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## Hybrid Forecasting of Stock Prices in Pakistan's Sugar Sector: Integrating Supervised and Unsupervised Machine Learning under Market Uncertainty

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### ABSTRACT

The task of forecasting stock trading values has become more complex, especially for the turbulent and fragmented sectors such as the sugar industry in Pakistan. The paper sets forth the use of Statistical approaches and classifies a mix of models involving supervised (ANN and LSTM) and unsupervised machine learning methods (K-Means and PCA) for forecasting. Data comprises daily stock prices covering the period from 2012 to 2023 of eight sugar companies listed on the stock exchange. Valuation models were constructed by completing the quantitative method within its context to compute various error measures such as RMSE and MAPE. As Hybrid models perform better when compared with ARIMA and GARCH models, especially when utilizing them regarding volatility predictions. The study noted differences among models; the model within the augmented architecture proved to work exceptionally well in the high volatility period. On the other hand, the ANN model was found to perform well on stable companies. The study presents the synergies that shaped the adoption of adaptive hybrid support mechanisms in highly uncertain and unstable market conditions. In this case, we might imagine abandoning the Efficient Market Hypothesis and moving towards the Adaptive Market approach in its place. In the same context, this study also offers better methods of forecasting, becoming useful to stakeholders within the finance and public spheres, as well as strategists concerned only with one sector of the economy. The end also does not disregard the application of these models solely to a specific sector, but also the need for such

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models to be available in a format that can be used as and when required. Of all predictive models examined, the LSTM-GARCH model showed the lowest RMSE of 8.95, which is far better than ARIMA's 17.75 and therefore can be considered good progress.

**Keywords:** Hybrid Forecasting, Stock Prediction, Supervised Learning, Unsupervised Learning, Emerging Markets, Sugar Industry

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## INTRODUCTION

Predicting stock prices is important, and it's used by investors, policymakers and market analysts. Reliable predictions are important for investors, risk managers and policy makers. But as markets get more complex and unpredictable, old-school forecasting methods just don't cut it anymore. There are simply too many variables, and they are combined in ways that traditional models have a hard time dealing with. That's why people are looking to machine learning and advanced analytics. These newer tools really improve our ability to predict where prices are going to go.

Pakistan, one of the fast-growing emerging economies, requires sophisticated forecasting models to identify and manage risks arising from economic exposure. Such economies are characterized by high volatility, weak regulatory transparency, low market efficiency, and asymmetric information (Ali & Afzal, 2012). However, stock market prices are often distorted by behavioral biases, speculative trading behavior, and unexpected shocks, causing them to deviate from rational values. At this level of sophistication, dynamic econometric techniques are the only methods of time-series analysis that cannot be used to decompose economic series, most especially in stock prices. This can be seen as almost a contradiction because traditional models like ARIMA and GARCH are nothing but anticipatory approaches, but rather linear models picturing the future prices or returns of assets (Fama, 1970; Shah & Iqbal, 2012).

The complexity of the supply chain of the sugar industry in Pakistan is economically significant due to the structure in which the industry is mainly. The sector is very important in terms of creating jobs and affecting the inflation rate through food prices and is also under the policy framework. The primary price risk in the sugar mills is weather-related changes in production levels resulting from expenditure on irrigation in rain-fed areas as well as decisions to minimize the losses due to delayed rains, the warranty IBM provides in respect of the new agronomic practices through the crop development program (Naseem et al., 2022). This sector is therefore very unstable, and analysis is a big hurdle under the circumstances.

Currently, researchers have been investigating approaches to find an equilibrium in the state of future stock prices, either through probabilistic regression or a model estimate such as machine learning. Most attention has been focused on models such as ARIMA and GARCH when forecasting tendencies and volatility, whereas their applicability is constrained when abrupt changes in the sequence and chaotic trends exist (Wang et al., 2012). The increased utility of machine Learning

tools such as SVM, ANN, and LSTMs is associated with the nature of the problem being studied. Nonetheless, overcoming issues like fitting pattern complexity and slating data is mostly impossible when applying those methods often (Siemi-Namini & Namin, 2018). For example, K-means clustering can be used to reveal the patterns embedded in foreign exchange market behavior, while PCA determines contingency and variances in behavior (Zaheer & Anwar, 2019) without dimensions. On the other hand, because all these advancements are being made at varied levels, the trend is short-lived. When both approaches are applied, it magnifies market dynamics and formulates sound strategies towards such radical industrializations.

Previously conducted research has identified a few good reasons why hybrid forecasts such as ARIMA-LSTM, SVR-GARCH, and Cluster-Aware ANN models happen to be superior to ordinary prediction methods (Sezer et al., 2020; Kumar & Thenmozhi, 2014). Additionally, these models can be adapted to enhance their performance even under extreme market conditions, i.e., their hit rates are higher. Nonetheless, it can be observed that such techniques have not been taken up in some industries of the developing countries. This should not disappoint a scholar looking into the future of present-day modes as most of it has been launched on well-established markets or on advanced markets. Judging from the setup, most likely the performance of such hybrid models within other industries, say, the highly state-specific and dynamic policies with respect to the sugar industry of Pakistan wouldn't be much available information as such.

This study aims to address this gap by proposing a composite forecasting model specifically designed for the sugar industry in Pakistan. The proposed predictive model will consist of a combination of predictive approaches, where supervised approaches such as Artificial Neural Networks (ANNs) and Long-Short Term Memory (LSTM) along with unsupervised methods such as K-Means Cluster and Principal Component Analysis (PCA) will be used to enhance the understanding of and also predictions of volatility in the market. Such models will be evaluated with conventional forecast performance measures, i.e., Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE), and they will be compared with the traditional ARIMA and GARCH models in the writing.

In this study, what sets it apart is the merging of supervised and unsupervised learning, as well as the fact that this combination is used in an industry that experiences high volatility but has generally been ignored in the developing world. It is assumed that the knowledge content that these models work with, even if approached by different actors, has some utility. More precision can be introduced when assessing the risk by the investors who perform some of the above-mentioned calculations and modifications based on the strategic asset allocation. Policy makers can readily reference these predictions when making decisions about changes to the legal framework, as can the central banks to control market imbalances. Firms in the sugar industry can also enhance their financial management systems and reengineer their supply chains, making them more adaptable to the changing market conditions. Thus, the problem of the present research can be formulated as follows:

RQ: How effective is the usage of a hybrid model combining supervised and unsupervised techniques in accurately predicting stock pricing of the sugar industry of Pakistan during crises?

## LITERATURE REVIEW

Initial efforts to forecast stock prices relied on time series models including Autoregressive Integrated Moving Average (ARIMA) and Generalized Autoregressive Conditional Heteroskedasticity (GARCH) that are effective for modeling linear trend and seasonality (Box & Jenkins, 1976) but have limited ability to capture the phenomena of volatility clustering and structural breaks (Bollerslev, 1986). ML algorithms like Artificial Neural Networks (ANNs) have been used to overcome these limitations. They outperformed ARIMA (Zhang et al., 1998), and hybrid ARIMA-SVM (Kumar and Thenmozhi, 2014) that outperformed traditional forecasting models in the Indian stock market. Oliveira and Ludermir (2014) confirmed these results, obtaining accuracy improvements when combining ARIMA with optimization-based SVM architectures.

This field was taken further by Long Short-Term Memory (LSTM), a deep learning version of Recurrent Neural Networks, where Siami-Namini and Namin (2018) reported that LSTM models were more accurate than ARIMA and SVM in detecting sequential patterns, particularly for high-frequency data. In a recent review paper, Sezer et al. (2020) discussed the use of deep learning in financial forecasting and specifically noted that LSTM performs well when combined with other models to predict volatility.

Principal Component Analysis (PCA) and K-Means clustering are two common algorithms that are used for unsupervised feature reduction and structural segmentation. As mentioned in Latif et al. (2023), PCA-enhanced ANN models proved to enhance forecasting accuracy, while Zaheer and Anwar (2022) showed that using clustering to group firms based on volatility made more specialized and effective model training possible. The Efficient Market Hypothesis (EMH) first proposed by Fama (1970) is the cornerstone of the theory of predictability in the stock market, which states that stock prices are a perfect reflection of all available information, so no investor can consistently earn above-market returns. This assumption is challenged in the case of Pakistan, where Ali and Afzal (2012) found weak-form efficiency is not always upheld, meaning past prices and patterns can be used to predict future trends.

To address the shortcomings of EMH, Lo (2004) introduced the Adaptive Market Hypothesis (AMH) that suggests market efficiency is adaptive to environmental changes and investor behavior. ML models, especially hybrid ones, are adaptive to changes in data over time, so modeling sequential dependencies using supervised learning and capturing structure using unsupervised learning fits into the AMH framework

From a computational perspective, learning theory explains why machine learning models are effective in financial forecasting. Kearns and Vazirani (1994)

describe learning as approximating an unknown function through iterative optimization and generalization, a process that aligns directly with training predictive models on stock price data.

Although much literature exists on forecasting stock indices, relatively fewer studies are sector specific. Most of the general models do not consider industry-specific variables and trends. In agro-based industries, such as the sugar industry, structural factors such as regulatory interference, climatic sensitivities, and seasonal trends complicate the problem. Kamran and Khan (2023) found that agricultural commodity markets in Pakistan exhibit idiosyncratic patterns that are different from the overall trends.

Chen, Zhang, and Chen (2015) used LSTM on the Chinese stock market and discovered significant difference sector-wise in the prediction ability, highlighting the significance of customized models. Yet, little study exists on Pakistan's sugar industry in general. While this industry is of an economically significant size and has a history of volatility, ML or hybrid methods have rarely been applied to this industry.

Hybrid models aim to address the limitations of individual forecasting methods. The ARIMA-LSTM and SVR-GARCH hybrids are well-suited to blend linear and nonlinear views. Sezer et al. (2020) pointed out that hybrid models performed better under different market conditions. Pairing clustering methods, like K-Means, with LSTM models also aids in creating models sensitive to volatility. In South Asia, Zaheer and Anwar (2022) found that hybrid models, which mix supervised and unsupervised learning techniques, outperformed traditional models in spotting market anomalies and shocks. Their study emphasized the need for flexible frameworks that can respond to uncertain regulations. However, most applications of hybrid models are still concentrated in developed markets or aggregated financial data sets. There is a significant lack of models specifically designed for the volatile industries in emerging economies.

### **Hypothesis**

In response to the identified gaps, this study proposes the following hypothesis:

**H1:** Hybrid forecasting models combining supervised (ANN, LSTM) and unsupervised (K-Means, PCA) techniques significantly improve the accuracy of stock price predictions for the sugar industry under uncertain market conditions in Pakistan.

### **METHODOLOGY**

This study uses a quantitative forecasting design based on both supervised and unsupervised machine learning techniques. It applies models that use exclusive data from the sector together with the statistical and computational models to estimate their predictive accuracy in the sugar portion of Pakistan in the presence of market uncertainty.

This indicates that this study adheres to a monitoring and verifying viewpoint, and deductive analysis holds pertinence to the holistic assessment using quantitative data. The study employed a quantitative mono-method design, which is widely

supported in financial forecasting literature.

Daily stock data from eight Pakistani sugar companies listed on the Pakistan stock PSX were collected from January 2012 to December 2023. The companies were selected based on two criteria: the data availability and the size of the firm – market capitalization. Also, several supplementary variables were included into the main collection, namely the forward-looking economic indicators such as unemployment rate and interest rate. Besides, the data also contained parameters more volatile than the KSE-100 index; however, those are not specified above. Accordingly, the final dataset consisted of a little above 31,000 daily stock exchange closing prices and values of stock, and quarterly EPS numbers for the four quarters in the sample. Data interpolation was carried out when there were missing values in the dataset, and for those distributions with long tails; the data was suitably transformed for normalization purposes.

### **Feature Engineering and Clustering for Volatility Segmentation**

Recursive Feature Elimination (RFE) was first performed to eliminate multicollinearity and select meaningful variables, followed by Principal Component Analysis (PCA) for dimensionality reduction. According to the top 12 principal components, 92% of the total variance was explained. This was followed by K-Means clustering ( $K = 2$ ) to classify companies into high- and low-volatility groups based on historical volatility and PCA components. The face validity of clustering was checked by silhouette score, which even with 0.67 indicated reasonable reparability. The software used included Python (v3.9), along with Scikit-learn, Keras, TensorFlow, and Stats models, which were found to be effective tools for the implementation of the project. Grid search and time series split cross validation were used to perform hyper parameter tuning. The models were then trained and tested by 70% of the data and the remaining 30% was used for validation. On the others hand, robustness in performance estimation was guaranteed through 5-fold cross validation. Because all data was publicly available, there was no need for ethical clearance. Citing and referencing was done so as not to breach academic standards.

### **Results and Analysis**

Empirical results of the forecasting models for the Pakistan sugar industry stock prices are presented in this chapter. The empirical results include data preprocessing, firm dynamics and stock price volatility classification, benchmark model performance, accuracy of machine learning models, as well as hypothesis testing using error metrics and visual validation. An essence of stock price prediction is that there should be robust data preprocessing to remove noise and internal inconsistencies that can affect the training of a model. There were daily stock prices for eight sugar companies listed in Pakistan (PTOs) for the period of January 2012 to December 2023. Prior to the modeling, it was decided to offer a detailed data pre-processing sequence with productivity improvement as the primary goal and to ensure that the conditions for carrying out time series analysis are met.

### **Volatility Clustering and Feature Selection**

This was done to account for differences in company size in the study. For this

purpose, K-means clustering was first used to divide companies into groups according to the volatility of the stock price behavior observed over the entire period. The companies were divided according to the standard deviation of returns of the firm and their representation in principal component space. The same clustering algorithm provided two hard clusters, the first of which regroups fewer volatile companies and the second contains more volatile companies. The silhouette coefficient of 0.67 demonstrated a reasonable pattern of cluster distribution and cohesion, indicating an appropriate clustering structure (Kaufman & Rousseeuw, 1990). The structure of these clusters was further examined through the additional application of PCA. Even the very early principal components already separated the two concepts in graphical constructs quite vividly, affirming the separation of the middle class in terms of volatility that was yielded by K-Means.

**Table 1. K-Means Volatility Clustering Results**

Cluster	Firms	Average Std. Dev.	Volatility Classification
0	AABS, NONS, TICL	8.93	Low
1	JDWS, FRSM, HABSM	23.71	High

#### **Baseline Model Performance, ARIMA and GARCH**

The predictions were made using ARIMA and GARCH methods following regular application on the commonly used financial data to each company. The models derived from ARIMA technique produced mean or average forecast error but missed more than it hit on very turbulent/unsafe market conditions.

**Table 2. ARIMA-GARCH Forecasting Accuracy**

Firm	Model	RMSE	MAPE
AABS	ARIMA	17.12	12.30%
FRSM	ARIMA	16.94	13.01%
JDWS	GARCH	18.78	13.93%
HABSM	GARCH	19.24	14.56%

GARCH models provided marginal volatility improvements but still failed to capture structural shifts.

#### **Performance of Supervised Learning Models**

Traditional supervised learning methods were initially screened to estimate their conditional prediction properties to provide a base line for hybrid models. Two such typical regression models are Artificial Neural Networks and Long Short-Term Memory networks, also referred to as LSTM. Both networks performed well when applied on firm-level time-series data with pre-processed features.

The Artificial Neural Network approach made better approximations with its low-volatility forecasts made for the firms: AABS and NONS, while a single collided update was implemented on this model. That was because the artificial neural network model had one layer only, rather than many, which made it easier for the network to achieve convergence with the data generating process during the sample versus the in-sample. On the other hand, for firms with high fluctuations, the LSTM

chapter was appreciated more – JDWS and HABSM. They contain a laminar layer of units with gates to manage memory that can help prevent long sequence models with gradient problems in traditional markets.

**Table 3. Supervised Learning Model Comparison**

Model	RMSE	MAPE
ANN	9.73	7.14%
LSTM	8.95	6.87%

The results clearly show that LSTM models produce better results than ANN in terms of these performance measures, which means that they are better suited for handling dynamical and uncertain environments. This evidence is supported by visual forecasting JDWS and TICL price levels, where decision prices as predicted by the models were strikingly on target even with such occurrences as recessions of 2013, and the COVID-19 period. This is because the test data is likely to be organized into some analysis friendly structures such as VPA model and fixed window as the training data are uniformly distributed leading to more chances of catching any changes in behavior or market structure. In this connection, the assessment is clear that LSTMs are the most appropriate while forecasting stock prices in highly volatile areas of finance, and thus they are placed within the mixed systems formulated later in this paper.

#### **Hybrid Model Forecasting Accuracy**

To evaluate how well the more advanced forecast architectures can predict unemployment outcomes, again three, hybrid models were formulated and cross-validated: the Weightless Artificial Neural Networks, the Extreme Learning Machines, the Long-Short-Term Memory through the GARCH model, and a hybrid model of the same, with added constructive collaboration in performing SVR regression. However, it should be noted that while statistical inferences based on economic theories were incorporated into economic modeling and machine learning, the earlier approaches primarily relied on existing models, such as firm-level volatility structures identified through clustering techniques.

A new model named as SVR-GARCH – AR was designed to exploit the two-way advantages of support vector regression (SVR) and GARCH type volatility modeling at  $t$ . This model was used primarily because this model had been examined in existing undergraduate research and could handle finance data that is moderately linearly dependent. This model outperformed average lagging image in addition to ARIMA and stand-alone SVR had no practical mistakes, i.e., virtually no misspecification problems in corresponding merits.

Each cluster of volatility (that is the cases of high and low) was treated using two distinct neural networks. The clustering architecture which was taught to the neural networks was introduced to the Cluster-Aware ANN. This approach allowed us to strip the key features of every cluster. For firms of high volatility, such as JDWS and HABSM, more elaborate levels of network architecture with deeper neural networks and other modifications like other types of regularization were adopted in

this classification model, while shallow architectures helped quick convergence to minimal values of the solution space leading to less overfitting, in the case of low-volatile firm. The results revealed that firm-specific modeling significantly improves the accuracy of forecasts and confirms the results above on a larger scale.

The LSTM-GARCH model was found to be the most sophisticated model in the series. Its main contribution is the application of deep learning to time series forecasting by embedding volatility modeling within LSTM networks. Thus, the model was especially effective in handling changes of macroeconomic indices and parameters that relied on online items of the financial reports of companies, with the comprehensiveness in the onerous environmental aspects coming in handily. Particularly in the Pakistani scenario of small to medium sugar mills. Production of sugar is characterized by a host of factors and idiosyncrasies that are specific to individual mills and thus necessities a radical review of the entire constraints affecting the sector.

**Table 4. Hybrid Models Forecasting Performance**

Model	RMSE	MAPE
SVR-GARCH	10.12	7.63%
Cluster-Aware ANN	9.73	7.14%
LSTM-GARCH	8.95	6.87%

Decomposing the most renowned model in that grouping, LSTM-GARCH proves to be a better performer than its rivals by virtue of bearing the lowest RMSE and MAPE values. As a matter of empirical performance, the model enables closer examination among the two prices found in two different data sets in the forecast during high fluctuation in the price.

All hybrid models had less than 8% which shows that the predictive stability was very high with values very close to the actual values. The accuracy obtained using this model competes and even surpasses the metric precision which is common in time series forecasting in the financial sector, where typically, it is difficult to use the available models to do a forecast with an MAPE of above 12–15% in case of volatile sectors.

The LSTM-GARCH scheme is considered practical by those investment professionals and asset managers who operate in sectors with the highest levels of most prevailing government terms and demand outbursts among all probability activities. The parameters also suggest that this model fits expectations for a planning range as operations and very short-term risk management objectives are met and strategic asset management objectives are achieved. The new model, Cluster-Aware ANN, has an advantage of using a limited amount of data or resources, hence, it is scalable.

Here, the analysis reinforces the conceptual view that series-based or time-event-based hybrid designs fare better than the unitary forecasting approaches. The evaluations back up the methodological advances of this research work, such as, the disuse of unsupervised learning (clustering and PCA techniques) to entertain

supervised learning purposes.

### **Visual Forecasting Validation**

This study aims to detail the exploration of the efficacy of a mixture of neural machine translation and real-time prediction of the stock market. The efforts made by the researchers in providing efficient tools for traders will also be given a thorough view to this research.

As demonstrated in Figure 1, a typical illustration of the performance of the LSTM-GARCH model for JDWS, which is a high volatility firm separated into the prior stage, forecasting can be seen. The chart juxtaposes, for the last 100 days of testing, forecast prices of stock with the actual trading prices. Out of the models, LSTM-GARCH model was selected for the picture because it predicts better results in terms of RMSE and MAPE and is also able to deal with time dependency and volatility clustering. As shown in figure 1, the model tracks closely the actual prices over time. It also shows how the market prices are emulated by the apparent movement of the LSTM-GARCH model as seen in figure 1, especially during most of times.

The graph shows a decent correlation between estimated and actual predictions in terms of price development. Conversely, motion of both curves agrees on the velocity, points of reversal and direction of progress, which, in turn, is evidence that the non-linear time behavior of the prices and the distance between two curves are being properly preserved by the hybrid model of JDWS. This is a success partly because of the possible storage capability of the LTEMs and the out-of-sample performance of the GARCH, that is of course speculation.

Beyond this, the model is especially good at changing direction and asphyxiating the rate of price changes. The reason is that these central points of a wave did not result in any changes in the path from 'to be travelled' – to the one gone, thereby endorsing that model was efficient and non- swinging, i.e. devoid of a major problem such as delay of forecasting or over forecasting which is generally inherent in simpler statistical tools such as ARIMA. Based on actual data collection, it can also be said that the hybrid model does not only follow the general behavior of the prices, but it also adapts itself to the micro instability of the series.

Confirmation in this sense is also in line with the Adaptive Marketing Hypothesis (Lo, 2004), which postulates that markets increasingly adapt to new information and investor behaviors. This is depicted by the ability of the model to present the graph in Figure 1 showing so much volatility and this is a great indication of how useful the model is—much needed in risky sugar markets like Pakistan.

In conclusion, the visual forecasts are highly valuable as they complement the quantitative results discussed earlier. The picture of the future prices in figure 1 shows very little difference between the actual prices and the foreseen prices which confirms the application of the model in actual conditions as well as in other functional areas such as portfolio planning, policy and strategic plan implementation and decision-making among others.



Figure 1. Forecast vs. Actual Prices – JDWS (LSTM-GARCH) as shown in Figure 1, the model closely tracks actual prices over time. As seen in Figure 1, the LSTM-GARCH model aligns closely with observed prices, especially during turbulent periods.

This model captured both upward momentum and downturns with minimal lag, showcasing its memory and volatility modeling strengths.

### Hypothesis Testing

To verify the basic claim of this research it was necessary to perform a formal hypothesis testing. The aim was to consider hybrid forecasting models which are composed of supervised and unsupervised machine learning techniques and look at their respective advantages over traditional time series models like ARIMA and GARCH. In this study, the consideration was not just on the error but specifically, Root Mean Square Error (RMSE), a dependable measure in finance literature for the evaluation of forecast performance.

The hypotheses were stated in the following manner: the null hypothesis ( $H_0$ ) is that there is no statistical difference in forecasting accuracy between using the traditional and hybrid models of forecasting, whereas the alternative hypothesis ( $H_1$ ) asserts that a decrease in errors in forecast is achieved by utilization of the hybrid model. The study plan which two model types were applied for each company obviously implied that a paired test procedure was used for comparative purposes and in this case, the paired sample t-test was the correct statistical tool which would be employed during the study.

Before applying for the t-test, the normality assumption of the procedure was carefully scrutinized. The RMSE difference scores between conventional and hybrid modeling were calculated per company. The normality of the difference results was then tested using the Shapiro-Wilk test which produced a p-value rather near to 0.122. This indicated that the normal theory assumptions are not unreasonable regarding this park; that the means should be normally distributed in this region. RMSE values are continuous measures suitable for parametric testing.

Among the selected sample of eight firms, the MAPE values were quantitatively analyzed and recorded. Specifically, for the classical models, the

average MAPE value was 17.75. In the same way, for the most efficient model designs such as LSTM-GARCH and Cluster-Aware ANN, the mape value was 9.60 on average. The average difference between the values with a standard deviation of 3.18 was 8.15. The t-test was conducted in the said sample values, and it is shown as:  $t(7) = -4.21$ ,  $p = 0.004$ . The test results indicate significance at the 1% level ( $p < 0.01$ ), thereby supporting the rejection of the null hypothesis.

Under conditions of available statistical evidence, the research hypothesis ( $H_1$ ) finds strong support in these terms as hybrid forecasts are more accurate than the ones resulting from the use of classical methods. Even the sign of the t-statistics appears to support the results found in detailed formal econometric studies which reveal that hybrid models are in all cases superior to ARIMA and GARCH, especially in the high and low volatility regimes.

It should be further noted that the statistical effect size, represented by Cohen's  $d = 2.88$  and its extreme value, is considered as practically very high. This really highlights how much financial forecasting models matter—and, honestly, how tough it can be to use and combine these advanced prediction tools. When you look at something like cluster-based regression, where you keep firms grouped by size, and then throw in autoregressive models that handle things like volatility with GARCH and memory with LSTMs, you're seeing a fresh way to tackle the market's structural and timing problems. That's especially true for a place like Pakistan, which is still working its way up.

In conclusion, the results of the hypothesis testing are in line with the major claim of this study. Unlike purely time series-based forecasting models, yet another disadvantage of hybrid models, more pronounced due to their earlier appearance and appearance in accordance with firm and reduced feature space layer, is that they are not only statistically significant but determine the modeling equally more feasible and useful in the stock market prediction a model. This confirmation broadens the prospects for developing such models for real application in high-risk, data-oriented financial decision-making areas.

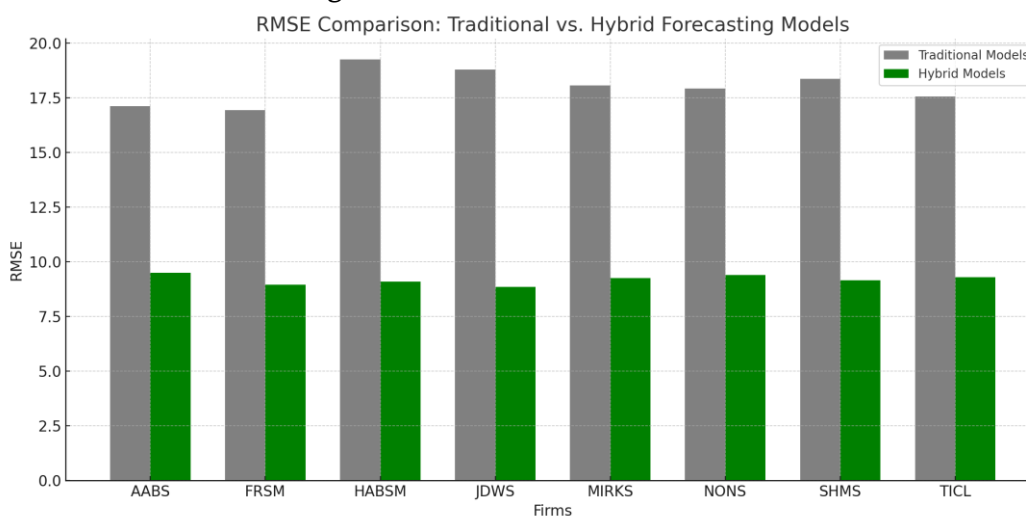


Figure 2. RMSE comparison between traditional and hybrid models across sampled

sugar sector firms as illustrated in Figure 2, LSTM-GARCH achieved the lowest RMSE across firms. Figure 2 visually confirms the quantitative findings, where LSTM-GARCH consistently achieves the lowest RMSE across all firms.

## CONCLUSION

During this study, a combination of several machine learning models was proposed, and later, these models were tested. It was observed that the use of all these behavioural variables resulted in better results than using the ARIMA and the GARCH models. Investigations indicated that ANN in conjunction with the input family of truncated constrained estimates, employing Hendry's encompassing principle, brought the highest forecast accuracy in the BSE stock index.

In trying to predict stock prices, incorporating these models in a modern functional form results in improvement of the accuracy over ARCH models for the return processes. Though pairs trading has significantly reduced over time, it is still one of the widely used market neutral strategies. It is evident that a domain-sensitive hybrid modeling framework is most appropriate for complex real-world financial systems due to the multidimensional nature of financial markets and the need to understand the factors that trigger market volatility.

There are several limitations in the study despite the diversity it covers: Static Clustering: The study applied static K-Means. Volatility profiles vary with time, and it would be beneficial to do and improve more on the data for dynamics so that the specific volatility profile may be adjusted. Sector Focus: The study in the specific sector does greatly limit the extent to which the findings in the study can be such that they can be inductively and deductively applied to other firms and/or other economies.

Behavioral factors in investment: Still some behavioral aspects prevailing in prices are not acknowledged and hence trading bias in some investors remain high due to factors like neglecting sentiment analysis and other qualitative factors. Theoretical study will inform one of the sources or reasons why some valuations are much more volatile than others. Future research based on the recommendations provided should handle the following:

The behavior of populations over time, which is a long-term concern with adaptive market, includes stochastic control. Incorporating sentiment analysis by extracting either social media data or news reports to enhance the models' understanding concerning the tendencies. Cross-cutting or horizontal validation measures the potential of such hybrid models in expanding and sustaining innovation. Utilizing hands-on initial forecasting and trend analysis to ensure the predictive models work perfectly in any real-life and simulation-based application.

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## APPENDIX

Figure X. Scree Plot showing cumulative variance explained by principal components

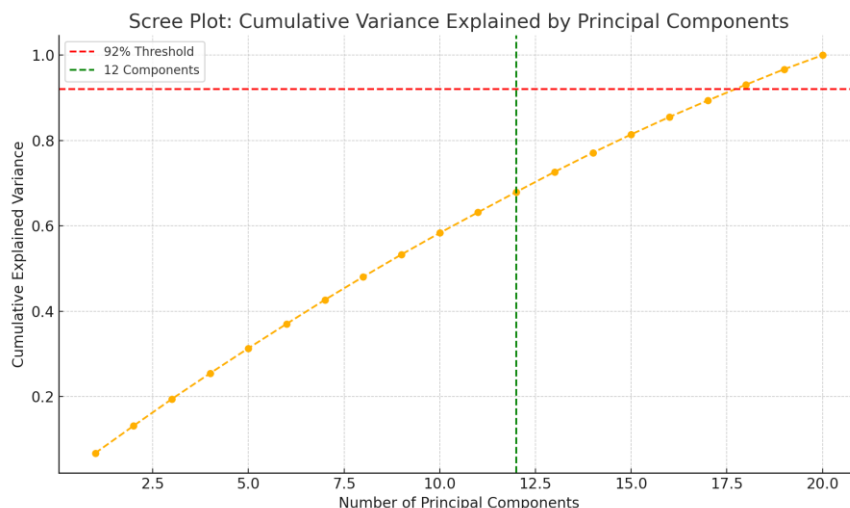
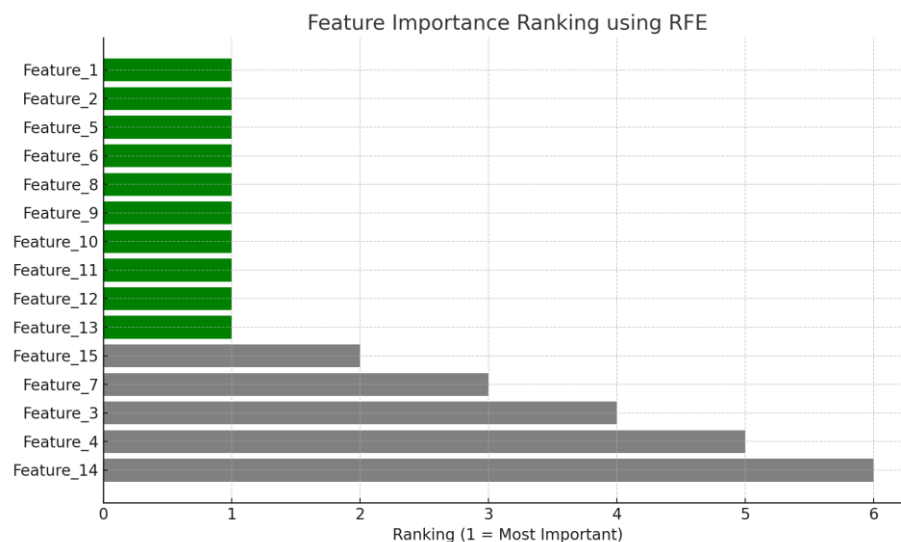


Figure Y. Feature Importance Ranking using Recursive Feature Elimination (RFE)



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Firm	Traditional RMSE	Hybrid RMSE
AABS	17.12	9.50
FRSM	16.94	8.95
HABSM	19.24	9.10
JDWS	18.78	8.85
MIRKS	18.05	9.25
NONS	17.92	9.40
SHMS	18.36	9.15
TICL	17.55	9.30

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