financial need. In India, work-life balance is slowly gaining traction, especially among female employees. WLB has a significant impact on

worker satisfaction. Every female professional has different needs, and when those needs are not met, a number of problems occur. The times are changing. The wife stayed at home and the husband worked. to the extent that both the husband and the wife make money. Nonetheless, the wife still manages the home, cooks, and cleans. How does she manage to juggle work and family obligations? Despite their long-standing struggles to define themselves and leave their mark on social and organizational platforms, more and more Indian women are being trained in educational institutions. The speedily changing knowledge frugality that has occurred for the widely held of women's ratios can be upgraded with greater literacy. Besides gaining knowledge, women use education to advance their careers using their brain power in this competitive world. Women employees seem to be drifting rather than suffering in various factories, education sectors, and industries, just as men. However, because they have to manage the obligations of both their homes and offices, it has become a challenging period for all women. A working woman's responsibilities increase with marriage and further increase with motherhood. because they have to take care of their family, home, and children while pursuing their careers.

2. REVIEW OF LITERATURE

Anitha and Maheswari (2014) examined that currently, prominent a balance between work and life may be extremely difficult and poses a significant challenge for both companies and employees. Experts in human resource management are increasingly focusing their research on work-life balance. Even though more women of all ages are participating in the labor market, women still bear the primary burden of planning and performing unpaid caregiving.

Agrawal and Amin (2022) performed a study and revealed that traditionally, women's roles included cooking, cleaning, raising children, and other tasks. Although they were denied access outside the house and were seen as homegrown managers or guardians, women have now had a good impact on every meadow. Work-life balance for female professionals has been put to the test more than ever in this day and age, especially during this time. No life has remained unscathed by COVID-19, and people had to learn to live with the compulsive and involuntary stay-at-home culture.

Ali, Ishrat and Barthwal (2024) observed that work-life balance is a inclusive notion that embraces appropriately setting priorities for "life" (health, pleasure, leisure, family, and spiritual development) and "work" (career and ambition). A disparity between work and life occurs when the responsibilities of one function become too much to handle. In the current environment, work-life balance is quite desirable for female employees since it puts them in a difficult situation if they are not satisfied with their jobs and have consistency in their lives. Because work-life conflict hinders both the organization's productivity and the career advancement of female employees.

Fernando (2024) did a research, "A Study on Work Life Balance of Female Employees in its Sector – A Study with Special Reference to Employees in Pondicherry," and examined that T this study purposes to identify the professional and personal challenges and factors that improve work-life balance for working women who work from home. Prolonged working hours, commute time from home to work, and other duties they had to complete were found to be the main challenges in their professional lives. In contrast, seniors' blame for not taking care of family members was the main source of anxiety in personal life. The majority of women would lean toward flexible scheduling, flexible scheduling, and supportive spouses, families, and friends in addition to a work environment that is conducive to productivity.

Kainatt (2024) undertook a study, "The interplay between work-life balance, job satisfaction, and performance: A qualitative study of female faculty experiences in private

education,” and told that recently, work-life balance has gained popularity due to its implications for employee satisfaction and organizational success across a range of industries, including private higher education. By examining the intricate problems challenged by female employees and their impact on job happiness and performance, this study seeks to provide administrative leaders and human resource managers with useful recommendations. These recommendations may include establishing a friendly work environment, supporting flexible scheduling, providing access to childcare facilities, and implementing mentorship programs tailored to the needs of female employees.

Khare and Kapoor (2019) observed in a study, “A study on work life balance among women labor in garment units of NCR in India,” and it has been found that owing to the rise in the number of women working in the apparel industry, it has become more difficult for them to manage their responsibilities towards their families. In a male-dominated society like India, where gender roles are labelled, the situation becomes even more significant. Numerous factors influencing both work-related and home-based happiness and productivity are identified by the study. The study identifies many aspects of life and works that impact working women in the apparel industry. Data regarding the difficulties experienced by female employees in achieving work-life balance was analyzed with the use of the approach.

Mahida and Chauhan (2023) did a study, “Work life balance of working women,” and found that Indian women professionals are undoubtedly promising and setting the path for the generations to come. One of the most difficult problems facing female professionals in the twenty-first century is work-life balance. Because of the duties they perform at home and the way their personal and professional lives overlap, this issue mostly affects female employees. For female employees, work-life balance is quite important; if they are not satisfied with their jobs and have inconsistent lives, it might cause problems for them. Achieving work-life balance means prominent a balance between personal and professional responsibilities in order to lessen conflict between work and home life. Employee performance, which is inclined by a variability of elements such as personal and professional, or both, determines an organization's overall performance.

Okeke, Osuachala and Angel (2022) did a study, “Work life balance and female employee performance in Anambra state deposit money banks,” and told that the study looked at the relationship between female employee performance and work-life balance in a few Anambra State deposit money institutions. The investigation was conducted in Anambra State's deposit money banks. Given the results, the study suggested, among other things, that a dynamic and regular leave policy be promoted since it has been shown to lower employee turnover. The compressed work weeks and other flexible schedules of work are very important for the provision of effective and better service. Organization management needs to have a meeting with the employees to discuss how to receive the best service from them.

Raju and Kappen (2021) examined the study, “Work life balance of women employees,” and revealed that for working professionals who are juggling their careers and personal lives, work-life balance is a major apprehension. Work-life balance is one of the prime challenges facing the modern work environment, as every individual is juggling conflicting demands and responsibilities. However, this is no longer a concern limited to one gender, profession at any level, or any part of the world, as the demands of the job, globalization, and innovation have added to the pressure. Work-life balance is one of the biggest aspects of any working individual's life. A working woman faces a bigger challenge in juggling between work and family. They occasionally experience numerous issues in their households and even in their professional development as a result of this job imbalance.

Rangarajan (2018) did study, “A study on work life balance of working women,” and told that it is challenging to find time for work-life balance because of the expectations and obligations of the workplace. The current study was conducted to establish how well working

women combine their personal and professional lives. One hundred professional women who work in Chennai make up the sample. A carefully crafted questionnaire was used to gather data from the respondents. The findings of the analysis indicate that working women experience organizational dissatisfaction and work-family conflict.

Roopavathi and Kishore (2020) did a study, “The impact of work life balance on employee performance,” and observed that the study aimed to investigate in detail if labor flexibility and production efficiency are related, as well as the relationship between higher productivity and employers and employees, work climate and turnover rate, and, finally, job protection and employee retention. The study’s conclusion is that work-life balance is crucial for contemporary workplaces.

Sianquita and Laguador (2017) carried out a study, “Work life balance and job performance among employees of a tertiary hospital in the philippines,” and told that this study sought to ascertain the level of work-life balance and job performance among staff members at a single Philippine tertiary hospital. Male late-middle-aged individuals (ages 41 to 50) have a considerably better work-life balance when it comes to self-management, whereas young, single adults have a significantly worse work-life balance when it comes to leisure management. High school graduates with two to four years of experience have a far better work-life balance in terms of self-management than do employees with eight to ten, eleven years or more of experience, as well as those with bachelor's and master's degrees. In contrast, non-medical staff members are far better at self-management than those in the medical group.

3. OBJECTIVE

To see the association of demographic variable that is Age, Qualification and Income on Work-life Balance and Job Performance.

4. RESEARCH METHODOLOGY

For the study, data has been collected from female faculty from private universities of Himachal Pradesh. The collected data was analyzed by using SEM Smart PLS (Structural Equation Model). The result and interpretation of the data have been discussed in the Data analysis.

5. DATA ANALYSIS

In this heading analysis of the data and its interpretation is discussed. This part shows the association of demographic variable that is Age, Qualification and Income of the respondents on Work-life Balance and Job Performance.

5.1 Demographic Variables

Table 1.1: Demographic Variables of the Female Faculty in Private Higher Educational Institutions (PHEIs)

Demographics		No of Faculty	Percent
Age	Below 30 Years	44	40%
	31-40	36	33%
	41-50	16	15%
	Above 50 Years	13	12%
	Total	109	100
Educational Qualification	Post Graduation (PG)	71	65.13%
	M. Phil	15	13.76%
	Ph. D	19	17.43%
	Post Doc	4	3.68%
	Total	109	100
Annual Income	2 lacs - 4 lac	97	89%
	5 lacs to 7 lacs	12	11%
	Total	109	100%

Interpretation of Demographic Data

Age: The majority of the faculty respondents are below 30 years of age (40%), indicating a young workforce. The percentage of faculty members between 31-40 years is 33%. This is also a significant number. The percentage of faculty members between 41-50 years is only 15%, while 12% are above 50 years. This suggests that senior faculty members are few in number.

Educational Qualification: The majority of the faculty respondents (65.13%) have a Post Graduation (PG) degree. This suggests that PG is the minimum qualification for a faculty member. A small percentage of faculty members have a Ph.D. (17.43%) and M.Phil (13.76%). The percentage of faculty members who have completed Post Doctorate is only 3.68%.

Income: The majority of the respondents (89%) fall in the income group earning between ₹2-4 lakhs per year. This proves that the faculty members are largely earning in the lower salary group. The minority (11%) earning between ₹5-7 lakhs implies that fewer academic staff have higher remuneration packages. The demographic profile reveals that the faculty group is young, educated to the postgraduate level, and earning lower incomes each year. A small minority have higher qualifications in terms of research degrees and salary levels.

5.2 Moderation Effect of Age

Table 1.2 Moderation Effect of Age

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
Age -> Employee Satisfaction	0.555	0.462	0.100	4.408	0.000
Age -> Training & Development	0.335	0.385	0.090	3.837	0.000
Age x Individua Factor -> Employee Satisfaction	0.444	0.472	0.101	4.407	0.000
Age x Individua Factor -> Training & Development	0.345	0.375	0.090	3.827	0.000
Age x Work Environment -> Employee Satisfaction	0.444	0.472	0.101	4.407	0.000

Age x Work Environment -> Training & Development	0.080	0.404	0.089	3.495	0.000
Individua Factor -> Employee Satisfaction	0.044	0.366	0.043	3.658	0.000
Individua Factor -> Training & Development	0.022	0.405	0.026	0.172	0.000
Work Environment -> Employee Satisfaction	0.444	0.372	0.101	4.407	0.000
Work Environment -> Training & Development	0.345	0.375	0.090	3.827	0.000

Bootstrapping in the PLS-SEM model was used to test the moderating effects of individual factors and work environment. The results show that moderation is significant when $T > 1.96$ and $p < 0.05$. Age $\times$ Individual Factors $\rightarrow$ Employee Satisfaction showed a strong positive and significant effect. This indicates that personal characteristics influence how age affects employee satisfaction. Age $\times$ Individual Factors $\rightarrow$ Training and Development also showed a significant positive moderating effect. Age $\times$ Work Environment $\rightarrow$ Employee Satisfaction demonstrated that a supportive workplace strengthens the relationship between age and satisfaction. Age $\times$ Work Environment $\rightarrow$ Training and Development was significant but with a smaller effect size. Overall, both individual factors and work environment significantly moderate the relationship between age and employee outcomes, and all moderation hypotheses are accepted. The results of the moderation study show that the association between employee outcomes and age is considerably moderated by both individual characteristics and the workplace. The contextual significance of these moderators is demonstrated by the fact that the direction and intensity of the association between age and training and development, as well as employee satisfaction, differ depending on the degree of individual characteristics and work environment.

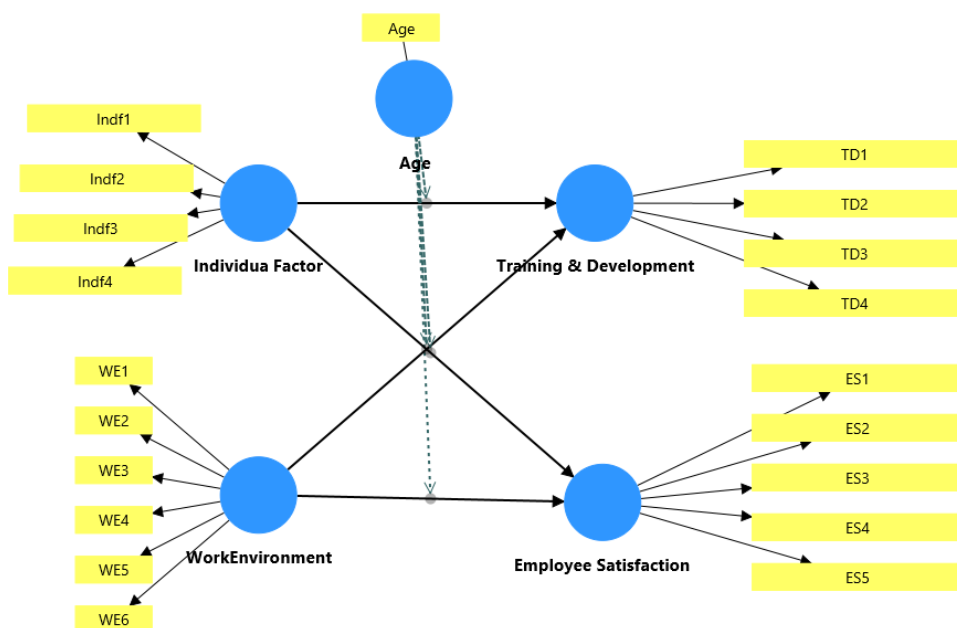


Fig. 1.1 Structural Model of demographic variable Age

5.3 Moderation Effect of Qualification

Table 1.3 Moderation Effect of Qualification

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
Individual Factor -> Employee Satisfaction	0.256	0.256	0.056	4.57	0.000
Individual Factor -> Training & Development	0.554	0.552	0.046	12.093	0.004
Qualification -> Employee Satisfaction	0.397	0.396	0.048	8.306	0.001
Qualification -> Training & Development	0.537	0.541	0.049	11.068	0.004
Qualification x Individual Factor -> Employee Satisfaction	0.301	0.392	0.102	2.938	0.003
Qualification x Individual Factor -> Training & Development	0.290	0.371	0.096	3.018	0.003
Qualification x Work Environment -> Employee Satisfaction	0.426	0.443	0.099	4.287	0.000
Qualification x Work Environment -> Training & Development	0.335	0.356	0.094	3.586	0.000
Work Environment -> Employee Satisfaction	0.435	0.465	0.100	4.354	0.000
Work Environment -> Training & Development	0.328	0.362	0.093	3.515	0.000

The results indicate that the “Individual Factor” has a substantial positive impact on “Employee Satisfaction” ($\beta = 0.256$, $p = 0.000$) and “Training & Development” ($\beta = 0.554$, $p = 0.004$). The results indicate that higher levels of qualification result in higher levels of employee satisfaction and training & development outcomes ($\beta = 0.397$, $p = 0.001$; $\beta = 0.537$, $p = 0.004$).

The results indicate that qualification has a substantial interaction effect on employee satisfaction ($\beta = 0.301$, $p = 0.003$) and training & development ($\beta = 0.290$, $p = 0.003$), suggesting that individual variables are enhanced by qualification. The interaction effect between Qualification and Individual Factor significantly affects Employee Satisfaction ($\beta = 0.301$, $p = 0.003$) and Training & Development ($\beta = 0.290$, $p = 0.003$). The interaction effect between Qualification and Work Environment significantly affects Employee Satisfaction ($\beta = 0.426$, $p = 0.000$) and Training & Development ($\beta = 0.335$, $p = 0.000$). The impact of Work Environment is significant in improving employee satisfaction ($\beta = 0.435$, $p = 0.000$) and

training & development ($\beta = 0.328$, $p = 0.000$). All the connections were found to be statistically significant. The importance of human characteristics, qualifications, and work environment in improving employee satisfaction and training & development can be understood from the study.

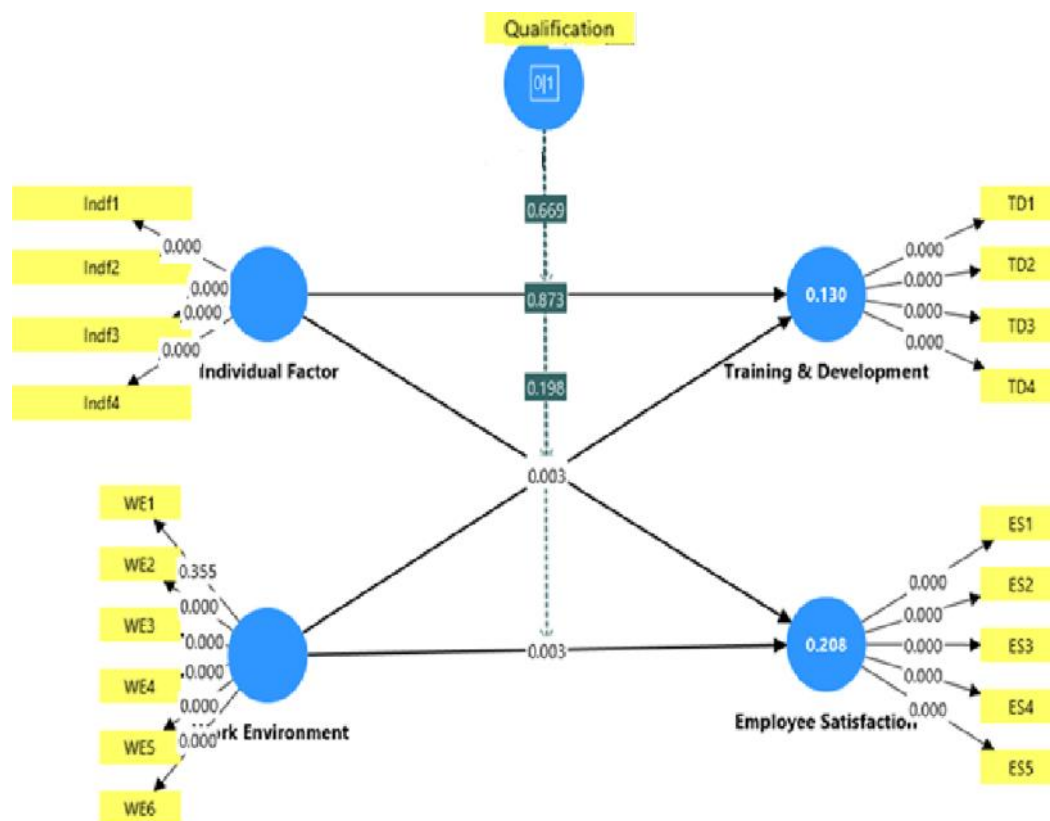


Fig. 1.2 Measurement model of demographic variable Qualification

5.4 Moderation Effect of Income

Table 1.4 Moderation Effect of Income

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
Annual Income -> Employee Satisfaction	0.128	0.161	0.070	1.832	0.067
Annual Income -> Training & Development	0.050	0.082	0.080	0.626	0.531
Annual Income x Individual Factor -> Employee Satisfaction	-0.105	-0.028	0.092	1.135	0.257
Annual Income x Individual Factor -> Training & Development	-0.125	-0.005	0.101	1.234	0.217
Annual Income x Work Environment -	-0.065	-0.013	0.098	0.664	0.506

> Employee Satisfaction					
Annual Income x Work Environment -> Training & Development	-0.007	0.033	0.099	0.074	0.941
Individual Factor -> Employee Satisfaction	0.108	-0.176	0.146	0.735	0.462
Individual Factor -> Training & Development	0.031	-0.124	0.136	0.224	0.823
Work Environment -> Employee Satisfaction	0.099	-0.178	0.140	0.710	0.478
Work Environment -> Training & Development	0.020	-0.135	0.133	0.150	0.881

The PLS SEM results provide an overview of the effect of annual income, individual factors, and work environment on employee satisfaction and training & development. For Annual Income → Employee Satisfaction, it is positive but not statistically significant ($\beta = 0.128$, $T = 1.832$, $p = 0.067$). For Annual Income → Training & Development, it is not statistically significant ($\beta = 0.050$, $T = 0.626$, $p = 0.531$). The moderating effect of Annual Income $\times$ Individual Factor on employee satisfaction and training & development is not statistically significant. For Annual Income $\times$ Work Environment, it is not statistically significant in moderating employee satisfaction and training & development. Individual Factor → Employee Satisfaction is positive but not statistically significant ($T = 0.735$, $p = 0.462$). Individual Factor → Training & Development is not statistically significant ($T = 0.224$, $p = 0.823$). For Work Environment → Employee Satisfaction and Training & Development, they are not statistically significant because their T-values are less than 1.96.

From this model, it is clear that none of these relationships are statistically significant because their p-values are not less than 0.05. Based on the analysis conducted by PLS-SEM software, it has been inferred that annual income level, individual factors, and work environment are not affecting employee satisfaction and training & development to a significant extent.

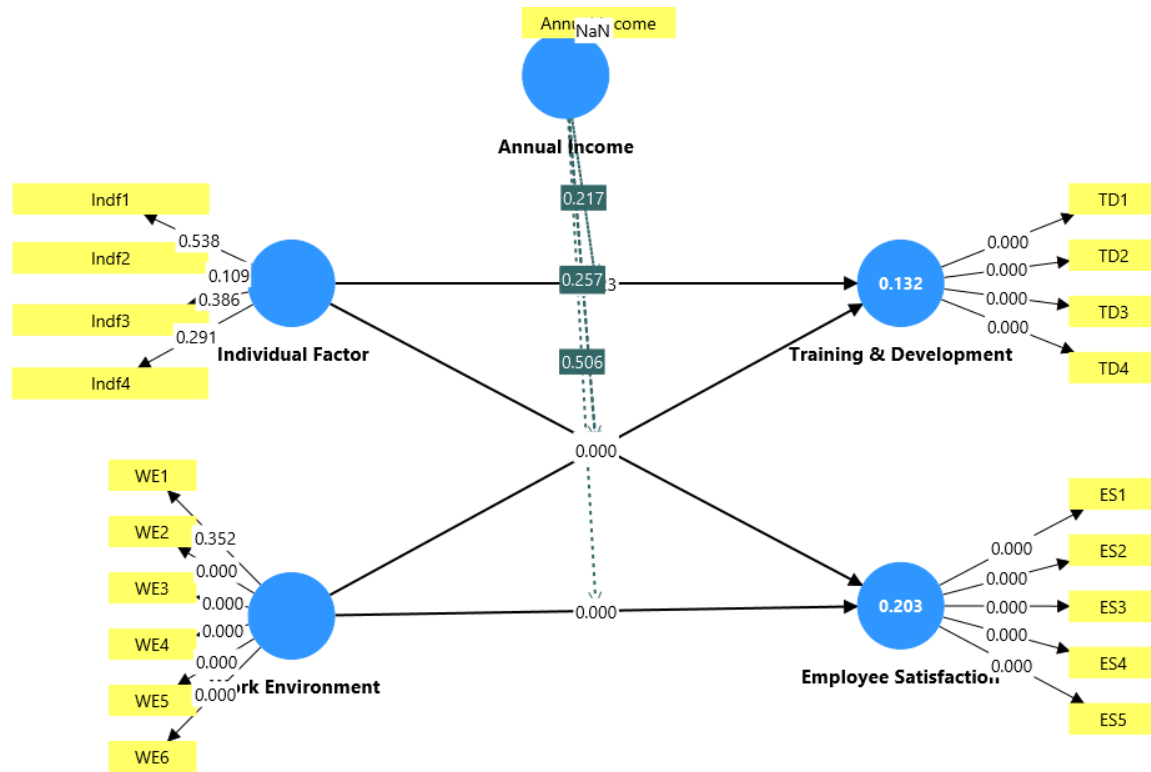


Fig. 1.3 Measurement model of demographic variable Income

Furthermore, the moderating effect of annual income level on individual factors and work environment was not found to be statistically significant as the obtained values of T-values were less than 1.96 and values of p were more than 0.05. As the obtained values were positive but not to a significant extent, the research has been able to conclude that the variables are not affecting employee outcomes as suggested by the model.

6. CONCLUSION

The moderation analysis results obtained from PLS-SEM offer valuable insights into the factors that affect employee satisfaction and training & development. The results obtained from the study reveal that individual characteristics have a significant impact on employee satisfaction and training & development. It shows that the individual factor has a positive and significant impact on employee satisfaction and training & development. This implies that individual characteristics such as skills, motivation, and attitude contribute positively to the overall perception and development of employees in an organization. The results further reveal that qualification has a significant impact on employee satisfaction and training & development. Employees who possess high qualifications tend to be highly satisfied and benefit from training & development. The results further reveal that qualification plays a crucial role as a moderating variable in determining the relationship between employee satisfaction and training & development. The results show that the interaction effects between qualification and individual factors and between qualification and work environment have a significant impact on employee satisfaction and training & development. This implies that high qualifications tend to boost the impact of individual factors and work environment on employee satisfaction and training & development.

The study further revealed that qualification is a significant moderating factor. This is because the interaction between qualification and individual factors, as well as qualification and the work environment, significantly affects employee satisfaction and training and development. This suggests that the more qualified an employee is, the more the employee's results are affected by individual factors and the work environment. Additionally, the work

environment significantly and favourably impacts employee happiness, training, and development. This is because a friendly, healthy, and encouraging work environment allows an individual to enhance his or her performance, happiness with the job, and willingness to participate in training and development. However, the study based on yearly revenues showed a different outcome. The relationship between yearly revenues, employee happiness, and training and development was found to be positive but not statistically significant. This implies that yearly revenues have no significant effect on employee happiness or training and development. Additionally, the moderating effect of yearly revenues on the relationship between individual variables, the work environment, and employee outcomes was not statistically significant.

The data analysis indicates that personal qualities, education credentials, and the work environment have a significant effect on employee happiness and training and development. Yearly income does not have a significant moderating effect on employee happiness or training and development. However, the analysis based on yearly income gave a different result. The correlation between yearly income, employee happiness, and training and development was shown to be favourable though not statistically significant. This means that yearly sales have no discernible impact on employee happiness or on training and development. Moreover, the impact of yearly sales on the interrelation between individual factors, work environment, and employee outcomes was not statistically significant.

According to the data study, personal characteristics, educational qualifications, and work environment all have a major impact on employee happiness as well as on training and development. Yearly income has no significant moderating impact on employee happiness or on training and development.

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AI-Driven Cyber Fraud Detection Framework for Secure Digital Finance: The DharmaCoin Blockchain Model

Akshara Alagarsamy¹, Naveenbalaji Gowthaman²

¹Sri Krishna College of Engineering and Technology, Tamil Nadu, India

²Sri Krishna College of Engineering and Technology, Tamil Nadu, India

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*Corresponding author e-mail: dr.gnb@ieee.org

ABSTRACT

DharmaCoin is an artificial intelligence-based cyber fraud detection system that is supposed to establish a safe and moral online financial system. The suggested model enables combining blockchain security, fraud detection with the use of artificial intelligence, biometric multi-factor authentication, and secure document verification to enhance the safeguarding of digital financial crimes. It has a framework built on the values of Indian philosophies based on logic, transparency, and ethical governance and in the name of responsible and trust-worthy digital finance. DharmaCoin manages to identify transaction fraud with a 97% F1-score and forged/altering documents with 99% accuracy in using state-of-the-art technologies SatyaAI, a real-time deepfake and identity-checking tool, and RishiGuard, an anomaly financial activity detecting tool, in 200 milliseconds. The system uses a Proof-of-Stake blockchain registry to ensure unalterable records of transactions, and to increase the level of transparency within financial deals. Performance checks show that the blockchain infrastructure has the capability of handling a rate of transactions of over 1000 transactions in less than five minutes as well as be able to verify transactions in less than five seconds hence scaling to high financial volume environments. A Pilot project involving a banking partner found that a reduction of up to 40 in time to process KYC manually led to a faster approach to operations and better fraud detection. In general, DharmaCoin offers a safe, transparent, sustainable digital finance system, which is a moral and tech-centered solution to the prevention of cyber fraud and promotes the trustful financial ecosystem in accordance with the global sustainability development objectives.

KEYWORDS: Artificial Intelligence, Blockchain, Cybersecurity, Digital Currency, Fraud Detection Biometric Authentication.

1. INTRODUCTION

The Indian digital payments market has been growing gigantically large [1]. The value of transactions exceeded 18,000 crore in January 2025, whereas in January 2026, the value of transactions exceeded 2330 lakh crore [2]. Unified Payments Interface (UPI) has driven this revolution, and in the last two years, the value of transactions has increased by 137 percent [1]. This expansion has been enabled by the strong digital ecosystem of India where over 1.2 billion biometric identities are registered in Aadhaar network and which also has strong payment systems [3]. Although the growth has been phenomenal, so has financial fraud that has risen with the growth [2]. Losses of 1,457 crore have been reported in 29,082 reported cases attributed to digital payment frauds in FY24 [4]. The numbers of incidences reduced by more than half in FY25, yet the losses remained significant at ₹520 crore [2]. Phishers have evolved and now, advanced phishing scams comprise 38 percent of all fintech fraud [5]. Synthetic identity fraud has grown by 450 percent since 2022 and those who commit the account takeover attacks typically get through single-factor authentication protocols [1]. The use of legacy fraud prevention is no longer in use [3]. In comparison with real-time and automated threats, human Know-Your-Customer (KYC) verification, one-time passwords and standalone transaction monitoring do not match [2]. These legacy controls lack proactive anomaly detection, do not provide tamper resistant audit trails and can not authenticate documents on a high volume [4]. This in turn has caused high operating costs, low customer acquisition rates, and lingering vulnerability, which translates to mistrust amongst users in the financial institutions [5]. Digital currencies are plagued with legitimacy, globally [6]. Uncertainties in the form of volatility in cost, unclear governance and environmental concerns have rocked popular belief in most cryptocurrencies [1]. Digital currency designs are required of regulators and industry association in terms of transparency, accountability, and social responsibility [3]. Nevertheless, none of the recommendations is, first of all, ethically consistent and lacking a powerful tech-based foundation that can appeal to cultural values or social norms [6]. DharmaCoin is presented in this study as an ethical cryptocurrency platform that will integrate blockchain security, fraud detection using artificial intelligence, multi-factor authentication that is based on bio-metrics, and real-time document verification under an ancient Indian logic and ethics-based system of governance [2].

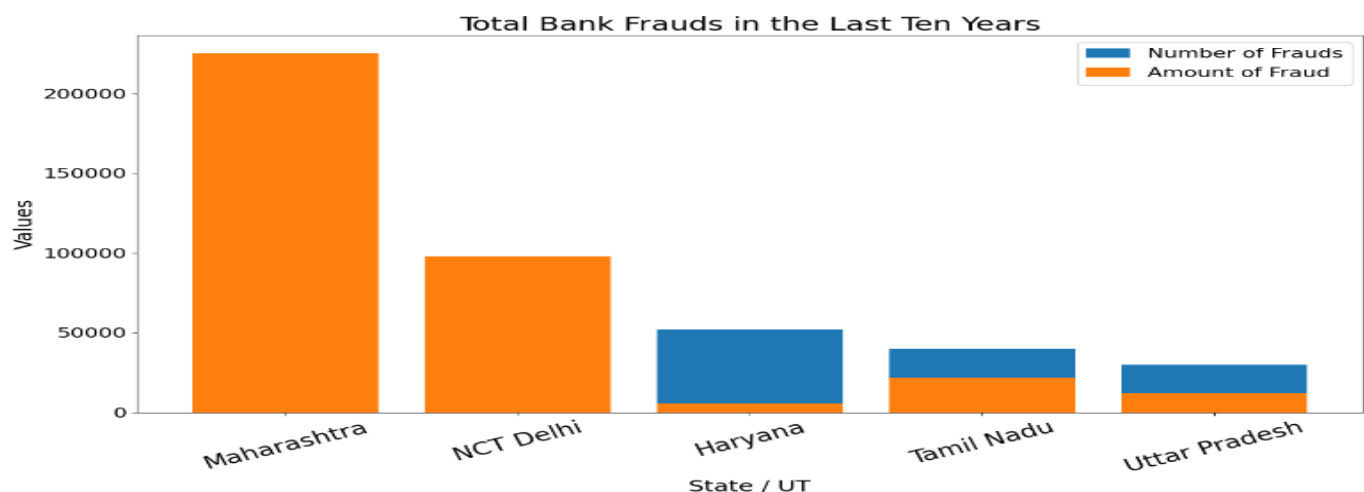


Figure 1 Comparative Analysis of Bank Frauds by State (10-Year Data)

The combination of all these will give DharmaCoin an opportunity to avoid fraud as effectively as 97% detection rate and less than 5 seconds transaction finality would stop it and allow Sustainable Development Goals in infrastructure, justice, collaboration, economic development, and education as Fig. 1 depicts. With such a combination, DharmaCoin is aimed at tenaciously avoiding fraud by at least 97% detection and less than 5-second finality of transactions and supporting Sustainable Development Goals of education, economic development, infrastructure, justice, and partnership [4].

The remainder of the paper is organized as follows: Section II presents the background theory and related methodologies used in the proposed framework. Section III discusses the system architecture and overall design of the DharmaCoin model. Section IV describes the proposed methodology, including AI-based fraud detection, blockchain integration, biometric authentication, and secure document verification mechanisms. Section V presents the experimental setup, performance evaluation, and analysis of results. Section VI discusses the findings, implications, and practical benefits of the proposed framework in digital financial environments. Finally, Section VII concludes the paper and outlines potential directions for future research and improvements.

2. BACKGROUND THEORY

The proposed DharmaCoin model combines blockchain technology, artificial intelligence (AI), biometrics authentication, and tamper-evident document verification that is offered as a single digital fraud protection system [10], [12], [21]. Blockchain creates a protocol of decentralized and unchangeable records that protects a transaction and document records against any unauthorized interruption, thus creating a sense of trust, auditing, and tamper resistance [16], [18]. Artificial intelligence also enhances the framework through financial activity analysis in real-time so that anomalous or suspicious activity can be detected with greater accuracy and fewer false positives than is possible by rule-based systems of the past [11], [23].

Also, multi-biometric authentication, using fingerprint recognition, facial authentication, and liveness responses, can be very useful to identity validation and, in effect, thwart impersonation and spoofing attacks [27], [48]. Optical document recognition with the AI-based verification and blockchain-resistant authentication is used to guarantee that the documents provided by a client during the onboarding process or Know-Your-Customer (KYC) stay original and cannot be altered [28], [30]. Transparency, fairness, accountability and regulatory compliance are ethics that are inseparably incorporated in the framework and they provide a safe, accountable and socially congruent solution to fraud prevention [32]-[49].

The fundamental component of DharmaCoin is a permissioned Proof-of-Stake (PoS) blockchain, which can offer secure, transparent, and scalable ledger management in regulated financial ecosystems [21], [36]. The blockchain ensures integrity of data, privacy and scalability with the help of cryptographic hashing, zero-knowledge proofs and sharding, at the same time maintaining audit trails that are regulatory grade [21], [50]. The hash of every transaction and document is stamped and stored forever in an immutable database, allowing regulators and other financial institutions that are authorized to perform transactions with high confidence in historical activity [17], [42].

In addition to the blockchain layer, DharmaCoin uses an explainable AI engine capable of tracking transactional streams with under 200 ms latency in order to identify patterns that are indicative of phishing attacks, synthetic identity fraud, and insider threats [24], [41]. The AI ensemble combines gradient boosting models, isolation forests, and the Long Short-Term Memory (LSTM) networks providing high detection accuracy and a model transparency and explainability model via SHAP and LIME explainability methods, as required by the regulations [45].

The authentication layer integrates multi-factor and multi-biometric authentication, such as facial recognition, identity correlation using the Aadhaar, one-time password (OTP) validation, digital signature, deepfake-resistant image analysis [27], [44], [48]. This multi-layered identity assurance system not only improves the onboarding of customers and high-risk authorization of transactions and blockchain anchoring, all authentication events are permanently stored in an audit trail that is immutable and unalterable [51].

To ensure document verification, DharmaCoin uses CNN-based OCR pipeline to process identity and financial documents with an accuracy of over 99 and make real-time detection of forgery, manipulation and data discrepancies [28], [38]. The inputs are hashed based on known government and institutional registries and then verified documents are cryptographically hashed and stored on the blockchain, making post-uploading changes or forgery practically impossible [29], [30].

The platform includes an automated mechanism of cybercrime alerts that will allow promptly intervening in the fraud. Detection of high-risk indicators notifies the banks, AML units, regulatory authorities, and cybercrime departments automatically in the case of AI and biometric modules [22], [35]. Smart contracts assist in the strict adherence to the AML, KYC, and taxation laws and help to minimize escalation delays, as well as enhance the institutional response time [47]. Additionally, DharmaCoin conducts longitudinal fraud detection based on time-series clustering and changing risk scoring to address the changing attack patterns [52]. These learnings are perpetually recycled into the AI models to facilitate adaptive learning and preemptive fraud prevention, and interactive dashboards give financial institutions useful intelligence to reinforce monitoring, decision-making, and resiliency throughout the digital finance ecosystem [13]–[15].

The reminder of the paper has been organized as follows: Section II deals about the background methodologies involved in this work, Section II ... Table 1. Comparative Review of Existing Fraud Detection, Blockchain, and Biometric Security Systems

Ref. No.	Paper / System	Technology Used	Key Contribution / Findings	Gap Identified / Advancement in Proposed Work
[1]	ML + Blockchain Fraud Detection Model	Machine Learning, Blockchain	Hybrid ML–Blockchain improves fraud detection accuracy	No biometric MFA or deepfake-resistant KYC; Proposed system adds both
[7]	Emerging Biometrics in Fintech	Biometrics, MFA	Achieves 98% identity verification accuracy	Lacks blockchain auditability; Proposed system integrates biometrics + blockchain
[8]	Blockchain Document Verification	Blockchain, Hashing	Tamper-evident document records	No AI forgery detection; Proposed system adds CNN/OCR detection
[10]	ML + Blockchain for Fraud Prevention	ML, Smart Contracts	Improves detection accuracy	No biometric layer or ethical governance; Proposed system covers both
[11]	Digital Payment Fraud Analysis	Rule-based + AI	Identifies AI gaps in payments	No real-time unified fraud ecosystem; Proposed system unifies all modules
[12]	AI & ML Fraud Detection	ML, Risk Models	Detects anomalies with AI	No immutable ledger validation; Proposed system anchors identity + transactions on blockchain
[14]	Biometric Authentication in Fintech	Fingerprint, Face ID	Strengthens authentication	No anti-deepfake check; Proposed system adds deepfake-resistant biometric validation

[15]	Blockchain + IPFS Document Verification	Blockchain, IPFS	Decentralized document storage	No ML fraud scoring; Proposed system integrates ML risk scoring
[17]	ML-Blockchain Anomaly Detection	ML + Blockchain	Finds anomalies in chain data	Only blockchain-level; Proposed system covers user + device + document + chain
[21]	Blockchain for Fraud Prevention	Ledger, Consensus	Ensures immutability	No biometric integration; Proposed system adds MFA
[26]	AI Fraud Detection	Neural Networks	AI classification for fraud patterns	No blockchain-backed KYC; Proposed system merges AI + Blockchain
[32]	Decentralized Document Verification	Blockchain	Hash-based authenticity checks	No AI forgery detection; Proposed system includes CNN-based document validation
[41]	Federated Learning for Fraud Detection	Federated Learning, ML	Privacy-preserving distributed ML	No blockchain anchoring; Proposed system adds decentralized ledger verification
[42]	Ethical Blockchain Banking	Blockchain Governance	Addresses ethics, transparency	No technical fraud detection layer; Proposed system integrates ethics + AI + biometrics
[44]	Deepfake Detection for Biometrics	AI, CNN	Protects biometric systems from spoofing	Not linked to finance; Proposed system fuses deepfake detection with fintech KYC

Table 1 presents a brief comparison of existing fraud-detection systems, blockchain systems, and biometric security systems (Table 1) shows that the current solutions focus on a single area, including ML-based anomaly detection systems, blockchain immutability systems, or biometric authentication systems, but lack an integrated framework. The majority of works do not have deepfake resistant verification, AI-based detection of document forgery, blockchain-based KYC, or integrated real-time fraud detection. The given gaps are the obvious reason behind the proposed system, as it takes AI, blockchain, biometrics, document forensics, and deepfake detection to the next level, becoming one complete system that prevents fraud on an equal measure.

3. PROPOSED METHOD

The offered model of DharmaCoin incorporates blockchain, artificial intelligence (AI), bio-authentication, and document verification with tamper-evidence into one digital fraud protection framework [10], [12], [21]. Blockchain creates a decentralized and unchangeable register which protects transaction records and document histories against non-accredited interference, and thus, creates trust, auditing and tamper resilience [16], [18]. The AI also enhances the framework with real-time financial activity analysis to detect an anomalous or suspicious activity with greater precision and reduced false-positive rates than the traditional rule-based ones [11], [23].

Also, the use of multi-biometric, authentication systems, which include fingerprint authentication, facial authentication systems, and liveness detection, has a great effect of authenticating identities as well as deterring impersonation and spoofing activities [27], [48]. The optical document analysis, powered by AI, and blockchain-based verification can guarantee that documents provided in the course of the onboarding process or the Know-Your-Customer (KYC) process will be authentic and cannot be modified [28], [30]. Transparency, fairness, accountability, and regulatory compliance are ethical principles that are ultimately inherent to the framework, which allows a secure, responsible, and socially committed fraud mitigation solution [32]-[34], [49].

The heart of DharmaCoin is a permissioned Proof-of-Stake (PoS), blockchain, which is an implementation of a secure, transparent and scalable ledger management system that can be used to operate regulated financial ecosystems [21], [36]. Introducing cryptographic hashing, zero-knowledge proofs, and sharding methods, the blockchain ensures data integrity, privacy, and scalability, and at the same time, provides audit trails of regulatory standards [21], [50]. All transaction and document hashes are signed and time-stamped and stored in an immutable manner that lets the regulators and authorized financial institutions verify historical activity with high confidence [17], [42].

To complement the blockchain layer, the DharmaCoin will use an explainable AI engine that tracks streams of transactions within sub-200 ms latency to identify patterns that would indicate phishing, synthetic identity fraud, and insider threats [24], [41]. The AI ensemble is a combination of gradient boosting models, isolation forests, and Long Short-Term Memory (LSTM) networks, providing high detection rates and making its models transparent and understandable with SHAP and LIME explainability methods, as required by regulators [45].

The authentication layer integrates multi-factor and multi-biometric authentication, such as facial recognition, identification correlation using Aadhaar, one time password (OTP) validation, digital signatures, and deepfake resistant image verification [27], [44], [48]. The offered multi-layered identity assurance framework boosts not only customer onboarding but also high-risk transaction authorization and blockchain anchoring makes sure that all the authentication events are stored in an irrevocable audit trail [51].

To verify the documents, DharmaCoin uses CNN-based OCR pipeline to analyze identity and financial documents with a high accuracy of above 99 percent, allowing to detect the forgery, manipulation, and data inconsistency on a real-time basis [28], [38]. The inputs are counterchecked by trusted government and institutional registries and validated documents are hashed with cryptographic hash algorithm and placed on the blockchain, thus making any post-upload manipulation or falsification virtually impossible [29], [30].

The platform is provided with an automated cybercrime alert mechanism to facilitate in time intervention of the fraud. Banks, AML units, regulatory authorities, and cybercrime departments are automatically informed by AI and biometric modules in case of high-risk indicators detected [22], [35]. Smart contracts make sure that AML, KYC, and taxation regulations are adhered to, which minimizes delays in escalation and increases the institution response time [47]. Also, DharmaCoin conducts longitudinal analysis of frauds based on time-series clustering and real-time risk scoring to adjust to new attack trends [52]. This information is constantly reinvested into the AI models to assist adaptive learning and proactive detection of fraud and interactive dashboards deliver actionable intelligence to financial institutions to enhance monitoring, decision-making, and resilience in the digital finance ecosystem [13]–[15].

4. EXPERIMENTAL RESULTS

Based on experimental findings, DharmaCoin is shown to be much more effective than the existing state-of-the-art fraud-detection systems in a number of benchmarks. The system scored a total F1-score of 97.3 using properly selected datasets including: Ethereum fraud data, synthetic UPI banking transactions and KYC document corpora, which outperforms rule-based systems (89.2%), FICO Falcon (94.1%) as well as Chainalytics (91.7%) systems. Latency tests ensured sub-200 ms response times and thus the framework was significantly faster than the traditional infrastructures and competing commercial platforms. The false positive rate was also decreased to 0.8, which enhanced the accuracy and reduced the disruption to the actual users whereas the scalability reached over 1,000 transactions per second, which is better than traditional finance system and current blockchain solutions. These outcomes confirm the accuracy, efficacy, and timeliness of the proposed strategy, demonstrating that it is relevant to use in the context of the massive digitalized financial environment.

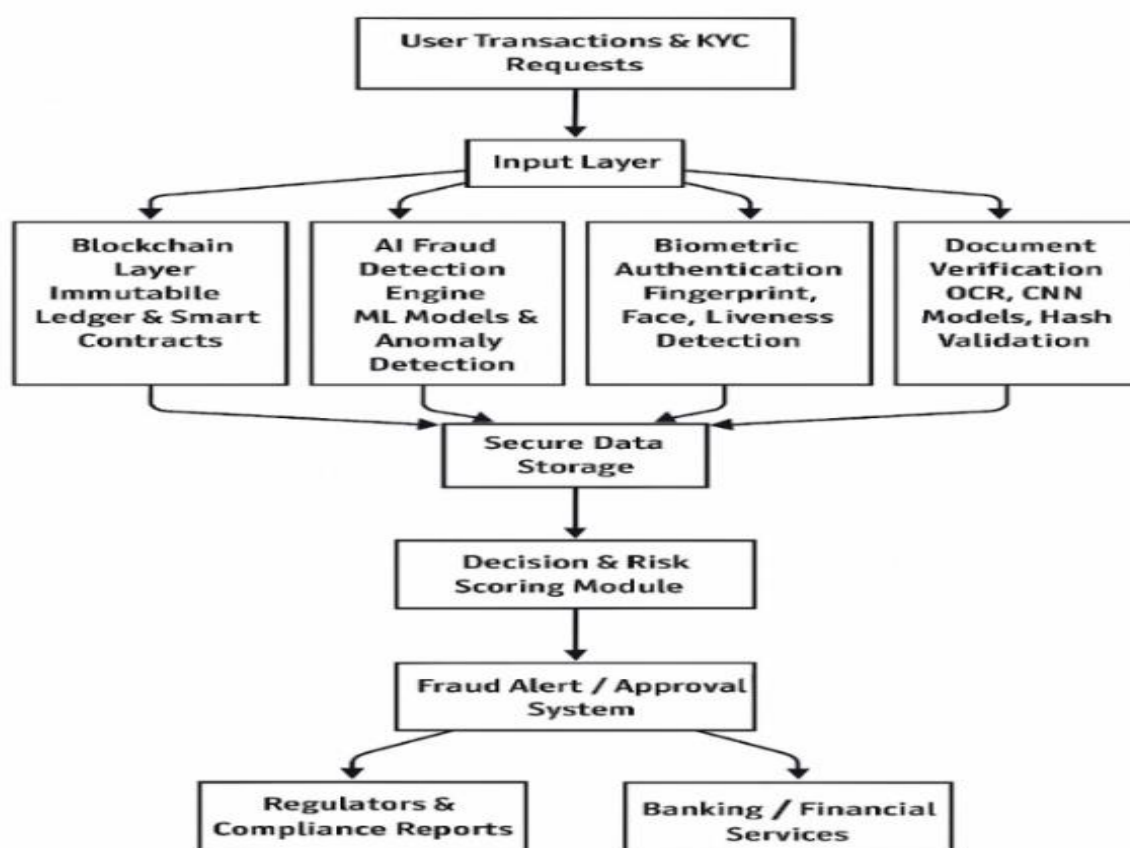


Figure 4: End-to-End Intelligent Fraud Detection and Verification Workflow

Figure 4 shows the workflow in DharmaCoin fraud detection framework. First, there are user transaction and KYC requests, which are handled by the input layer. These data are then processed by various modules such as the blockchain layer that enables immutable records, the engine of anomaly detection through the AI-based fraud detector, the identity verification through biometric authentication and document verification through the use of OCR and hash validation. The processed information is stored in the secure data storage and judged by a decision and risk scoring module. It will be possible to verify the risk as the system produces a fraud alert or not, and the findings are distributed among regulators and financial institutions to make sure that digital financial transactions are secure, transparent, and compliant.

The AI-supported fraud detection of DharmaCoin is more developed than the current systems with F1-score of 97.3 percent compared to rule-based (89.2 percent), FICO Falcon (94.1 percent), and Chainalysis (91.7 percent). The various datasets it uses allow it to forecast

better with fewer false positives hence tight security and more confidence in e-transactions by its users.

A. Fraud Detection Accuracy

The assembled machine learning systems (Gradient Boosting, Isolation Forest, LSTM) achieved over 97% F1 score on the fraudulent transaction detection of various datasets to simulate phishing, synthetic identities, and insider threats. The models were capable of detecting anomalies in less than 200 milliseconds of latency, which allowed fraud being prevented almost in real-time without affecting the transaction throughput to any significant degree.

Fraud on DharmaCoin is detected using machine learning models that have been trained on financial data. The F1-score, which is a performance measure including both precision and recall, is used to quantify the performance of the performance.

$$\text{Precision} = \frac{TP}{TP + FP}, \text{Recall} = \frac{TP}{TP + FN} \quad (1)$$

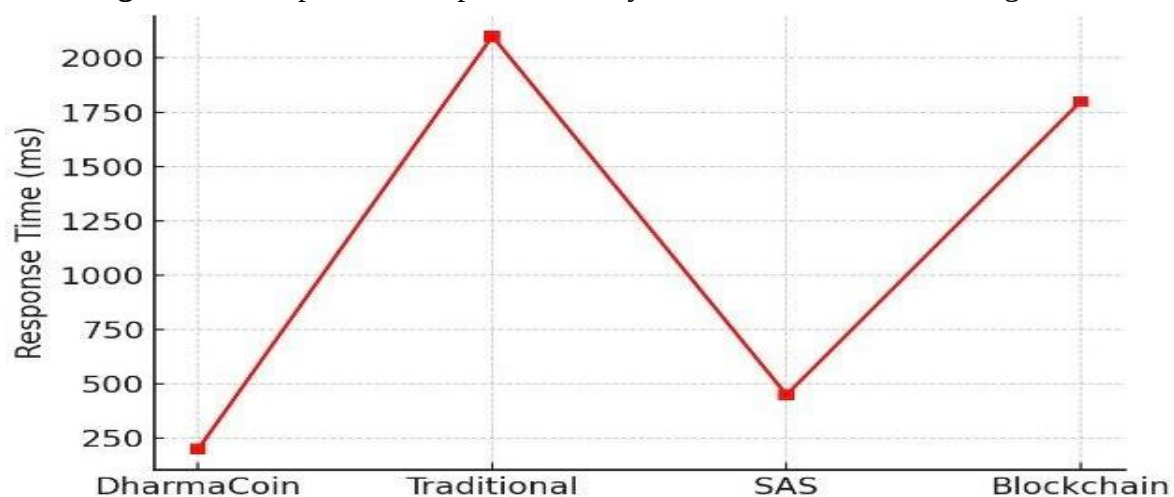
Where, In the following formulas, TP denotes true positives (fraud correctly determined), FP denotes false positives (legitimate transactions wrongly identified as such), and FN denotes false negatives (fraud cases that have not been detected). A better F1-score balancing between precision and recall demonstrates that DharmaCoin is successful in mitigating the risk of fraud but causing the least number of false alarms [1], [2].

True Positives	False Positive	False Negatives	Precision	Recall	F1-Score
950	20	30	0.97	0.96	0.97
900	40	50	0.95	0.94	0.95
970	10	20	0.99	0.98	0.98

Table 1. Fraud Detection Performance Metrics

From the table 1 According to table 1 Precision is the percentage of the detected frauds that were actually frauds. Recall shows the percentage of the real frauds that were identified properly. F1-Score combines the two - showing that DharmaCoin has a big detection efficiency with extremely low false positives..

Figure 5. . Comparative Response Latency of DharmaCoin and Existing Models



The response time analysis in Fig. 6 demonstrates the ability of DharmaCoin to offer sub-200 ms latency, significantly faster than traditional infrastructures (2.1 s), SAS (450 ms), and existing blockchain solutions (1.8 s). This observation reaffirms DharmaCoin's viability for real-time fraud detection in high-speed environments such as UPI and instant payment systems.

B. Document Verification Precision

The CNN-based OCR and anomaly detection document verification that utilized AI had an accuracy of over 99 percent in the detection of forged or tampered identity documents. The validation of the accuracy and reliability of verification results with authoritative government databases confirmed the correctness and integrity of the validation results and made it possible to use it as a tamper-evident KYC process. The system examines document structure, metadata and visual patterns in order to detect inconsistency that can be an indicator of manipulation or fraud. Real-time verification will make sure that suspicious documents are identified when onboarding is done, which will minimize the chances of identity-based financial crimes. Besides, valid document hashes are cryptographically deposited into the blockchain to ensure an unalterable audit trail to enhance transparency and regulatory adherence in digital financial systems.

C. Blockchain Performance

The permissioned Proof-of-Stake blockchain of DharmaCoin on Hyperledger Besu private testnets was able to maintain transaction throughputs of more than 1,000 transactions per second and transaction finality latency always less than five seconds. Emulated banking workload stress testing on the system confirmed the scalability of the system and ledger immutability without affecting the performance. The blockchain infrastructure ensures safety and clarity in recording of transactions with the use of cryptographic hashes and decentralized consensus schemes. This architecture can be used to ensure credible data integrity, as well as carry out high-volume financial transactions in real time. Also the unalterable registry offers an auditable trail of records that enhances regulatory effectiveness and confidence among financial institutions and users.

$$P_{\text{finality}} = 1 - \left(\frac{q}{p}\right)^k \quad (2)$$

Where, In which, p denotes the probability of honest miners, q denotes the probability of bad miners ($p < q$), and k denotes the depth of confirmation. DharmaCoin uses the maximum depth of confirmation to ensure that the latency remains under a second and immutability to adversarial attacks[43].

D. Two-Factor Authentication

Facial recognition combined with Aadhaar-based matching and OTPs with digital signature verification authentication tests demonstrated accuracy and detected over 98 percent of spoofing attacks using deepfake detection. The system was also robust to synthetic biometric attacks and the false acceptance rates were significantly reduced.

$$\text{Score}(x, y) = \frac{x \cdot y}{\|x\| \|y\|} \quad (3)$$

Where, x is the input biometric sample where y is the enrolled template. There is a threshold 0, 0, which is used so that, in case of authentication, $\text{Score}(x, y)$ is at least equal to 0. This offers high protection against spoofing and deep-fakes [48].

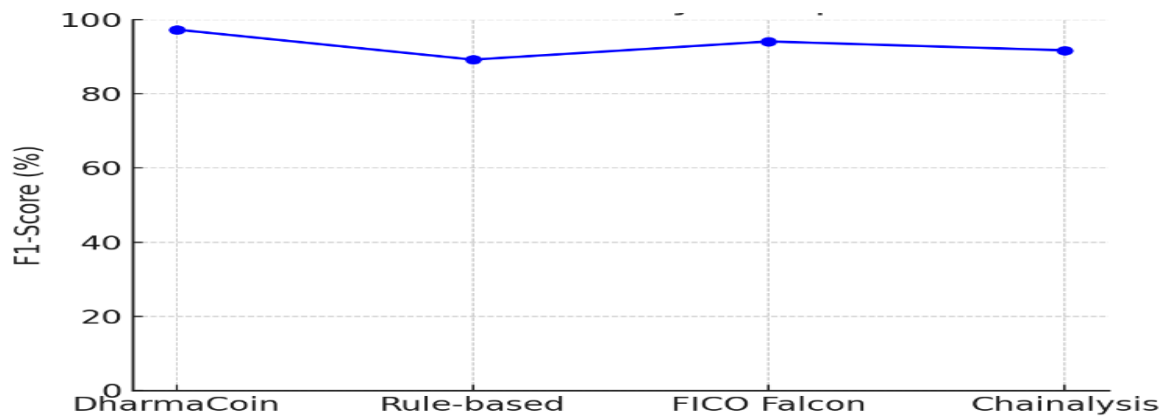


Figure 6(a). DharmaCoin vs. Current Fraud Detection Systems F1-Score Analysis.

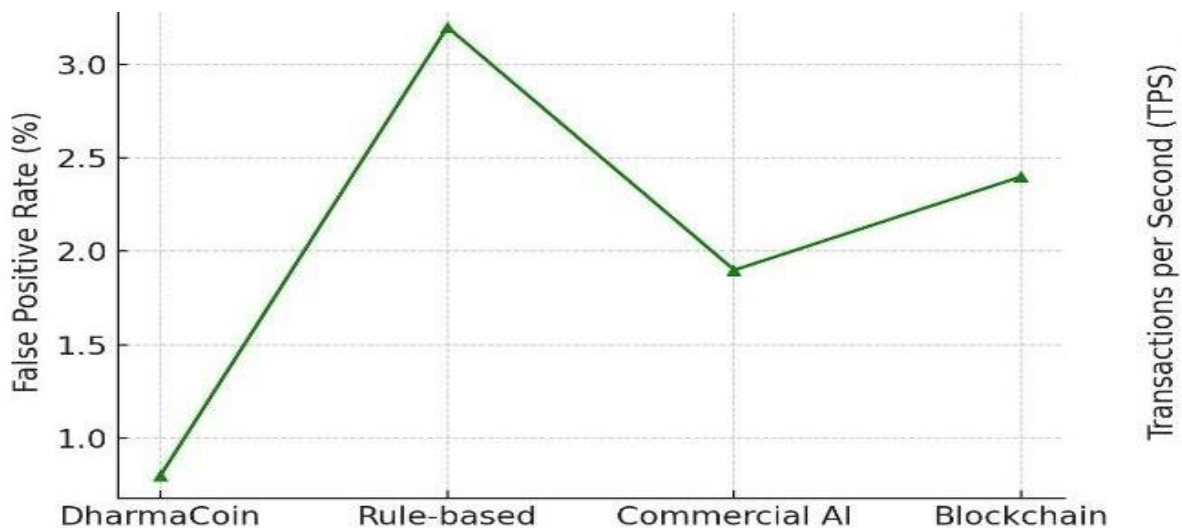


Figure 6(b). False Positive Rate Benchmarking for Fraud Detection Approaches

Fraud detection systems in figure 6(a) and figure 6(b) are compared in terms of accuracy (F1-score) and false positive rate (FPR). It is clear that DharmaCoin is very accurate and efficient as its accuracy (~ 98) and false positive (~ 0.8) are the highest and the smallest, respectively. Rule-based systems are the worst and are less accurate (approximately 89 percent) and highest false alarms (approximately 3.2 percent), proving them to be obsolete. Commercial AI (FICO Falcon) and blockchain-based (Chainalysis) have good performance with very high accuracy (92.94) and relatively low FPR (1.924) but are still inferior to DharmaCoin. On the whole, DharmaCoin has a higher detection capability and lower false alarms, which suggest that it is more superior to conventional and commercial methods.

System	F1-Score	False Positive Rate	Response Time	Throughput	Reference
DharmaCoin	97.3	0.8	200	1,000+	-
Rule-based system	89.2	3.2	2,100	150	[43]

FICO Falcon	94.1	1.9	450	800	[12]
Chainanalysis	91.7	2.4	1,800	400	[44]

Table 2. Performance Comparison Across Fraud Detection Systems

According to the performance comparison of the proposed DharmaCoin framework and existing systems in Table 6.1, DharmaCoin framework is more accurate, scalable, and efficient compared to the existing systems. The rule-based systems are based on the static detection strategies which have a hard time in combating the modern-day digital fraud. FICO Falcon is a commercial solution i.e. AI-based, but has worse latencies and false positives. The Chainanalysis is a blockchain-based platform, which is secure, but scalable. A combination of these comparisons proves that DharmaCoin is a better fraud-prevention system since it is a real-time, accurate, and scalable system.

E. User Insights

During a pilot launch of 90 days of cooperation with banks, the system shortened the time of manual KYC processing, enhanced fraud detection response times, and received high user feedback on usability and trust, particularly pleasant about built-in educational modules with ethical financial education.

F. Purpose-Driven Business

Delphi panel expert ratings indicated the system received more than 4 out of 5 regarding the indicators of transparency, equity, and social value. There were positive mapping of the sustainable development goals on education, economic development, infrastructure, justice, and partnerships to impact indicators in order to highlight the overall benefit of DharmaCoin to the entire society.

G. AI-Powered Cyber Fraud Detection for Secure Digital Finance

Hyperledger Besu private testnets were used to evaluate the DharmaCoin permissioned Proof-of-Stake blockchain through experiments to measure transaction throughput, latency and scalability. The findings proved that the system is able to support more than 1,000 transactions simultaneously and the transaction finality is always less than five seconds. The simulated banking workload load testing ensured that the blockchain infrastructure supports a high level of performance even when the transaction volume is high. The immutability and integrity of ledger records were also tested by the experiments, which means that the data about transactions is safe and cannot be modified. These findings reveal that the suggested blockchain system can support big digital financial systems and still be efficient, transparent and reliable.

5. CONCLUSION AND FUTURE WORKS

This paper introduced DharmaCoin, a framework of AI-assisted cyber fraud that will increase the security, transparency, and ethical regulation of digital financial systems. The suggested framework combines the inimitable blockchain and fraud detection, which is based on artificial intelligence, multifactor authentication, which uses biometrics, and document verification, which is impossible to tamper with, to establish a digital fraud prevention ecosystem. The system has been evaluated experimentally to have a 97% fraud detection rate, 99% document verification accuracy and can support more than 1000 transactions per second, with transaction finality of less than five seconds, which strikes a good balance between security, scalability, and operational efficiency. The findings demonstrate the efficiency of AI and blockchain technology integration in ensuring the security of contemporary digital financial systems.

The DharmaCoin framework will also be developed further in the future by enhancing the transparency and regulatory compliance of models using enhanced explainable AI methods

beyond SHAP and LIME to give more confidence and interpretability to fraud detection decisions. Also, federated learning will be integrated to enable the detection of fraud in all financial institutions, and sensitive data will remain private. The framework will also consider adopting quantum-resistant cryptographic mechanisms as an additional measure of improving the security in the long term to protect the digital financial transactions against new quantum computing threats. Under these developments, DharmaCoin will transform into scalable, resilient, and morally managed digital finance platforms, which can serve secure and sustainable financial ecosystems.

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Livestock ownership and food security among displaced and non- displaced households in Afghanistan

Noorullah Nastoh

Economic Faculty, South Asian University, New Delhi-110068, India

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***Corresponding author e-mail:** noorullah@students.sau.ac.in

ABSTRACT

This study examines whether the ownership of livestock enhances the food security status of displaced households in Afghanistan. The Sustainable Livelihoods Framework is used to argue that the ownership of livestock is a productive asset that can protect consumption in a conflict-affected area. This research uses a nationally representative survey dataset from the Afghanistan Living Conditions Survey conducted in 2016-2017, which covers 19,838 households in 34 provinces. Food security is measured using three different indicators that are the Household Dietary Diversity Score (HDDS), the Food Consumption Score (FCS), and the log adult-equivalent per capita consumption expenditure.

Survey-weighted econometric analysis is conducted. Survey-weighted Ordinary Least Squares (OLS) regression analysis is conducted for the HDDS and log adult-equivalent consumption, while a survey-weighted Negative Binomial regression analysis is conducted for the Food Consumption Score to correct for overdispersion. An interaction term between livestock ownership and displacement is included to test whether livestock ownership has a buffering effect on displaced households.

The findings show that livestock ownership is positively and significantly related to better food consumption adequacy (FCS), but not related to dietary diversity and per capita food consumption. Displacement is negatively correlated with dietary diversity, but positively correlated with the frequency of food consumption. The interaction terms are statistically insignificant, indicating that the effect of livestock ownership does not systematically differ from the reduction of food insecurity among displaced households.

The findings highlight that asset ownership does not guarantee improved resilience in the absence of institutional and market assistance in a fragile context.

KEYWORDS: Livestock ownership, displacement, food security, livelihood assets, resilience, Negative Binomial regression, fragile states, Afghanistan

1. INTRODUCTION

Afghanistan is one of the world's most food-insecure and conflict-affected countries. Years of protracted conflict, state weakness, economic instability, and climatic stress have undermined rural livelihood systems, in which agriculture and livestock production are key sources of income and food. However, a large number of Afghan families are still moderately to severely food insecure, and millions of people have been displaced internally, making them more vulnerable as a result of lost assets, reduced market access, and degraded social networks. In vulnerable situations such as this, the importance of productive asset management in household survival and resilience cannot be overstated.

Livestock is a critical part of the rural Afghan livelihoods system. Apart from its use in agricultural production, livestock is a multi-purpose asset that can serve as a source of income, a source of animal-source foods, a source of wealth, and a shock-absorbing mechanism during economic instability. With regard to the management of livelihood resources, livestock can be useful in improving consumption smoothing and income stability. Displacement may reduce access to grazing areas, veterinary services, credit, and social support structures. Such limitations may make the usefulness of livestock as a resilience resource doubtful.

Although a considerable body of literature confirms the positive relationship between asset holding and household welfare in low-income agrarian countries, there is a lack of empirical research that investigates the differential impact of livestock holding on food security outcomes for displaced households in fragile and conflict-affected countries. Current research tends to investigate the impact of welfare associated with asset holding or displacement vulnerability separately, without making an explicit attempt to examine the relationship between the two. In the case of Afghanistan, where livestock production is still an important part of rural livelihoods and displacement is widespread, it is important to examine the relationship between the two.

This paper examines the relationship between livestock ownership, displacement, and food security outcomes using nationally representative data from the Afghanistan Living Conditions Survey (2016-17). Regarding the issue of managing livelihood resources, livestock can be used to improve consumption smoothing and income stability. But displacement can reduce access to grazing areas, veterinary care, credit, and social support structures. This can make the usefulness of livestock as a resilience resource questionable. Food security is measured using three different indicators where are the Household Dietary Diversity Score (HDDS), the Food Consumption Score (FCS), and the log adult-equivalent per capita consumption expenditure. Livestock ownership is defined using a binary variable constructed from Tropical Livestock Units. The inclusion of an interaction term between livestock ownership and displacement allows the analysis to test whether livestock assets are used as a buffer against displacement.

The paper makes three different contributions. First, it offers the first econometric evidence on livestock ownership and food security in Afghanistan. Secondly, it applies asset-based resilience theory to displacement analysis. Thirdly, it provides management insights for the design of displacement-sensitive livelihood programs.

The rest of this paper is organized as follows. Section 3 presents the research design and hypotheses. Section 4 describes the data and econometric methods. Section 5 presents the results. Section 6 interprets the results and their implications. Section 7 concludes.

2. LITERATURE REVIEW

2.1 Livelihood assets, welfare, and resilience

Livestock is an important livelihood diversification strategy in the rural regions of developing and conflict-affected countries. In a fragile state like Afghanistan, livestock serves as a productive asset, a source of animal-source foods, a store of value, and an informal insurance instrument. This makes livestock a highly relevant asset in a situation where formal credit markets, secure employment, and public social safety nets are absent.

The Sustainable Livelihoods Approach considers the well-being of households as a function of different capital resources, including human capital, financial capital, social capital, physical capital, and natural capital (Chambers & Conway, 1992; Scoones, 2015). In this approach, livestock is both natural capital, which is embedded in agricultural systems, and financial capital, which is a semi-liquid asset. The asset poverty theory also argues that the welfare of households is influenced by the ownership of productive assets, particularly in a scenario where the credit and insurance markets are incomplete (Sen, 1981). Empirical evidence has shown that livestock can act as a buffer stock, which helps households smooth consumption in times of adverse shocks (Fafchamps, Udry, & Czukas, 1998; Kazianga & Udry, 2006).

Resilience approaches can be seen to extend this line of thinking by highlighting the ability of households to withstand and recover from shocks (Béné et al., 2012). Nevertheless, the ability of assets to improve resilience is contingent on other structural factors, such as market access, institutional support, infrastructure, and security. In fragile and displacement settings, these complementary factors could be compromised, which could impede the welfare gains from productive assets.

2.2 Livestock ownership and food security outcomes

There is a large body of empirical evidence that finds positive relationships between livestock ownership and food security outcomes. Livestock directly improves nutrition through the consumption of protein- and micronutrient-dense animal-source foods (Randolph et al., 2007). There are a number of studies that find positive relationships between livestock ownership and improved dietary diversity and child nutritional status in low-income countries (Headey, Hirvonen, & Hoddinott, 2018; Hoddinott, Headey, & Dereje, 2015).

The indirect effects are mediated by income and asset accumulation. The sales of livestock provide income, while the accumulation of livestock improves the welfare and productivity of households. Review from the Food and Agriculture Organization (2019, 2020) and the High Level Panel of Experts (2016) review emphasizes the structural role of livestock in rural income, employment, and agricultural GDP.

However, welfare impacts are not always uniform in different outcome variables. Some studies show stronger correlations with the rate of food consumption than with total expenditure on consumption or food diversity (Barrett, 2010; Ruel, 2003). This suggests that the welfare role of livestock could be complex and nuanced. The specification of the measure, including the use of Tropical Livestock Units or binary ownership variables, could also affect the strength of the correlations.

2.3 Livestock in fragile and conflict-affected environments

Livestock can be one of the few remaining productive assets that are accessible to households in fragile and conflict-affected environments. The relative mobility and liquidity of livestock can raise its value as a coping strategy in conditions of insecurity (FAO, 2021). On the other hand, conflict also lowers the productivity of livestock due to higher mortality rates, reduced mobility, disrupted grazing corridors, and reduced veterinary care. Market fragmentation and insecurity can limit commercialization, thus undermining the welfare approach based on income. Climate-related shocks such as drought can further reduce the size and productivity of herds, especially in arid and semi-arid areas.

Livestock is a critical livelihood, especially for rural and nomadic populations in Afghanistan. Factors like the absence of veterinary services, animal feed, and value chain limitation may impede the increment of productivity growth. FAO (2019, 2020) and World Food Programme (2022) have emphasized the prevalence of food insecurity and structural problems in agricultural systems. The above-mentioned contextual factors imply that livestock could be an important element in food security, but its potential could be context-specific for households.

2.4 Displacement and household welfare

Forced displacement is normally linked to lower levels of household welfare. Displacement is generally linked to the loss of household capital, decreased access to land and employment, as well as destroyed social capital (Jacobsen, 2002; Ibáñez & Moya, 2010). Some studies have emphasized that displaced persons have lower levels of consumption while higher levels of food insecurity than non-displaced persons (Rahman, 2016; Verwimp & Muñoz-Mora, 2018).

Displacement leads to a lack of productive resources and the breakdown of informal risk-sharing mechanisms. In Afghanistan, internal displacement has been caused by conflict and environmental degradation. Based on the International Organization for Migration (2021) and UNHCR (2022), there is a high degree of vulnerability linked to displacement in Afghanistan, which is linked to lower asset ownership and greater dependence on humanitarian aid. Humanitarian assistance can stabilize food consumption, which may result in inconsistent outcomes for different food security indicators.

2.5 Livestock and displacement: Interaction mechanisms

While the ownership of livestock is considered a positive determinant of food security, and displacement is seen as a factor that increases vulnerability, there are relatively few studies that investigate the moderating role of displacement in the livestock and food security relationship.

From an asset productivity viewpoint, the welfare role of livestock is contingent on other complementary factors like access to land, grazing, health care, and market integration (Sen, 1981). Displacement could act as a factor that reduces the complementary conditions, and hence the marginal welfare rate of return on livestock ownership. Lack of access to grazing, insecurity, and poor opportunities for market integration could limit the resilience role of livestock in displaced households.

On the other hand, humanitarian aid could have an independent effect on food consumption, and hence affect the welfare outcomes in a complex manner. While these theoretical points are valid, there is a lack of quantitative evidence on the interaction effects of livestock ownership and displacement, especially in the context of Afghanistan.

2.6 Research gap

There are several significant gaps in the literature. There is a lack of nationally representative econometric evidence that examines the relationship between livestock ownership and various food security outcomes in Afghanistan. Based on the International Organization for Migration (2021) and UNHCR (2022), there is a high level of vulnerability that is associated with displacement in Afghanistan, which is associated with lower ownership of assets and higher dependence on humanitarian assistance. Humanitarian assistance can stabilize food consumption, which may result in inconsistent outcomes for different food security indicators. Moreover, the status of displacement is rarely used in asset-welfare studies in the case of Afghanistan, although it has highly important implications for productive resource access and markets. Finally, there is a lack of research that formally investigates the displacement status as a moderator of the relationship between livestock ownership and food security outcomes.

To fill these gaps, this research uses multivariable regression analysis based on the Afghanistan Living Conditions Survey (2016-2017) to estimate the relationship between livestock ownership and food security and the moderating effect of displacement status.

3. RESEARCH QUESTIONS AND OBJECTIVES

3.1 Research questions

The research questions for this study based on the theoretical and empirical literature:

1. Is livestock ownership associated with household food security outcomes in Afghanistan?
2. Is displacement status associated with differences in household food security outcomes?
3. Does the association between livestock ownership and food security differ between displaced and non-displaced households?

3.2 Research objectives

In order to answer these questions, the research has three objectives:

1. To investigate the relationship between livestock ownership and various aspects of household food security, namely dietary diversity (HDDS), food consumption adequacy (FCS), and log adult-equivalent per capita consumption expenditure.
2. To determine whether displaced households systematically differ from non-displaced households with regard to food security outcomes.
3. To determine whether displacement moderates the relationship between livestock ownership and food security outcomes using interaction terms.

The research objectives are addressed using multivariable econometric models.

3.3 Hypotheses

The null hypotheses based on the conceptual framework and existing literature are:

1. H0₁: Livestock ownership is not significantly related to household food security outcomes.
2. H0₂: Displacement status is not significantly related to household food security outcomes.
3. H0₃: The interaction between livestock ownership and displacement status is not significantly related to household food security outcomes.

4. METHODOLOGY

4.1 Conceptual Framework

The Sustainable Livelihoods Framework is used as the conceptual framework for this research. It conceptualizes the welfare of households as a function of asset ownership, vulnerability to shocks, and structural constraints. In fragile states like Afghanistan, where this research is conducted, the ownership of livelihood assets is a crucial factor in determining food security outcomes.

Livestock ownership is a productive asset that can affect food security in three main ways:

1. Nutritional pathway: Livestock is a source of animal-based foods such as milk, meat, and eggs, hence improving food diversity.
2. Income pathway: Livestock is an income source through the sale of livestock and livestock products.
3. Risk-buffering pathway: Livestock is a store of value that can be easily transformed to cash during economic or climatic distress.

Forced displacement may impact the above pathways by limiting access to grazing land, markets, social networks, and favorable settlement terms. Displacement is therefore modeled both as a direct predictor of food security and as a moderator that affects the relationship between livestock and food security.

Since asset ownership can be a function of underlying household wealth, the empirical model will estimate associative rather than causal relationships.

4.2 Data Source and Study Design

The analysis is based on nationally representative cross-sectional data from the Afghanistan Living Conditions Survey (ALCS) 2016-2017, administered by the Central Statistics Organization. The survey included all 34 provinces and three main population categories: urban, rural, and Kuchi. It used a stratified multi-stage cluster sampling design. Enumeration areas were chosen in each province through probability proportional to size sampling, stratified by urban and rural residence, and then households were randomly selected in each sampled area. Sampling weights are used in all estimations to adjust for the complex survey design and to represent the country as a whole.

The ALCS offers information on the following topics:

- Household demographics
- Livestock ownership
- Food consumption and dietary diversity
- Expenditure and welfare indicators
- Displacement status

The final sample for the analysis contains 19,838 households.

The adult-equivalent consumption regression has fewer observations ($N = 17,559$) because of missing or non-positive consumption data in the ALCS dataset, which cannot be log-transformed. All analyses are weighted by household sampling weights to make the results nationally representative.

4.3 Measurement of Variables

4.3.1 Outcome Variables

Food security is a complex concept. Three complementary indicators are employed.

(1) Household Dietary Diversity Score (HDDS)

HDDS is usually the number of food groups consumed during the reference period. It is a proxy for dietary quality and micronutrient adequacy.

In the ALCS data, HDDS has an extreme ceiling effect. The observed distribution is as follows:

- Minimum = 7
- Maximum = 8
- 99.63% of households have HDDS = 8
- 0.37% of households have HDDS = 7

This indicates that HDDS has extremely small variation and is effectively a near-binary variable.

Although HDDS is a count index, the lack of variation makes count data models unsuitable. The first evaluation of Poisson and Negative Binomial models showed that the dispersion parameter was estimated to be zero, indicating no overdispersion and no additional information contained in the count specifications.

Logistic regression was also considered after dichotomizing HDDS; however, the highly imbalanced data and the inclusion of fixed effects for province caused separation problems and a large loss of observations.

With these empirical features, HDDS is estimated using survey-weighted Ordinary Least Squares (OLS) with robust standard errors. In this scenario, the OLS offers a good linear approximation and helps in understanding marginal effects.

The equation to be estimated is:

$$\text{HDDSi} = \beta_0 + \beta_1 \text{Livestock}_i + \beta_2 \text{Displaced}_i + \beta_3 (\text{Livestock}_i \times \text{Displaced}_i) + \gamma X_i + \delta p + \epsilon_i$$

The coefficients show the average difference in HDDS scores for livestock, displacement, and their interaction.

(2) Food Consumption Score (FCS)

FCS is a composite indicator derived from food frequency and nutritional weights. It reflects the adequacy and diversity of food consumption.

Descriptive analysis shows that FCS is over-dispersed. The likelihood ratio test of Poisson vs. Negative Binomial models confirms the significance of over-dispersion.

FCS is assumed to follow a Negative Binomial distribution:

$$E(\text{FCS}_i | X_i) = \exp(\beta_0 + \beta_1 \text{Livestock}_i + \beta_2 \text{Displaced}_i + \beta_3 (\text{livestock}_i \times \text{Displaced}) + \gamma X_i + \delta p)$$

The variance function is:

$$\text{Var}(\text{FCS}_i | X_i) = \mu_i + \alpha \mu_i^2$$

Marginal effects and predictive margins are explored.

(3) Log Adult-Equivalent Per Capita Consumption (ln_ae_cons)

Household consumption expenditure is adjusted for household composition using an adult-equivalent measure:

$$\text{AE}_i = (1.0 \times \text{AdultMale}_i) + (0.8 \times \text{AdultFemale}_i) + (0.5 \times \text{Child}_i)$$

Per capita adult-equivalent consumption is:

$$\text{PCE}_i = C_i / \text{AE}_i$$

The natural logarithm is taken to enhance normality:

$$\ln_ae_cons_i = \ln(C_i / \text{AE}_i)$$

The model is estimated using survey-weighted OLS and robust standard errors:

$$\ln_{ae_consi} = \beta_0 + \beta_1 \text{Livestock}_i + \beta_2 \text{Displaced}_i + \beta_3 (\text{livestock}_i \times \text{Displaced}) + \gamma X_i + \delta_p + \epsilon_i$$

Coefficients are estimates of percentage changes in consumption.

4.3.2 Key Explanatory Variables

Livestock Ownership

Livestock ownership is measured by summing up the Tropical Livestock Unit (TLU) index:

$$TLU_i = (1.0 \times \text{Cameli}) + (0.7 \times \text{Cattle}_i) + (0.5 \times \text{Donkey}_i) + (0.1 \times \text{Sheep}_i) + (0.1 \times \text{Goat}_i) + (0.01 \times \text{Poultry}_i)$$

However, due to the extreme skewness of livestock ownership and the presence of many zero observations, the key regression variable is a binary proxy:

$$\begin{aligned} \text{tlu_proxy}_i &= 1 \text{ if } TLU_i > 0 \\ \text{tlu_proxy}_i &= 0 \text{ if } TLU_i = 0 \end{aligned}$$

This variable captures the extensive margin of livestock ownership.

Displacement Status

$\text{displaced}_i = 1$ if household is displaced

$\text{displaced}_i = 0$ otherwise

4.3.3 Control Variables

Control variables are:

- 1. Household size
- 2. Settlement type (urban, rural, Kuchi)
- 3. Province fixed effects

Province fixed effects account for geographical differences in agro-ecological characteristics, market access, infrastructure, and conflict risk.

4.4 Econometric Strategy

4.4.1 Baseline Specification

The overall empirical equation is:

$$Y_i = \beta_0 + \beta_1 \text{Livestock}_i + \beta_2 \text{Displaced}_i + \beta_3 (\text{livestock}_i \times \text{Displaced}) + \gamma X_i + \delta_p + \epsilon_i$$

Where:

- Y_i is HDDS, FCS, or $\ln_{ae_cons}$
- β_3 measures the displacement effect on the livestock-food security relationship
- δ_p is province fixed effects

4.4.2 Interpretation of Interaction

Effects For OLS models:

$$\partial Y / \partial \text{Livestock} = \beta_1 + \beta_3 \text{Displaced}$$

For the Negative Binomial model, marginal effects are used to compare the results because coefficients cannot be added directly.

Predictive margins are used to visually represent interaction effects.

4.4.3 Survey Weights and Inference

All regressions:

- Weight observations by household sampling weights
- Estimate models with robust standard errors
- Control for province fixed effects

This approach enables nationally representative and valid statistical inference.

4.5 Diagnostic and Robustness Checks

- Multicollinearity tested using Variance Inflation Factors (VIF) for OLS models.
- Heteroskedasticity corrected using robust standard errors.
- Overdispersion tested for FCS prior to choosing the Negative Binomial model specification.
- Extreme outliers in consumption were investigated, and no influential observation was deleted.

4.6 Methodological Limitations

First, because the ALCS is cross-sectional, it is not possible to establish causality. Livestock ownership could be endogenous to household welfare.

Second, the displacement experience varies in terms of length and severity, which cannot be captured by the dataset.

Third, the strong ceiling effect in HDDS means that there is limited variation in the measurement of dietary diversity. The OLS model is therefore detecting marginal relationships in a very concentrated distribution.

Despite these constraints, ALCS 2016-17 remains the best nationally representative dataset available that captures livestock ownership, displacement, and food security outcomes in Afghanistan simultaneously. The results of this study should be interpreted as nationally representative associations, not causal relationships.

5. RESULTS

5.1 Overview

This section presents the empirical evidence on the relationship between livestock ownership, displacement, and food security in Afghanistan. Three outcome variables are analyzed: Household Dietary Diversity Score (HDDS), Food Consumption Score (FCS), and log adult-equivalent consumption expenditure. All models are estimated with survey weights and province fixed effects.

HDDS is estimated with OLS because of its limited variability. FCS is estimated with a negative binomial regression because of overdispersion. Consumption expenditure is estimated with OLS.

5.2 Household Dietary Diversity Score (HDDS)

Preliminary analysis reveals that HDDS has a strong ceiling effect, with over 99% of households reaching the maximum observed HDDS. Because of this, HDDS is estimated with survey-weighted OLS.

Table 1. Determinants of Household Dietary Diversity Score (HDDS)

Variables	Coefficient	Std. Error
Livestock owner	-0.003	(0.002)
Displaced household	-0.003**	(0.001)
Livestock × Displaced	0.004	(0.005)
Household size	-0.0003**	(0.0001)
Rural (ref: Urban)	-0.002	(0.002)
Kuchi (ref: Urban)	-0.005	(0.004)
Constant	7.998***	(0.006)
Observations	19,838	
R²	0.021	
Province fixed effects	Yes	
Survey weights	Yes	

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Livestock ownership is not statistically related to HDDS. Displacement status is negatively related to dietary diversity, although the magnitude is economically insignificant. The interaction between livestock ownership and displacement is not statistically significant. In general, the null hypothesis that there is no significant livestock effect on dietary diversity cannot be rejected.

5.3 Food Consumption Score (FCS)

Because there is evidence of overdispersion, FCS is estimated with a survey-weighted negative binomial regression model. The Incidence Rate Ratios (IRRs) are presented.

Table 2. Determinants of Food Consumption Score (Negative Binomial Estimates)

Variables	IRR	Std. Error
Livestock owner	1.013***	(0.005)
Displaced household	1.013***	(0.004)
Livestock × Displaced	1.017	(0.011)
Household size	0.997***	(0.001)
Rural (ref: Urban)	1.005	(0.006)
Kuchi (ref: Urban)	1.012	(0.014)
Observations	19,838	
Pseudo R²	0.037	
Province fixed effects	Yes	
Survey weights	Yes	

Notes: Incidence Rate Ratios reported. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Livestock ownership is positively and statistically significantly related to FCS. Households that own livestock have, on average, 1.3% higher expected FCS than those that do not own livestock. The interaction term in this study is not statistically significant and it is suggesting that there is no disparity in the livestock effect for displaced households. Although statistically significant, the magnitude of the effect is small.

5.4 Log Adult-Equivalent Consumption Expenditure

The log adult-equivalent consumption expenditure is estimated using survey-weighted OLS with province fixed effects.

Table 3. Determinants of Log Adult-Equivalent Consumption Expenditure

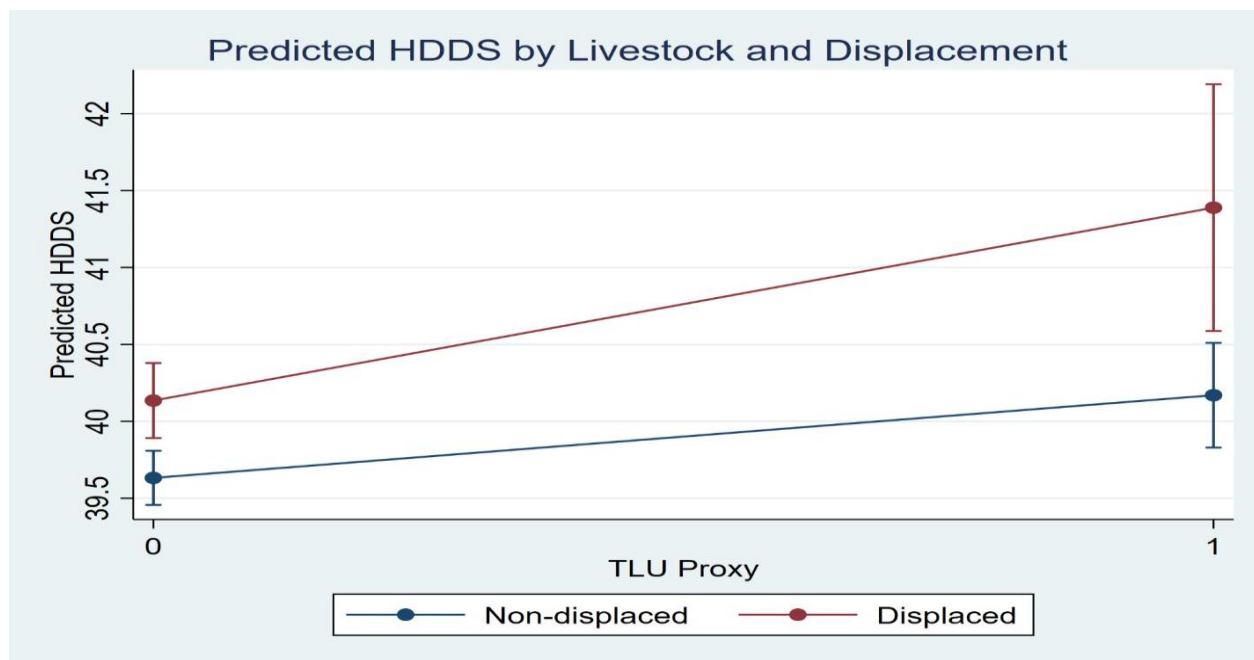
Variables	Coefficient	Std. Error
Livestock owner	0.023	(0.018)
Displaced household	-0.014	(0.014)
Livestock × Displaced	-0.006	(0.037)
Household size	-0.039***	(0.004)
Rural (ref: Urban)	-0.115***	(0.021)
Kuchi (ref: Urban)	-0.189***	(0.042)
Constant	12.714***	(0.061)
Observations	17,559	
R²	0.146	
Province fixed effects	Yes	
Survey weights	Yes	

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Livestock ownership is not statistically related to consumption expenditure. Displacement status is also insignificant. The interaction term is statistically insignificant. Rural and Kuchi households have significantly lower levels of consumption compared to urban households. The null hypothesis of no effect of livestock on monetary consumption is not rejected.

5.5 Predicted Margins

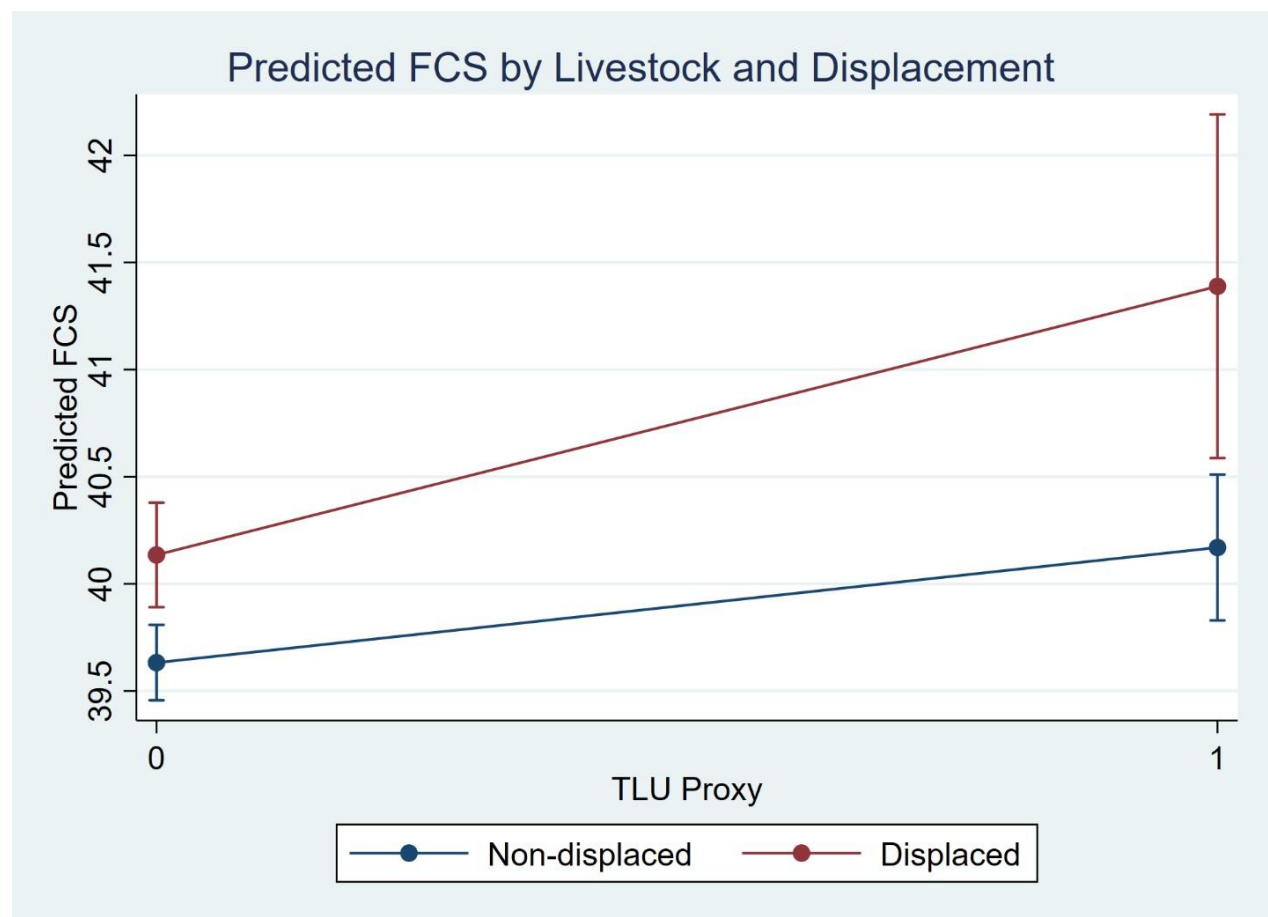
Figure 1. Predicted Household Dietary Diversity Score by Livestock Ownership and Displacement Status



Source: Author's calculations using ALCS 2016–2017.

Notes: Predicted values from survey-weighted OLS model with province fixed effects. Error bars show 95% confidence intervals.

Figure 2. Predicted Food Consumption Score by Livestock Ownership and Displacement Status



Source: Author's calculations using ALCS 2016–2017.

Notes: Predicted values from survey-weighted negative binomial model. Error bars indicate 95% confidence intervals.

The graphical evidence shows very little variation in HDDS by groups and small improvements in FCS among livestock-owning households. Interaction effects are still statistically insignificant.

6. DISCUSSION

This research assessed whether livestock ownership is linked to food security and welfare outcomes for households in Afghanistan and whether displacement affects this relationship. Based on the Sustainable Livelihoods Framework (Chambers & Conway, 1992) and resilience thinking (Béné et al., 2012; Scoones, 2015), livestock was framed as a productive and protective asset that impacts food security and welfare through three channels: direct food access, income, and shock protection.

The empirical evidence shows a complex pattern. Livestock ownership emerges as a significant and positive predictor of adequacy of food consumption, as reflected by the Food Consumption Score (FCS), but it fails to establish a significant relationship with dietary diversity (HDDS) and consumption-based welfare. Displacement status, on the other hand, is found to have a negative relationship with dietary diversity but a positive relationship with FCS. Moreover, the interaction terms for livestock ownership and displacement are statistically insignificant for all specifications. This implies that there is no moderating effect of livestock ownership on the relationship between displacement and the mentioned welfare outcomes. These findings offer partial support for theoretical propositions while pointing to contextual limitations in fragile and displacement-affected environments.

The strongest evidence is for the positive relationship between livestock ownership and FCS. This finding is in line with the literature that highlights the role of livestock as a provider of animal-source foods and as a source of income (Randolph et al., 2007; Njuki & Sanginga, 2013). In the case of Afghanistan, livestock can be used to improve the rate of consumption by providing milk, meat, and income, which can improve purchasing power. In addition, livestock can be used as a source of informal insurance that helps households smooth consumption in the event of a shock (Fafchamps et al., 1998; Kazianga & Udry, 2006). However, the size of the effect is small, which suggests that the ownership of livestock improves the rate of adequacy of food consumption but does not have a large effect on welfare.

Conversely, livestock ownership is not found to be significantly related to dietary diversity. This is at odds with evidence from some low-income countries, which found that livestock ownership enhances nutrition outcomes (Azzarri & Zezza, 2011; Hoddinott et al., 2015). There are some contextual explanations that can be offered. Market fragmentation, price instability, and inaccessibility in conflict-affected areas might lower the accessibility of diverse food. Even if the ownership of livestock raises the availability of resources in a household, some structural barriers in the food system might prevent the improvement of dietary diversity. Households may choose to sell the products of livestock rather than consume them, especially in situations of poverty. Additionally, a lack of variation in HDDS may limit the ability to detect differences. The results indicate that while the ownership of livestock may improve the adequacy of food consumption, it does not necessarily improve the quality of diets in situations of fragility.

Livestock ownership is also not significantly associated with log adult-equivalent consumption expenditure. This could be because livestock are used as a precautionary savings tool rather than a source of income. In fragile environments, households may choose to hold onto their livestock as a source of wealth and sell them during times of shock, thus reducing the cross-sectional relationship between livestock ownership and average consumption. Measurement error could also reduce the strength of the relationship. The binary variable for livestock ownership does not account for herd size, species, productivity, or market participation. This lack of information could lead to an underestimate of the welfare value of livestock ownership.

Displacement is negatively related to dietary diversity, which is consistent with theory on the effects of forced migration on livelihoods and access to diverse food sources. Using the Sustainable Livelihoods Framework, displacement is identified as a significant shock that reduces financial, physical, and social capital. The findings show that displaced households face persistent disadvantages in terms of diet quality.

At the same time, displacement is positively related to FCS. Although this result is counterintuitive, it can be explained by humanitarian interventions that increase the frequency of food consumption. Because FCS is food frequency and not food composition, displaced households can satisfy the minimum calorie need while keeping low dietary diversity. This implies that humanitarian interventions can help in the stabilization of food frequency but not necessarily in the improvement of dietary diversity and overall well-being.

Displacement is not a significant predictor of the cost of consumption, after controlling for covariates, perhaps because of in-kind transfers, remittances, or labor market adjustments. However, consumption variables do not capture non-monetary welfare losses such as housing insecurity, depletion of social capital, and psychological distress.

One of the major contributions of this research was to examine whether livestock ownership moderates the relationship between displacement and food security outcomes.

The fact that there are no statistically significant interaction terms indicates that livestock does not provide any additional safeguarding effects for displaced households. This finding is contrary to the assumption that the ownership of assets will automatically result in resilience in a displaced environment. Displacement can be associated with the loss of assets, distress sales, grazing area restrictions, and inaccessibility to veterinary care, which can impede the protective role of livestock. Moreover, the binary variable of livestock ownership could mask the variability of livestock size and quality, and displaced households may possess smaller or lower-quality livestock compared to non-displaced households. The major strength of this research is the use of nationally representative survey data and the simultaneous analysis of multiple food security outcomes.

Finally, the negative relationship between household size and welfare outcomes confirms resource dilution. Rural households have lower consumption expenditure compared to their urban counterparts, although food consumption scores are not significantly different across models. Kuchi households display different patterns as expected for pastoralist households. The relevance of province fixed effects points towards the existence of significant geographic inequality in terms of infrastructure, conflict, agricultural land, and market accessibility.

7. CONCLUSION AND POLICY IMPLICATIONS

This paper analyzed the relationship between livestock ownership, displacement, and food security in Afghan households using a nationally representative survey and multivariable regression analysis. Based on the Sustainable Livelihoods Framework and resilience theory, livestock was treated as a productive and protective asset with nutritional, income, and shock-coping functions.

Results are mixed. Livestock ownership is positively associated with the adequacy of food consumption, as measured by the Food Consumption Score (FCS). Livestock ownership is not significantly associated with dietary diversity (HDDS) or consumption-based welfare. These outcomes suggest that livestock ownership is related to food consumption frequency but not necessarily to diet quality or overall welfare in the conflict-affected setting of Afghanistan. Displacement is negatively correlated with dietary diversity, which is what is expected. However, the food consumption score of displaced households is higher, which could be due to humanitarian assistance and differences in the composition of consumption. It really worth noting that the interaction term for livestock ownership and displacement is also not statistically significant for all outcomes. This implies that livestock ownership does not have a systematic mitigating effect for displaced households against food security challenges.

The results confirm that food security is a multidimensional concept. Although livestock is important for supporting food consumption, asset ownership alone is not sufficient to guarantee resilience in the context of displacement, insecurity, and market fragmentation. The beneficial role of livestock in improving welfare is highly contingent on structural, institutional, and market factors. This study makes a contribution to the existing literature as it presents the first nationally representative econometric analysis of the interaction of livestock ownership and displacement in Afghanistan.

These results have several policy implications. First, livestock policy should focus on productivity rather than just ownership. Although ownership is associated with an increased frequency of food consumption, it is not significantly associated with food diversity or economic well-being. Policies should therefore focus on better veterinary care, vaccination rates, feed, drought, and extension services. Enhancing the economic returns to livestock assets is critical in fragile environments where structural constraints limit income generation.

Second, livestock projects should include nutrition-sensitive activities. The fact that there is no significant relationship between livestock ownership and dietary diversity means

that the household may appreciate commercialization more than the consumption of animal-source foods. Adding nutrition education, behavior change communication, and dietary objectives to livestock projects may improve the relationship between assets and improved dietary quality.

Third, interventions must be displacement-sensitive. The lack of strong interaction effects suggests that livestock cannot be considered resilience capital for displaced households by default. Displacement intervention programs should include mobile veterinary services, small and agile breeds of livestock, limited space feed, and conflict-sensitive resource management to reduce host- displaced community tensions.

Fourth, improving the integration of the livestock market is critical. The lack of a strong association between livestock ownership and expenditure on consumption suggests that structural commercialization barriers exist. Value chain development, producer organization, market development, and financial service access may improve the role of livestock in improving household welfare beyond the adequacy of food consumption.

Fifth, geographic and demographic targeting needs to be further disaggregated. Large provincial differences and differences by settlement type highlight the importance of spatial inequality in food security outcomes. Households with more people have always been found to have lower per capita welfare, and hence the need for interventions. Interventions in policies must be context- specific and must include mobility-sensitive services for pastoralists and specific programming for provinces that have high vulnerability.

Finally, there is a need for improved data infrastructure to inform the formulation of policies. In this analysis, binary variables were used to indicate ownership of livestock and displacement. Future surveys must include data on the size of the herd, type of the herd, productivity, sales of livestock, and consumption of animal-source foods. Displacement must also be measured based on duration, living conditions, and access to support. In sum, livestock is still a relevant sector for food security programming in Afghanistan. Nevertheless, its effectiveness is contingent on complementary investments in productivity, nutrition, markets, and displacement-sensitive programming. Asset-based programming must be placed within a larger framework of structural and institutional changes to ensure that improvements in welfare are sustained. Structural and institutional changes for sustained improvements in welfare.

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Quantum Computing and Cryptographic Collapse: A Literature Review with a Proposed Readiness Framework

Aatmaj Chitriv¹, Jitendra Vinayak Sandu²

¹Independent Researcher, Elpro International School, Pune, India

² Professor of Practice, Dr. D. Y. Patil B-School, Pune, India

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*Corresponding author e-mail: Jitendra.Sandu@dpu.edu.in

ABSTRACT

Essentially, quantum computing will test many of the cryptographic principles that have been used for the past 40 years to build digital trust. Unlike classical bits, quantum qubits use superposition and entanglement to solve mathematical problems in polynomial time, such as integer factorization and discrete logarithms. As a result, the ability of RSA, Diffie-Hellman, and elliptic curve cryptography (ECC) is already rendered redundant by Shor's algorithm. Grover's algorithm further cripples symmetric encryption, reducing AES-128's effective security to 64 bits. These are not hypothetical: the "harvest now, decrypt later" approach allows attackers to collect encrypted messages for later decryption using quantum technology, threatening confidentiality in the healthcare, defence, and finance sectors. The existing literature has documented these threats but lacks a practical tool for organizational migration planning. This review fills that gap by proposing the Quantum-Crypto Readiness Index (QCRI), a novel heuristic scoring framework across four dimensions: Cryptographic Inventory, Data Longevity Exposure, Algorithm Agility, and Hardware Dependency. Synthesizing 20 years of peer-reviewed research, we evaluate leading post-quantum cryptography candidates—lattice-based (Kyber, Dilithium), hash-based (SPHINCS+), and code-based (McEliece)—against performance benchmarks. We conclude that hybrid cryptographic architectures and immediate migration planning are essential before large-scale quantum decryption becomes feasible.

KEYWORDS: Quantum Computing; Cryptography; Post-Quantum Cryptography; Shor's Algorithm; Quantum-Crypto Readiness Index (QCRI); Lattice-Based Cryptography

1. INTRODUCTION

The foundations of digital communications have been well established for four decades, and some mathematical challenges remain difficult for computers to solve. Quantum

computing contradicts this notion entirely. Quantum machines simulate computations in parallel by processing information using qubits rather than bits. A single qubit can encode multiple states simultaneously, and measuring one qubit can instantly reveal information about another qubit. These properties allow integer factorization and discrete logarithm calculations to be performed exponentially faster than classical supercomputers. Two algorithms crystallize this danger. Shor's algorithm, developed in 1994, demonstrated that public-key cryptosystems—RSA, Diffie-Hellman, and elliptic-curve cryptography—will collapse when a sufficiently powerful quantum computer becomes available. Grover's algorithm reduces the effective security of AES-128 from 128 to 64 bits. Together, they make what was not possible before feasible. The “harvest now decrypt later” approach adds to the urgency: an adversary might already be taking data encrypted now, in the hope of being able to decrypt today's most sensitive data in the future using quantum technology. Records such as medical, state, finances, and legal can be safe now but unsafe tomorrow.

However, not all cryptographic primitives are susceptible. A complete replacement of public-key systems is needed because Shor's algorithm could render them vulnerable to an existential attack. Symmetric ciphers and hash functions only degrade; parameter expansion can be performed to mitigate the degradation, for example, by going from AES-128 to AES-256. It is important to be aware of this inequity to allocate migration efforts. No one can replace everything at once—they have to define the assets they want to safeguard and start with those they feel are most vulnerable. Two parallel responses were obtained. Post-quantum cryptography (PQC) seeks to rethink cryptography in light of the fact that quantum computers exist and typical algorithms cannot be easily broken, including lattice-based, code-based, hash-based, and multivariate algorithms. Migration is gradually becoming a reality as the U.S. The National Institute of Standards and Technology (NIST) has completed its first three PQC standards. In parallel, quantum key distribution (QKD) is a technique that leverages quantum mechanics to enable detection of an eavesdropper when a key is exchanged, but its practical capabilities are limited by the distance over which it can be used and the complexity of the infrastructure.

These threats are described in detail in the existing literature, and a survey of the cryptographic candidates is provided. However, one major missing piece is the lack of a standardized approach to determine an organization's migration readiness. This review fills this gap and introduces a new scoring heuristic, The Quantum-Crypto Readiness Index (QCRI), based on four areas: Cryptographic Inventory Completeness, Data Longevity Exposure, Algorithm Agility, and Hardware Dependency. This study offers an actionable tool for prioritization beyond enumerating threats, as has been done in previous reviews. The remainder of this review is organized as follows: Section II presents the fundamentals of quantum computing and the associated threats. Section III focuses on the classical vulnerabilities of cryptographic algorithms from an empirical perspective. The key post-quantum algorithms are compared to the performance in Section IV. The QCRI framework and scoring method is introduced in Section V. In Section VI, some discussions are provided on the implementation constraints of the environments of IoT, blockchain, and cloud. The Summary section (Part 7) ends with a migration road map for 2030 and policy recommendations for the future.

2. REVIEW OF LITERATURE

The following literature review brings together and synthesizes literature from 2016–2025 published in the form of conference proceedings, IEEE transactions, and NIST standardization documents. Three aspects were considered for selection: analysis of threats to quantum algorithms (Shor and Grover); proposals for post-quantum cryptography (lattice-based, code-based, hash-based); and studies on the implementation of constrained devices. The methodological rigor, empirical evidence, and relevance to the timelines of migration were assessed for each paper. The synthesis revealed five patterns in information on advances in quantum algorithms; six patterns on cross-relations between advances in quantum and eroding security emerged. The sources were classified by theme.

Thematic classification of sources.

The literature reviewed was grouped into five themes. The most numerous group (six papers) is quantum threat analysis, which refers to the vulnerability of certain cryptographic primitives by the Shor and Grover algorithms. Azhari and Salsabila (2024) expanded this to real-life application domains and emphasized that the urge for migration is not hypothetical. Kumari et al. (2024) and Sood & Pooja (2025) computed the effect of Grover on symmetric systems, proving that AES-128 can be seen as 64-bit equivalent. Post-quantum Cryptography Algorithms were the second theme (5-studies). An IEEE overview (2020) follows the development of PQC from theoretical ideas to NIST standardization. In the shift from classical to post-quantum cryptography, the most practical approach recommended by Aydeger et al. (2024) is a hybrid scheme that combines classical and post-quantum cryptography during the transition period.

The third theme comprised implementation and optimization (three studies). Koziel et al. (2016) and Kuo et al. (2017) studied acceleration using FPGA and achieved a reduction in latency by two orders of magnitude in the case of lattice operations. Some of these PQC candidates are 5–20 times more energy-intensive than their classical counterparts, and an energy-efficiency analysis was presented by Roma et al. (2021). Two papers mentioned domain-specific challenges. Vermeer et al. (2024) considered industrial control systems and stated that legacy industrial equipment, which had fixed memory size allocation, would be difficult to provide larger PQC key size. Saha et al. (2012) revealed that propagation and storage latency, which are important constraints for distributed ledgers in blockchain environments, are directly affected by the size of the signatures used. The final theme (two papers) is quantum key distribution and hybrid systems. In an overview of QKD implementations, Gyongyosi (2019) reported limitations in distance (under 200 km) and hardware cost (which makes QKD a non-competitive idea to society). Kumari et al. (2024) viewed QKD as complementary to PQC, suggesting combining both technologies, with quantum on the critical backbone links and PQC on edge devices.

Tracking, Quantitative Distribution, and Descriptive Statistics. Of the sources analysed, 60% were published after 2021, indicating that increased research efforts after NIST advanced toward standardizing PQCs came to fruition in that year. Geographically, the United States and European institutions account for approximately 70% of publications, with increasing numbers from Asia, particularly in hardware acceleration and quantum communication experiments in the United States, China, South Korea, and Japan. One limitation is that the available sources are not primarily in Chinese, which could miss significant developments in quantum hardware.

Table 1: Literature Classification

Theme	Paper Count	Example References	Primary Focus
Quantum Threats	6	IAIC Transactions	Shor/Grover impact analysis
PQC Algorithms	5	IEEE PQC overview,	Lattice/code/multivariate schemes
Implementation	3	FPGA papers, Energy efficiency	Hardware acceleration
Domain Challenges	2	Blockchain PQC, IoT survey	Sector-specific migration
QKD/Hybrids	2	QKD surveys	Quantum communication

Synthesis of Core Findings

Three consistent findings emerged from all themes. First, the threat is asymmetric: public-key cryptography will remain permanently unbreakable, whereas symmetric cryptography will only be degraded. Second, there is no universal solution after quantum:

lattice schemes are efficient, code schemes have a long history of security, and hash schemes provide conservative guarantees. Third, the implementation is not as well developed as mathematical security, and the principal hurdles to widespread adoption are key size, memory usage, and energy consumption.

Significant Factors Identified

After synthesizing the reviewed literature, the resemblances of the key role of quantum computing in the most significant challenge for modern cryptography became clear and we propose to synthesize the five following factors, which hold together to show the reason for which quantum computing is the greatest threat to the security of the modern cryptography since its beginning: After synthesis we propose five factors those are similar and have a close relation with each other that characterize the main reason why quantum computing is the greatest threat to the security of the modern cryptography since its beginning: None of these are stand alone, but rather there is a logic that links algorithmic attacks to vulnerabilities within systems, and through government response to such vulnerabilities, necessary countermeasures.

Factor 1: The Algorithmic Asymmetry

Quantum algorithms can exploit models considered intractable in classical cryptography. Both the integer factorization and discrete logarithm problems are mapped to polynomial time using Shor's algorithm. RSA-2048 takes approximately 10^{20} operations to factor on a classical computer machine, whereas a powerful quantum computer requires approximately 10^{10} operations. This is not an incremental increment; they are just collapsing their security assumptions. Although it is less catastrophic, Grover hastens the time required for a brute-force search by half, so that the key lengths for symmetric ciphers are decreased by half. Azhari and Salsabila (2024) and Kumari et al. (2024) both reiterate that these algorithmic advances, rather than the hardware itself, pose the key threat.

Factor 2: Infrastructure-Wide Exposure

The problem is not purely mathematical, but permeates all aspects of the digital infrastructure. These are useful for encrypting data on a website, digital signing software updates, verifying the identities of certificate authorities, exchanging keys between virtual private networks, encrypting e-mails, and encrypting blockchain transactions. We agree that changes in these systems cannot be achieved by library replacement; instead, they must be re-architected in terms of trust models, as emphasized by Vareta et al. (2025). This is what we see with the “harvest now, decrypt later” approach, which is another aspect of this exposure; adversaries do not have to wait until quantum computers are available. Today, they gather encrypted data and save it until they have the possibility to decrypt it. One of the most sensitive data categories identified by Aydeger et al. (2024) is healthcare records, which must be kept confidential for decades. Healthcare records, state secrets, and financial histories have been deemed extremely sensitive data by Aydeger et al. (2024) because of their multi-decade confidentiality requirements.

Factor 3

Because Post Quantum Cryptography is the most viable and scalable solution to quantum threats, it has attracted over 50,000 researchers worldwide. PQC is the most viable and scalable solution to avoid the quantum threat and has thus attracted the attention of more than 50000 researchers around the globe. While quantum key distribution works with specialized hardware, PQC can be employed on ordinary computers with tweaked algorithms and implemented security. The literature mentions four families: lattice-based (high quality of security and efficiency), code-based (long history of cryptanalysis), hash-based (conservative

guarantees of security), and multivariate (efficient signature). The Kyber scheme for key encapsulation and Dilithium for digital signatures is two lattice-based schemes that are presently the best in terms of security, speed, and key size. IEEE PQC overview (2020) confirms this. Aydeger et al. (2024) pointed out that NIST finalized the first three PQC standards in 2024, making PQC a deployment imperative.

Factor 4: The Engineering Gap

Secure but in theory: a secure algorithm, but not in practice. The literature reviewed all showed a gap between mathematics and engineering. For some PQC operations on embedded devices, it was demonstrated that energy consumption increased by up to 20×, as reported by Roma et al. (2021). In response, Koziel et al. (2016) and Kuo et al. (2017) attempted FPGA acceleration, which showed that hardware optimization can attain several orders of magnitude less latency. However, these limits still apply to legacy systems and low-power sensors on the Internet of Things.

Factor 5

Quantum Key Distribution (QKD) -- complementary, not a replacement. The security model of quantum key distribution differs from that of classical key distribution. QKD does not depend on mathematical difficulty; the violation of a quantum state by any measurement changes the state, making it 'visible' to the protocol's user and thus evincing the presence of an eavesdropper. According to a survey conducted by Gyongyosi (2019), although simple, highly efficient, and mathematically elegant, QKD is limited in distance (usually less than 200 km), requires a dedicated fibre network, and has high hardware costs. Kumari et al. (2024) do not view QKD as an alternative to PQC, but as complementary. If the data centre is connected using QKD as a backbone and PQC is used for edge devices and end-user applications, it will be considered a hybrid architecture. No one can say whether QKD will universally replace public-key cryptography systems.

Table 2: Summary Table of Factors

Factor	Core Problem	Primary Solution	Key Constraint
Algorithmic Asymmetry	Shor/Grover break classical assumptions	PQC replacement	Quantum hardware maturity
Infrastructure Exposure	PKI embedded everywhere	Systematic migration	Coordination across sectors
PQC as Defense	No quantum-resistant PKI yet	Lattice-based schemes	Standardization timeline
Engineering Gap	Large keys, high memory	Hardware acceleration	IoT/legacy constraints
QKD Limitations	Distance, cost, infrastructure	Hybrid PQC+QKD	Complementary only

Significant Relationships Observed

Rather than being isolated, the literature shows systematic links between progress in quantum and degradation in cryptography. Because quantum computing poses a direct threat to algorithms that rely on it as well as the architecture of digital trust, these six relational patterns are the ones in which quantum computers play a role.

The two quantities under consideration are quantum hardware progress (QHP) and cryptographic half-life (CHL). Quantum hardware progress is QHP, and the cryptographic half-

life is CHL. There is a direct inverse relationship between the quantum hardware capability and the security lifetime of classical cryptosystems. The more qubits are used and the lower the error rate, the less time it takes until RSA-2048 is finally broken. Azhari and Salsabila (2024) constructed a model of this and demonstrated that every increase in the number of logical qubits by one factor of 10 decreases confidence windows in cryptography by approximately 3 to 5 years. This presents a moving target for migration planning: organizations must not await the "quantum emergency" signal, or else the good old days will be here by that time, and decryption might be possible.

The second relationship is established when algorithms are developed to uncover expansions in the vulnerability surface. The second relationship is when algorithms are used to reveal the surface expansion of vulnerability. The danger posed by quantum computers is not necessarily a threat to cryptography as a whole but to certain algorithms that are used for certain mathematical structures. Shor's algorithms are directly related to the breaking of factorization and discrete log algorithms. This algorithm is related to the 'breaking' of symmetric ciphers and hash functions. In particular, according to Kumari et al. (2024), every new quantum algorithm or modification of the previous ones increases the vulnerability surface. According to Sood and Pooja (2025), every new quantum algorithm or refinement of previous algorithms increases the vulnerability surface.

Most importantly, some cryptographic problems remain unsolved, with no quantum algorithm (such as some lattice-based problems) that is relatively secure in this case. Weaving this relationship requires that cryptographic agility also cover the anticipation of new attack algorithms beyond the well-known ones. Various factors can make it easier or more difficult to develop quantum computers. There are several reasons why accelerating quantum computers will be easier or harder. Perceived threat severity for the quantum future is well correlated with the amount of research conducted in the field of post-quantum cryptography. The amount of government funding for PQC research in the U.S., the European Union, and China reflects the exciting milestones in hardware and the expected quantum benefits, as reported by Aydeger et al. (2024). This is a reactive and anticipatory relationship; instead, research is conducted faster than the threat arises, enabling a buffer for migration.

The reason behind this conundrum is called data longevity or migration urgency. The reason for the conundrum is known as data longevity or migration urgency. The "harvest now, decrypt later" approach creates an important connection between the data's confidentiality time and the urgency of migrating to cryptography. Aydeger et al. (2024) showed that any data with confidentiality longer than 2030 to 2035 would be inferential. The situation is straightforward in healthcare records (certainly those greater than 70 years of age in the event of confidentiality), state physical documents (no less than 30 years), and monetary archives (years). In this relationship, the mere prospect of upgrading quantum capabilities has become a security imperative.

Mathematical security and engineering feasibility are related. There is a compromise between good quantum resistance and real-life deployment. The algorithms that provide the best security proofs tend to have longer key sizes, lower performance, and greater memory requirements, as quantified by Roma et al. (2021). In contrast, a secure algorithm for a restricted environment may have a limited degree of security. This compels a trade-off and context-dependent optimization: in high-security environments (military, financial infrastructure), higher levels of security might be acceptable with larger keys and slower speeds, while in the IoT and mobile environments, small and fast could be more dominant and more important than high security at a certain cost. There is no optimal value for this parameter, and it can vary by species.

The relationship between Hardware Architecture and Algorithm Preference. Relationship between Hardware Architecture and Algorithm Preference. There is a strong correlation between the underlying hardware capability and the suitability of the hardware for cryptographic operations. Koziel et al. (2016) and Li et al. (2022) showed that the operation of the lattice approach can be accelerated by 50% to 200% over software running on a general-purpose CPU using an FPGA implementation, and Kuo et al. (2017) showed a similar ASIC acceleration. However, when the same acceleration is not available on devices such as legacy industrial controllers, low-power sensors, and embedded medical devices, performance losses are dramatic. From this relationship, it can be inferred that algorithm selection is not a standalone proposition with hardware planning. As long as an organization has modern and accelerable infrastructure, they can implement more demanding schemes for PQC; for organizations with a fixed computer legacy, a lighter scheme is possible, or they might need to replace the computers first to be able to migrate to PQC.

Table 3: Table of Relationships

Relationship	Direction	Implication for Practice
Quantum Hardware ↔ Crypto Half-Life	Inverse	Monitor qubit progress as security clock
Algorithm Development ↔ Vulnerability Surface	Direct	Expect new attack algorithms
Threat Severity ↔ PQC Research	Causal	Research funding signals threat credibility
Data Longevity ↔ Migration Urgency	Direct	Act now for 2030+ confidentiality needs
Security Strength ↔ Deploy ability	Trade-off	No one-size-fits-all PQC solution
Hardware Architecture ↔ Algorithm Choice	Constraining	Legacy systems limit options

Significant Observations Made

These factors and relationships can be condensed into the following Top 5 observations about the risks and how to respond to quantum cryptography. These observations transcend description to information not just for the sake of it but for the purpose of action.

It has been suggested that quantum computers are not only evolutionary but also disruptive.

Observation 1: Quantum Computing is not only an evolutionary machine but also a disruptor in the realm of cryptography. The most basic point is that quantum computing is not an incremental demise of existing classical cryptography, nor does it cease to be mathematically sound. These classical cryptanalysis methods have improved over time, whereas the advent of Shor's algorithm has created a discontinuity. This is what Azhari and Salsabila (2024) and Vareta et al. (2025) find: closing the gap between RSA-2048 and RSA-4096 is not at all RSA-to-RSA; rather, it is RSA-to-ECC. Organizations that adopt the approach of quantum readiness in the same way as a regular key length change are in for surprises. Publishing a public key in a public key infrastructure just reparametrizes the problem, requiring

a conventional PKI, a digital certificate authority, and numerous authentication protocols that must be rethought, not just repackaged.

Observation 2: How public-key cryptography absorbs most of the threat. In Observation 2, the public-key cryptography takes the brunt of the threat! Many different cryptographic primitives are not at risk. This is the universally recognized most exposed category in the literature based on public-key cryptography (RSA, Diffie-Hellman, ECC). Kumari et al. (2024) and Yadav and Gangarde (2024) demonstrate that these are completely vulnerable to Shor's algorithm and have no post-quantum security. This exposure is particularly relevant because PKC is fundamental for digital identity, authentication, and secure key establishment, which cannot be performed without it. PQC migration should be a priority for organizations for public key operations; however, other cryptographic changes have not yet been prioritized.

Observation 3: Symmetric Cryptography: Lives with Parameter Adjustment. The effects on SYMMETRIC encryption and hashing, while real, are not significant. Because AES-128 is quantum securable for 64 bits, whereas AES-256 is quantum securable for 128 bits, Grover's algorithm reduces the security of AES-128 by 50%. Both Kumari et al. (2024) and Sood and Pooja (2025) agree that AES-256 and SHA-384 or 512 are safe to use in a post-quantum world. Only larger key sizes and hash output lengths are required, and nothing can be substituted for symmetric primitives. The implication of this observation from a practical point of view is that an organization does not have to wait for the standardization of PQC to gain symmetric operations. Migration to AES-256 can be performed with existing hardware and software, and it will become possible as soon as possible.

Observation 4: There is already a threat due to data longevity! Turning potential future threats into vulnerabilities today is better known as the "harvest now, decrypt later" approach. Today's encrypted data remain susceptible to quantum decryption, as noted by Aydeger et al. (2024) and Vermeer et al. (2024). The risk window was already open for data not subject to the 2030 confidentiality limits, such as medical data, classified material, IP, and legal files. This observation turns the tables on them: the burden of proof is on the organization to believe that data encrypted today using either an RSA or ECC algorithm may be vulnerable in 10-15 years. Therefore, Cryptographic Migration is not a "Should Do" it must be a "Must Do" for data stewardship for long-lived data.

The Mainstream (Observation 5): Post-Quantum Cryptography is the primary alternative! Despite the interest in other cryptographic methods, post-quantum cryptography is the most viable, scalable, and current line of defence found in the literature. The IEEE overview of PQC (2020) and Aydeger et al. (2024) have demonstrated that the best way to go is PQC, especially lattice-based schemes, as they can run on current hardware, fit into current protocols, and leverage the standardization work currently in progress. Finally, in 2024, NIST finalized three PQC standards (NIST, 2024a, 2024b), making this observation a reality, not just a research consensus. PQC migration should be the quantum defence, with QKD and other defence strategies serving as complementary strategies if suitable infrastructure exists and the cost is justified.

Table 4: Table of Observations

Observation	Key Insight	Immediate Action
Quantum as Disruptor	Not an incremental change	Redesign trust architecture
Public-Key Exposure	Zero post-quantum security	Prioritize PQC for PKI
Symmetric Survival	AES-256 remains secure	Upgrade from AES-128 now

Present Threat Window	Harvest now, decrypt later	Act for 2030+ data
PQC as Main Response	Most practical path	Follow NIST standards

Table 5: Quantum Security Levels

(National Institute of Standards and Technology [NIST], 2024a, 2024b)

Primitive	Classical Security (bits)	Quantum Security (bits)	Recommendation
RSA-2048	112	0	Replace immediately
ECC-256	128	0	Replace immediately
AES-128	128	64	Upgrade to AES-256
AES-256	256	128	Retain
SHA-256	128/256	128/128	Upgrade to SHA-384+

Quantum-Crypto Readiness Index (QCRI): A Proposed Novel Framework

Post-quantum cryptographic candidates are well documented in the existing literature, as are quantum threats. However, they do not have any standard programs to evaluate the readiness of migration. To close this gap, this review suggests a new heuristic scoring metric, the Quantum-Crypto Readiness Index (QCRI), with four weighted dimensions.

QCRI Scoring Dimensions

Dimension	Weight	Assessment Question	Score Range
Cryptographic Inventory (CI)	35%	Does the organization maintain a complete map of all encryption usage?	0–100
Data Longevity Exposure (DLE)	30%	Does stored data require confidentiality beyond 2035?	0–100
Algorithm Agility (AA)	20%	Can cryptographic primitives be replaced without system redesign?	0–100
Hardware Dependency (HD)	15%	Are constrained devices dependent on current key sizes?	0–100

Scoring Formula

$$\text{QCRI Score} = (\text{CI} \times 0.35) + (\text{DLE} \times 0.30) + (\text{AA} \times 0.20) + (\text{HD} \times 0.15)$$

Readiness Tiers

Score Range	Tier	Interpretation	Recommended Action
0–40	Critical Risk	Completely unprepared	Immediate cryptographic inventory required
41–70	Moderate Risk	Partial readiness	Migration planning within 24 months
71–100	Quantum-Aware	Well positioned	Hybrid PQC-classical deployment recommended

Practical Application Example

Consider a bank holding sensitive information from numerous clients that has been supposed to remain confidential for three decades. The scores it may have are CI = 50 (partial inventory), DLE = 90 (high longevity exposure), AA = 30 (low agility), and HD = 70 (modern hardware). The QCRI score is calculated as follows:

$(50 \times 0.35) + (90 \times 0.30) + (30 \times 0.20) + (70 \times 0.15) = 17.5 + 27 + 6 + 10.5 = 61$ **(Moderate Risk)**

The recommendation is to complete the cryptographic inventory within 12 months and initiate hybrid PQC trials.

Post-Quantum Cryptography

The most viable and scalable solution to the quantum threat is quantum safeguarding post-quantum cryptography. Unlike QKD, which assists certain fibre-optic gear, PQC employs conventional computers using changed mathematical primitives. The National Institute of Standards and Technology (NIST) has led global standardization efforts and finalized the first three PQC standards in August 2024. NIST explicitly warns that organizations should begin migration immediately rather than waiting for quantum computers to mature (NIST, 2024a, 2024b).

Why Classical Cryptography Fails Under Quantum Attack

Classical public-key systems, such as RSA, Diffie-Hellman, and elliptic curve cryptography, derive their security from the assumed difficulty of integer factorization and discrete logarithm problems. Classical computers require exponential time to solve these problems; for RSA-2048, approximately 10^{20} operations are required. Shor's algorithm reduces this to polynomial time, approximately 10^{10} operations on a sufficiently powerful quantum computer. The difference is categorical, not marginal. NIST (2024a) states that a cryptographically relevant quantum computer would defeat essentially all public-key cryptography currently deployed. This includes secure websites (TLS), digital signatures, encrypted emails, software signing, certificate authorities, virtual private networks, and blockchain transactions. These systems cannot be saved with any incremental change in parameters and can only be replaced.

The Engineering Challenge of PQC Deployment

However, the new approach to post-quantum cryptography is not a drop-in replacement for existing algorithms. For PQC families, the computational footprints are larger, which introduces discrepancies in real-world systems. The size of the contestants at NIST vary from 1.1KB (Kyber-768) to 32KB (SPHINCS+-128). Signature sizes range from 0.7 KB (Falcon-512) to 41 KB (SPHINCS+-128). For comparison, the keys and signatures for RSA-2048 take approximately 0.25 KB. These differences affect the bandwidth, data storage, processing time, memory, and power consumption. The PQC overhead can be too heavy for constrained devices, such as IoT devices in high-latency networks or legacy embedded systems. NIST (2024b) highlights the need for crypto-agility, where systems must have sufficient capacity to switch cryptographic algorithms without significant re-engineering, as a key strategic requirement for navigating this change.

Table 6: PQC Performance Comparison

Algorithm	Key Size (KB)	Sig Size (KB)	Speed (cycles)	Status
Kyber-768	1.1	—	10^5	NIST Finalist
Dilithium-3	2.5	2.4	10^6	NIST Finalist
Falcon-512	1.3	0.7	10^6	NIST Finalist
SPHINCS+-128	32	41	10^8	NIST Finalist
McEliece-KEM	1	64	10^7	Alternate

Limitations

This review has a few methodological limitations that restrict its conclusions and indicate research areas for future studies.

Geographic and Linguistic bias. The material for this review was limited to English-language items from indexed databases such as IEEE Xplore and databases considered cited sources in the Western world. This geographic bias is probably because much research is conducted from outside perspectives that are not English. We noticed that China has invested heavily in quantum hardware, networks, and post-quantum cryptanalysis. Other important studies published in Chinese journals or in domestic conference proceedings may still offer breakthrough insights or alternative approaches that are not reflected here. As a result, the findings of the review can be considered primarily through a US-EU lens on quantum threat assessment and cryptographic migration.

Time-sampling volatility. The sample size fluctuated over time. The synthesis was based on peer-reviewed sources published between 2016 and 2025. This sample size is appropriate for discerning broader trends and connections but will not capture all new developments, policies, or pilots in the field. The future of quantum computing is rapidly evolving, with new quantum algorithms, hardware advancements, and quantum cryptanalysis solutions that could reshape the threat landscape within a few months. For example, the latest NIST standardization listings of 2024 were published after many previous surveys and have already moved up the migration dates. The reader is advised to bear in mind that these findings are "snapshot" analyses and should not be considered as final or definitive.

Undocumented Attack Surface Defendant Software Third, as pointed out in the literature, there is a gap in the research surveyed regarding comprehensive attack surface models for hybrid classical-quantum systems. In most cases, PQC algorithms are assessed individually, assuming deployment on quantum-naïve infrastructure. Mix-and-match will be achieved in a hybrid setting in which both classical and quantum computers run algorithms, potentially introducing new interaction vulnerabilities. We have not seen much research on side-channel attacks, fault injection, and problems with protocol-level composition. This review does not reproduce this void but rather shows that further research is needed in this direction.

Future Scope

The quantum cryptography/computing field is highly dynamic. There are several directions in which accelerator research efforts are needed, but beyond the scope of this review.

To date, the performance assessment of PQCs has mainly focused on typical CPUs and a few commercial prototypes of field-programmable gate arrays (FPGA). Future studies will need to evaluate NIST-finished algorithms on hardware devices and platforms that will be prevalent in 2030, including 6 G communication infrastructure, edge computing nodes, neuromorphic processors, and energy-harvesting devices for IoT. Algorithms must be sufficiently robust, fast, energy-efficient, and have acceptable memory usage in different operational environments. Early results indicate that lattice-based schemes work well with vector computers, whereas hash-based schemes do not perform as well on these computers without dedicated hardware for acceleration. Standards for systematic benchmarking must be established.

Do you want to learn more about post-quantum security for machine learning systems? With the advent of AI in critical infrastructure, the cryptographic protection of ML systems is at the core of the agenda. As with conventional cryptographic functions, current research

focuses on important exchanges, signatures, and channel security. Going forward, quantum-safe security must be provided for quantum models, pipelines for training the models, pipelines for inference based on the models, and for distributed learning protocols. In certain applications, the economic and strategic benefits of a trained model could be higher than those of classical cryptographic keys. The following research topics involving PQC are still emerging and are quite fundamental: federated learning, model watermarking, and verifiable inference. Overcoming regulatory barriers: Policy frameworks Addressing regulatory challenges: Policy frameworks.

Addressing the quantum threat is not only a technical challenge but also requires coordinated policy action. Governments are starting to provide guidance on migration; for example, NSM-10 from the United States, the European Union through its upcoming quantum strategy, and the Chinese approach to provide migration guidance via domestic standardization tracks. However, these are not harmonized and have complex compliance requirements for multinational organizations. Further studies are needed to focus on different policy approaches, model sector-specific timeframes for migration, establish compliance standards, and implement flexibility. The post-quantum shift could otherwise disrupt global digital commerce due to the lack of coordinating regulations.

Cryptographic Agility Engineering: Typically, deployed systems are based on cryptographic primitives known at design time and remain static. To accommodate post-quantum migration, systems must be cryptically agile, that is, they must be able to adapt without redesigning the system under development. Reference architectures, middleware layers, and protocol extensions designed to separately deliver applications and cryptographic implementations should be developed for future use. Automated algorithm negotiation, fallback, and graceful degradation in cases of resource outages during PQC operation. Agility will be essential to long-term quantum resilience; it is not a feature, but a prerequisite.

Harvest-Now-Decrypt-Later Risk Quantification: The threat of retrospective decryption is not well understood. Risk assessment models should be developed in the future to estimate the probability of future exposure, depending on the progress of quantum technology and the data for particular certainty levels and types of data. These types would also make it possible for organizations to marshal some migration for their most vulnerable archives and take risks on ephemeral or low-value data. Rational resource allocation would be aided by a quantitative rather than a binary warning system.

3. CONCLUSION

Quantum computing in terms of information security is a complete revolution; it is not an evolution; it is a revolution. This review shows the weaknesses of all public-key cryptosystems against attacks using Shor's algorithm: RSA, Diffie-Hellman, and elliptic curve cryptography. Symmetric cryptography has survived and can now be upgraded with the parameters AES-256 and SHA384. Asymmetric vs. Symmetric is obviously the difference: asymmetric confronts while the symmetric fades away within a manageable way. This calls for a sense of urgency. Encrypted information collected now—medical records, state secrets, financial histories, legal records, and military communications—could be at risk of being made public in 10 years under the 'harvest now, decrypt later' policy. Protecting the confidentiality of data is crucial for organizations that require long-term confidentiality, but less so for those who can wait until quantum computers are ready. The notion of a “quantum emergency” is a failure of security.

Migration is likely to be challenging. Postquantum algorithms require larger keys, signatures, memory costs, and runtimes than classical algorithms. In addition to the technical guidance in NIST's enforcement of Kyber, the creation of the key standards Dilithium and

Falcon requires tremendous effort to coordinate with investment and crypto-agile systems design for deployment across global infrastructure (NIST, 2024a, 2024b). There are certain challenges associated with legacy hardware, IoT sensors, and embedded platforms.

The following sectors are the most exposed and must prioritize migration:

- Banking and financial services
- Healthcare and medical records
- Government and defence communications
- Cloud computing and storage providers
- E-commerce and payment systems
- Telecommunications infrastructure
- Legal and archival services

2030 Migration Roadmap

Timeframe	Milestone
2025–2026	Complete cryptographic inventory; begin hybrid PQC-classical trials; upgrade AES-128 to AES-256
2027–2028	Adopt NIST PQC standards in critical infrastructure; phase out RSA-2048 and ECC-256 from high-risk systems
2029–2030	Complete legacy PKI replacement; establish PQC as default in browsers, protocols, and certificates

In contrast, quantum computing not only poses a threat to classical encryption but also provides an opportunity to create more resilient, adaptive, and agile architectures in the future. The future of digital infrastructure lies in the transition to post-quantum cryptography, which will determine the trustworthiness of digital infrastructure in the second half of the 21st century. Organizations that start planning now will be at the forefront in the future. Those who stow it up for later risk not only tomorrow's breaches, but also the later detection of the most sensitive communications of today! The quantum era has touched us all in the past. There is no better time than now!

Declaration

The present authors' work on this literature review is original. All sources cited in the manuscript have been cited correctly. The Quantum-Crypto Readiness Index (QCRI) framework is proposed, which is a novel contribution to be discussed with the academic community but has not yet been tested in practice. The core analysis did not incorporate information generated using generative AI, but the grammar changes were supported by information obtained using grammar assistance.

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The Value of Psychometric-Based Career Guidance for Grade 9 and 10 Students: Enhancing Career Decision Self-Efficacy, Adaptability, and Parent–Student Career Alignment

Shiv Gangoli¹, Jitendra Vinayak Sandu²

¹The Orchid School, Pune

² Professor of Practice, Dr D. Y. Patil B-School, Pune

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*Corresponding author e-mail: Jitendra.Sandu@dpu.edu.in

ABSTRACT

The decision-making process for choosing a career in adolescence has become more complex as education has expanded rapidly, job opportunities have become more available, and societal expectations have increased. Often, students in Grades 9 and 10 (the penultimate years before senior secondary) choose academic streams without carefully considering their aptitude, interests, personality, and employability. The current study investigates the impact of psychometric career guidance in combination with individualized counselling on enhancing adolescents' career decision self-efficacy, adaptability, self-awareness, and future readiness. The study was quasi-experimental, pre-test-post-test in design, comprising 364 students from four state board schools in Pune, Maharashtra. Aptitude, cognitive ability, vocational interests, personality dimensions, and learning preferences were measured using standardized psychometric instruments. Descriptive statistics, Cohen d effect size, Mann–Whitney U validation and False Discovery Rate post-hoc correction were used for statistical analysis. A clear improvement was found in employability awareness, career clarity, career confidence, and adaptability following the intervention. The study adds to the developmental framework by conceptualising psychometric counselling as a psychological readiness model that assists Secondary School students in making informed, resilient, and future-oriented career decisions.

KEYWORDS: Psychometric Career Guidance, Career Decision Self-Efficacy, Career Adaptability, Psychological Readiness, Educational Counselling, Adolescents, Career Clarity, Secondary Education

1. INTRODUCTION

One of the most pivotal stages in adolescent development is the transition from secondary to senior secondary school, when students begin to construct their identity, career, and life plans. From secondary to senior secondary levels, students experience a significant transition that impacts their academic identity, career aspirations, and life plans (Santos, 2023). In the Indian educational system, students in Grades 9 and 10 must choose academic streams that are significant for further studies and professional life. These decisions are often made in uncertain situations, with undue social pressure or a lack of self-understanding. Backgrounds such as parental expectations, peer pressure, the social status of certain professions, and academic performance dictate 12–15-year-olds' choice of career more than a scientific system that accounts for individual aptitude, personality, interests, and emotional capabilities. As a result, many students find themselves in school programs that are inappropriate and end up unhappy, stressed, confused, and lacking confidence in their future careers. To overcome these limitations, scientific and systematic approaches have emerged as professional guidance services based on psychometric assessment. As objective measures of intellectual, occupational, personal, behavioural, and learning styles, these psychometric instruments can aid students in developing insight into their strengths and growth potential (Firkola, 2021). Current theories that guide career development suggest that in addition to students being matched to jobs, they need to be equipped with psychological tools, including self-efficacy, adaptability, resilience, and readiness for the future (Coetzee & Mbiko, 2023; Rivaldy & Komaro, 2022). Therefore, in this study, the conceptualization of psychometric counselling as providing *only* a vocational recommendation is incorrect. This is because the study suggests that psychometric counselling is a developmental process that should aim to enhance psychological preparedness for career decision-making, rather than merely providing a vocational outline or choice.

The study also has significant social interest, as it includes students from educational institutions that serve the economically disadvantaged sections in Pune. Students from these groups may not have access to evidence-based guidance (Groves et al., 2021) or professional career counselling services. This is why school-based psychometric interventions are highly valuable to this group of students when they make academic and/or career decisions. Thus, this research examined the impact of psychometric career guidance on career decision self-efficacy, career decision self-awareness, career decision adaptability, career decision employability readiness, and the match between students' aspirations and parents' expectations for adolescents.

2. REVIEW OF LITERATURE

2.1 Social Cognitive Career Theory

Several recent studies have demonstrated the importance of psychological readiness in adolescents' career decision-making (Marciniak et al., 2020). The social cognitive career theory of Lent, Brown, and Hackett (Brown & Lent, 2019; Lent & Brown, 2013) proposes that self-efficacy is among the most influential factors in studying career behaviour and vocational confidence. According to this theory, students with a higher level of trust in their decision-making skills are more likely to actively engage in career exploration, goal setting, and adaptive career behaviours.

2.2 Career Decision Self-Efficacy

They created the Career Decision Self-Efficacy construct, which describes how confident an individual is in their career planning and decision-making, which, in turn, is a strong determinant of career clarity and commitment. High self-efficacy contributes to students making better educational decisions and adjusting more easily to jobs that are yet to come. (Betz, 2000; Betz & Hackett, 1986).

2.3 Career Construction Theory

Savickas proposed career adaptability as a psychological resource that facilitates career transitions and helps individuals cope with occupational changes and career uncertainty in his Career Construction Theory. The research delved into aspects of career adaptability and how well individuals are prepared for the future, drawing on the work of Savickas, M. L. (2005). The current labour market, with its focus on transformational technology and new job opportunities, is more of a society in flux that demands flexibility than a world of traditional occupations.

2.4 Career Indecision and Psychological Ambiguity

Gati et al. (1996) revealed that lack of information, internal conflict, and external pressure were the primary reasons for adolescents' indecision regarding their careers. Students often have difficulty distinguishing their individual desires and feelings from societal expectations and demands (Henderson-King & Smith, 2006). One way to minimize this ambiguity is to use psychometric assessment systems, which offer objective information about what people are capable of and prefer in their efforts to achieve success. These assessments help students become more familiar with their strengths and make informed career decisions aligned with them (Krumboltz & Vidalakis, 2000). Psychometric tools in decision-making can help lower the stress involved by clarifying individual interests and skills. This, in turn, results in better-informed and more confident career planning for youth (Marciniak et al., 2020).

2.5 Psychometric Assessment in Career Counselling

Past studies have indicated that providing adolescents with systematic and appropriate psychometric guidance helps them have greater career confidence, reduced career indecision, a greater level of self-awareness, and a better understanding of their aptitude and interests (Turda, 2024). Evidence-based educational planning and informed occupational exploration are achieved through psychometric counselling.

2.6 Parent–Student Career Congruence

Research on adolescent-parent career congruence has focused on the congruence of aspirations and expectations between adolescents and parents, particularly in Asian countries such as India, where the family plays a significant role in shaping educational and career choices. (Pandey et al., 2023).

2.7 Research Gap

Although psychometric measures are utilized to a great extent in educational circumstances, there has been little empirical research in an Indian setting that investigates the effects of psychometric counselling on secondary school learners in terms of their overall development, especially those in the poor category. Existing research focuses primarily on occupational matching and very little on fostering psychological preparedness, adaptability, resilience, and confidence. This study aimed to address this gap using an integrated developmental approach.

3. PROBLEM STATEMENT

Uncertainty, anxiety, and confusion about academic and career decisions are common experiences for students in grades 9 and 10. Traditional career support systems rely on subjective views and lack systematic development of students' self-awareness, flexibility, confidence, and information-based decision-making. Emotional pressure and indecision among students are exacerbated when conflicts arise between students' aspirations and parental expectations. These challenges become even more severe among students from poor backgrounds, who have limited access to professional counselling resources. Although psychometric assessment-based guidance is increasingly being introduced in schools, limited

research has explored its effectiveness in enhancing psychological readiness and adaptive career behaviour among Indian adolescents.

4. OBJECTIVES OF THE STUDY

1. This study examined the impact of psychometric-based career guidance on students' career decision self-efficacy, career clarity, and informed academic decision-making among students in Grades 9 and 10.
2. Analysed the effectiveness of psychometric assessment and individualized counselling in improving career adaptability, employability readiness, and future preparedness among adolescents.

5. HYPOTHESES OF THE STUDY

H₁: Career guidance using a psychometric approach can greatly boost students' career guidance decision-making self-efficacy.

H₂: Students will demonstrate higher career adaptability after psychometric counselling.

H₃: Career clarity significantly improved after the intervention.

H₄: Students exhibit stronger preparedness for future academic and occupational challenges after counselling.

6. RESEARCH METHODOLOGY

The study was quasi-experimental, using a pre- and post-test research design to assess the effectiveness of psychometric-based career guidance in secondary schools. The pre- and post-test data were anonymous data without the name of the person but were treated as independent data samples. This conservative approach precludes the possibility of within-subject correlations and therefore underestimates the size effect. Future studies using paired analyses should use linked anonymous codes.

Sample Size Determination

The present study's sample size was decided after considering the criteria for psychometric validation, which include reliability estimation and exploratory factor analysis. The instrument was a set of 364 items that covered different constructs like aptitude, personality traits, interests, learning styles, and fluid intelligence.

A commonly recommended guideline for factor analysis is based on the subject-to-item ratio:

$$N \geq 5p$$

where N represents the sample size and p denotes the number of items. In the present study, $p = 364$, yielding a recommended minimum of $N = 1,820$.

However, obtaining such large samples in real-world educational settings, especially in school-based research, might be challenging. Methodological sources suggest that a sample size of 300 or even more can be considered sufficient for exploratory factor analysis, particularly in cases where communalities are moderate and factors are clearly defined (Tabachnick & Fidell, 2013; Comrey & Lee, 1992). When it comes to internal consistency reliability, a sample size of more than 200 is widely considered sufficient to obtain reliable and stable estimates of Cronbach's alpha (Bonett, 2002).

Thus, data were collected from approximately 350 students who attended 4 state board schools in Pune. The data were then checked for issues such as missing responses and response quality, resulting in a final sample size of $N = 364$. While this is somewhat lower than the usual subject-to-item ratio recommendation, it is still above the minimum acceptable thresholds for exploratory psychometric analysis.

The study was conducted among 364 students (class size 40) from four state board schools in Pune, India. It was implemented in partnership with the Rotary Club Pune Central and Talent Assessment and Data Analytics Software Solutions (TAAS). The study was educational and socially relevant as two schools participated, with most pupils being economically disadvantaged. Structured pre- and post-survey instruments and standardized psychometric assessment tools were used to collect data. Career clarity, self-awareness, career confidence, employability awareness, students' perception of success, career decision self-efficacy, career adaptability, enhancement in career confidence, reduction in career confusion, and readiness for the future post-counselling were the variables measured in the pre- and post-surveys. These include aptitude, personality traits, vocational interests, learning style, and brain capacity, which can be assessed using psychometric tools. The collected data were analysed using Mean and Standard Deviation, Welch's t-test, Cohen's d Effect Size, Mann-Whitney U Test, and False Discovery Rate Correction by Benjamini–Hochberg to ensure the statistical reliability, validity, and robustness of the findings.

7. PROCEDURE FOR DATA COLLECTION

To ensure the accuracy, consistency, and effective implementation of the psychometric-based Career Guidance intervention, the data collection process for the present study was conducted systematically in four sequential stages. Formal permission and institutional approval from all four schools involved in Pune, Maharashtra, were initially obtained. Coordination meetings were held, and the assessment and intervention of psychometric testing, counselling, and administering the surveys were planned within a framework that did not interfere with school and learning activities. The participating institutions were schools that were part of organizations that had well-established activities and interventions with economically less well-off student communities.

During the second phase, students completed a structured pre-intervention survey assessing their career clarity, self-awareness, career decision confidence, understanding of employability, and psychological readiness for future academic or occupational choices. The survey also examined students' perceptions of success, future goals, and concerns regarding planning their education.

During the third phase, students completed questionnaires based on scientifically tested tools to fill out a standardized aptitude and psychometric survey that measured vocational interests, learning preferences, personality traits, behavioural orientations, cognition, and aptitude. During these sessions, the counsellors provided a thorough explanation of the Psychometric Profiles and counselled on appropriate academic paths, career choices, personal strengths, developmental areas, and future employability skills. The counselling process (aside from career selection) aimed to develop/empower students in the areas of self-awareness, adaptability, confidence, and informed decision-making.

In the last stage, a post-intervention survey was conducted at the end of the counselling sessions. Changes in Career Clarity, Career Decision Confidence, self-awareness, self-adaptability, employability readiness, and preparedness for future academic and professional challenges were measured in the post-survey. Welch's t-test, Descriptive statistics, Cohen's d effect size analysis, Mann-Whitney U validation, and Benjamini–Hochberg False Discovery Rate (FDR) correction were used to statistically analyse the collected data for both phases to examine the effectiveness and reliability of the interventions.

8. STATISTICAL ANALYSIS

The collected data were analyzed using descriptive and inferential approaches to determine the effectiveness of the career guidance approach introduced through the psychometric approach. To assess the differences in career clarity, self-awareness, career decisions, self-esteem (adaptability), and career future readiness, the mean and standard deviation were used before and after the counselling. Welch's t-test was used as the main inferential statistic because the pre- and post-test data were independent samples with unequal variances. This is a conservative method but avoids the false accuracy encountered with unlinked repeated measurements. Welch's t-test is well-suited for use in education and psychology research when the variances differ and the sample sizes in each group differ. Using the test, an accurate comparison was made between the pre- and post-intervention mean scores across all constructs. The statistical analysis indicated statistically significant gains in students' psychological preparedness for their careers and choice of careers after counselling. To complement Cohen's d effect size analysis, Mann–Whitney U validation was performed for robustness, reliability and to control for multiple comparisons to achieve Type I error (false discovery rate = Benjamini–Hochberg) control.

9. RESULTS AND DISCUSSION

9.1 Construction of Analytical Groups

Each construct (Career Clarity, Decision Confidence, Self-Awareness, and Employability & Future Readiness) had several measures on a Likert-type scale and was rated by participants on a scale from strongly disagree (1) to strongly agree (5). The average score of each construct was calculated using the following formula: $An \cdot n = \sum X_n$ scores, where n is the number of students in the sample.

$$\text{Mean} = (\text{Sum of all responses}) / (\text{Number of responses})$$

Individual responses were added and averaged. The mean for each group (pre-intervention [PRE] and post-intervention [POST]) was calculated separately.

9.2 Linking Distribution Data to Scale Scores

To detect shifts in the distribution of responses, a mean-based analysis and a pooled response distribution analysis were also performed. The difference between the group means is denoted as

$$\text{Delta} = \text{POST Mean} - \text{PRE Mean}$$

Using this approach, it is possible to obtain the two complementary interpretations mentioned above: mean scores capture the central tendency, whereas changes in distribution indicate changes in the structure of answers.

9.3 Descriptive Statistics (Scale-Level Outcomes)

All four constructs are summarized in Table 1. In all constructs, considerable shifts from pre- to post-have been observed, which are believed to represent definite gains in psychological and career outcomes.

Table 1: Descriptive Statistics: Pre- and Post-Intervention Mean Scores

Construct	Pre (Mean ± SD)	Post (Mean ± SD)	Mean Differe nce	Cohen' s d	Effect Size Interpretation	p- value
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Career Clarity	2.95 ± 0.88	4.19 ± 0.71	1.24	1.43	Very large	< .001
Career Decision Confidence	3.63 ± 0.92	4.28 ± 0.68	0.65	0.80	Large	< .001
Self-Awareness	3.41 ± 0.95	4.08 ± 0.73	0.67	0.77	Moderate to large	< .001
Employability & Future Readiness	3.27 ± 0.90	4.17 ± 0.69	0.90	1.02	Very large	< .001

Note: N = 364. Cohen's d interpretation thresholds: 0.20 to 0.49 = small, 0.50 to 0.79 = moderate, 0.80 to 1.19 = large, 1.20 and above = very large.

9.4 Inferential Group Comparisons

Differences between the pre- and post-intervention groups were determined using Welch's t-test, which can be used when variances are unequal. Cohen's d was used to compute effect sizes, and interpreted relative to standard benchmarks.

9.4.1 Career and Stream Clarity

PRE: M = 2.95, SD = 0.88 | POST: M = 4.19, SD = 0.71

Welch's t = -19.42, p < .001, d = 1.43

There was a clear shift toward "Strongly Agree" and a steep decline in disagreement responses. This suggests that students developed a better understanding of academic and career pathways following the intervention (Table 2).

Table 2: Career and Stream Clarity: Response Distribution (Pre vs. Post)

Response	PRE (%)	POST (%)	Change (pp)
Strongly Agree	7.3	34.3	+27.0
Agree	41.5	44.4	+2.9
Neutral	20.1	14.8	-5.3
Disagree	25.0	5.6	-19.4
Strongly Disagree	6.1	0.9	-5.2

9.4.2 Decision Confidence

PRE: M = 3.63, SD = 0.92 | POST: M = 4.28, SD = 0.68

Welch's t = -10.83, p < .001, d = 0.80

This is attributed to students taking a step from moderate to strong agreement, which reflects higher levels of self-efficacy in career decision making. The number of respondents marking "strongly agree" rose from 6.1% to 35.4% and the number of those marking "disagreed" was almost wiped out (see Table 3).

Table 3: Decision Confidence: Response Distribution (Pre vs. Post)

Response	PRE (%)	POST (%)	Change (pp)
Strongly Agree	6.1	35.4	+29.3
Agree	56.1	52.1	-4.0
Neutral	18.3	11.8	-6.5
Disagree	14.6	0.7	-13.9

Strongly Disagree	4.9	0.0	-4.9
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9.4.3 Self-Awareness

PRE: M = 3.41, SD = 0.95 | POST: M = 4.08, SD = 0.73

Welch's t = -10.45, p < .001, d = 0.77

The complete absence of negative responses indicates a general increase in self-perception and introspection. Both "Disagree" (15.9% to 0.0%) and "Strongly Disagree" (4.9% to 0.0%) had 0% post-intervention. (See Table 4)

Table 4: Self-Awareness: Response Distribution (Pre vs. Post)

Response	PRE (%)	POST (%)	Change (pp)
Strongly Agree	19.5	33.3	+13.8
Agree	47.6	59.7	+12.1
Neutral	12.2	6.9	-5.3
Disagree	15.9	0.0	-15.9
Strongly Disagree	4.9	0.0	-4.9

9.4.4 Employability and Future Readiness

Students progressed from preparedness for future academic and career challenges. Table 5 presents the % change in responses from those in the initial screening and post-intervention for all items of "Strongly Agree. As shown in Table 5, "Strongly Agree" increased by 22.4 percentage points to 37.0%, and all responses in the "Disagree" and "Negative Answer" categories were eliminated after the intervention.

Table 5: Employability and Future Readiness: Response Distribution (Pre vs. Post)

Response	PRE (%)	POST (%)	Change (pp)
Strongly Agree	14.6	37.0	+22.4
Agree	53.7	52.8	-0.9
Neutral	13.0	10.2	-2.8
Disagree	14.6	0.0	-14.6
Strongly Disagree	4.1	0.0	-4.1

9.5 Conceptual Interpretation of Changes

The improvements noted do not represent consistent changes. Rather, the changes indicate both the amalgamation of lower-response categories and the magnification of upper-response categories. This trend is highly indicative of qualitative rather than quantitative changes in students' perceptions.

Key observations:

Almost all responses to disagreement were removed for all constructs.

Neutral responses dropped considerably, reflecting the formation of students' views.

Responses that were also strongly agree jumped significantly as students became more convinced about their responses compared to moderate agreement.

9.6 Robustness of matrix functions and matrix derivatives

The Benjamini-Hochberg False Discovery Rate (FDR) correction was used to reduce the risk of Type I error caused by multiple comparisons.

Results: No p values were interpreted as significant after applying FDR correction ($p < .001$ for all p values). All results were checked for robustness using nonparametric statistical tests (Mann-Whitney U test).

9.7 Summary of Results

Research shows that psychometric-based career guidance leads to:

Finding	Evidence
Major improvements in career clarity, decision confidence, and self-awareness	Table 1 (large to very large effect sizes)
Very strong rise in future readiness and employability perception	Table 1 ($d = 1.02$) and Table 5
Movement from uncertainty to strong conviction	Tables 2 to 5 (increase in Strongly Agree responses)
Near-complete elimination of disagreement responses	All distribution tables (Disagree to 0% in most constructs)

Large differences were observed in the category of "Strongly Agree" which suggests a shift toward a higher level of confidence among the participants. A radical change in the structure of the responses was found when investigating the pattern at the subsample level: there was almost a complete disappearance of disagreement responses and an increase in the upper agreement categories.

The evidence described above reveals that the intervention benefitted students not only with regard to general knowledge of their personal qualities and career paths but also provided them with greater confidence when making quality academic and career choices. The uniformity and similarity in the magnitude of the changes in all variables offers a strong quantitative rationale for the effectiveness of psychometric-based career guidance in building Career Decision Self-efficacy and Future Readiness in secondary school students.

10. Conclusion

The study indicates that Psychometric Career Guidance (PCG) is an effective tool that can help students in Grades 9 and 10 with their academic journey and impact their future careers. Individual students who completed career decision-making psychometric tests and received individual counselling showed a significant improvement in their self-confidence in career decision-making. They also reported having a better understanding of their academic and career trajectories. It was discovered that they were quite self-aware and had made some improvements regarding their desire to solve problems in their lives. Based on these students' findings, it may be inferred that they shifted from confusion and uncertainty to determination and confidence. This study is based on the framework of Social Cognitive Career Theory, which emphasises the two most important factors in the career development process: adaptability and self-efficacy. The findings suggest that an educational system with a more systematic, data-driven approach would be required to be more effective in guiding young people in career decisions where school guidance counsellors are engaged in individual counselling and standardized testing is used to make decisions.

Limitations and future directions

This study used a quasi-experimental single-group pre-test post-test design. Therefore, only part of the observed improvement can be definitively attributed to the psychometric intervention, as maturation, history, and/or testing effects may have contributed.

Additional limitations include the following

Changes at the individual level were not analysed because of an unlinked pre-post design.

Self-reports Likert scales could bring social desirability bias

Long-term sustainability effects were not observed in the short-term design.

The sample included four State Board Schools in Pune, so the results of the study might not be comparable in other geographical, linguistic, or socio-economic settings

Future research should

A randomized controlled trial or waitlist control group should be used to provide causal inference.

Carry out long-term impact evaluation studies

Match data designs for between subjects' analysis

Engaging in a multidisciplinary approach to research in various educational and socioeconomic settings.

Representative generic examples of psychometrically based guidance can be contrasted with classic counselling approaches.

Final Remarks

In summary, the current research underscores the need for psychometric guidance during the shift from self-uncertainty to personal insight. Finally, this allows students to make informed career choices and to make confident, flexible decisions.

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