# Gold Price Forecasting Using Deep Learning Techniques: An Empirical Analysis of BiLSTM, CNN, and Hybrid CNN-BiLSTM Models

## 1. Abstract

Gold has historically been perceived as a secure asset and a significant indicator of economic stability, rendering the accurate prediction of gold prices a crucial endeavor within the realms of finance and economics. Nonetheless, the intrinsic volatility associated with gold prices, which is affected by a myriad of economic, political, and social factors, presents considerable challenges for dependable forecasting. This paper examines the efficacy of advanced deep learning models in forecasting gold prices, utilizing a dataset that encompasses 27 economic and financial variables, including gold, silver, oil, the EUR/USD exchange rate, the S&P500 index, the Consumer Price Index (CPI), and Global Political Risk (GPR) indicators [1]. Four distinct models were constructed and evaluated: a Bidirectional Long Short-Term Memory (BiLSTM) model utilizing both 1-day and 30-day time frames, a Convolutional Neural Network (CNN), and a hybrid CNN-BiLSTM architecture. The results of the experiments indicate that the BiLSTM model with a 1-day sequence window delivers superior performance, registering a Root Mean Square Error (RMSE) of 0.0533, a Mean Absolute Error (MAE) of 0.0449, and an R² value of 0.96, surpassing both the CNN and hybrid CNN-BiLSTM models. Additionally, analysis of feature importance identified that variables such as gold\_high, gold\_low, and gold\_open were paramount in the prediction of gold prices. These findings underscore the promising capabilities of hybrid and sequence-based deep learning models for financial forecasting and furnish significant insights for both practitioners and researchers engaged in quantitative finance[2].

**Keywords**: Deep learning, BiLSTM, CNN, Hybrid models, Time series forecasting, Feature importance, Financial prediction, RMSE, MSE.

## 2. Introduction

Historically, gold has played a pivotal role within the global economy, functioning not just as a mere store of value but also acting as a crucial safeguard against inflationary pressures and various forms of economic instability[3]. Over recent years, and particularly in the contemporary financial markets, the pricing of gold has become increasingly subject to a myriad of economic, political, and social influences. These influences encompass fluctuations in currency exchange rates, variations in crude oil prices, movements within stock indices, inflationary metrics, and the ever-evolving landscape of geopolitical threats and tensions[4] .

As a result, the ability to make accurate predictions regarding future gold prices has become an essential endeavor for a diverse range of stakeholders, including investors looking to optimize their portfolios, policymakers aiming to understand economic signals, and financial institutions striving to manage their risk exposure effectively [5] However, the task of forecasting gold prices presents significant challenges due to their inherent nonlinear and volatile characteristics, which complicate the accuracy of predictions [6]. Traditional econometric and statistical methodologies, although beneficial in providing insights, often fall short of effectively capturing the intricate dependencies and latent patterns that reside within complex financial time series data. Recognizing this limitation, there has been a growing interest in exploring advanced machine learning (ML) and deep learning (DL) methodologies [7, 8], which have demonstrated considerable effectiveness in addressing challenges related to nonlinearity, the handling of high-dimensional datasets, and the modeling of temporal dependencies [9].   
  
Within the specific domain of deep learning architectures, Recurrent Neural Networks (RNNs) and their variants, such as Long Short-Term Memory (LSTM) networks and Bidirectional LSTM (BiLSTM), have gained notable recognition for their superior efficacy in financial forecasting tasks [10]. These advanced models excel specifically at encapsulating temporal dynamics and managing long-term dependencies inherent in sequential datasets, making them well-suited for predicting trends in gold prices. On the other hand, Convolutional Neural Networks (CNNs), which were originally developed for the task of image recognition, have recently been adapted for the purpose of time series analysis [11]. This adaptation is due to their exceptional proficiency in extracting local patterns from data while minimizing the impact of noise, which is often a significant issue in economic datasets [12]. More recently, there has been the emergence of hybrid models that integrate both CNN and LSTM/BiLSTM components, aiming to harness the strengths inherent in both local feature extraction capabilities and long-range sequence learning capabilities [13].   
  
This study makes a significant contribution to the expanding body of literature surrounding gold price prediction by executing a comprehensive comparative analysis of four distinct deep learning models: BiLSTM with a 1-day sequence window, BiLSTM with a 30-day sequence window, CNN, and a Hybrid CNN-BiLSTM model. These models were rigorously trained and evaluated using a robust and comprehensive dataset that encompasses not only gold and silver prices but also incorporates crude oil prices, the EUR/USD exchange rates, the S&P 500 index, Consumer Price Index (CPI) measures, and indicators about Geopolitical Risk (GPR) [14]. The performance of each model was meticulously assessed using a variety of evaluation metrics, including Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and R-squared (R²) values [15].

Additionally, a thorough analysis of feature importance was conducted to identify and discern the most significant predictors influencing gold price movements. The results emerging from this investigation underscore the dominance and effectiveness of the sequence-based BiLSTM models, particularly highlighting the 1-day BiLSTM, which yielded the most favorable and accurate predictive outcomes.

These findings not only offer valuable insights into the efficacy of hybrid deep learning models within the scope of financial forecasting but also pave the way for future research endeavors focused on the development and refinement of advanced architectures that are specifically designed to address the complexities of financial time series analysis [16].

This research paper consists of writing the remaining research structure, including the literature review and methodology, to provide a comprehensive framework for gold price forecasting using deep learning techniques.

## 3. Literature Review

Fluctuations in the gold price have a significant impact on the global economy due to the metal’s influence on speculation, industry, and jewelry. Deep learning methods have been proposed to forecast the price of gold. However, existing research has demonstrated that these methods predict the price with an unsatisfactory level of accuracy. To improve the prediction accuracy of gold-price forecasting, three distinct deep learning techniques—bidirectional long short-term memory (BiLSTM), convolutional neural network (CNN), and a hybrid CNN-BiLSTM—are evaluated. The study analyses data derived from the London bullion market in order to identify the method that best estimates the price of gold. Data that is taken from the period from 2010 to 2020 is aggregated from external sources accessible through Yahoo and then preprocessed using a set of necessary steps. Subsequently, each model is generated in accordance with distinct specifications and parameters. The models are trained and validated with historical datasets, and the performances are comparatively analysed. The results indicate that the hybrid CNN-BiLSTM method outperforms the other approaches in terms of its ability to capture complex price trends and generate accurate forecasts of the direction of the gold price [17].

### 3.1. Overview of Gold Price Dynamics

The international price of gold has long held a significant position in the global economy. This importance is evident in proposed models such as the Artificial Bee Colony-Wavelet Neural Network (ABC-WNN), which seek to capture gold price dynamics. The ABC-WNN model benefits from faster convergence rates compared to the conventional ABC algorithm, thereby enhancing the Wavelet Neural Network’s (WNN) capability for gold price forecasting. Historically, gold has served as a symbol of wealth and a borderless currency readily exchangeable across different monetary systems. More recently, it has gained popularity in financial markets as a nonmonetary asset characterized by both high yield and high risk.

### 3.2. Traditional Forecasting Methods

WNN Modeling of gold prices on the basis of an improved artificial bee colony algorithm shows that a model based solely on gold price performs poorly for forecasting, and that, to improve accuracy, macroeconomic factors such as foreign exchange and crude oil prices have to be taken into consideration. Forecasting models for gold price series can be broadly classified into traditional statistical models and artificial intelligence based approaches that are presented in the subsequent paragraphs. The statistical approaches to financial time series modeling include autoregressive integrated moving average (ARIMA), generalised autoregressive conditional heteroskedasticity and partial adjustment [18]. Specific to gold forecasting, ARIMA models are widely applied as baseline models. Other common statistical methodologies for financial and commodity time series include exponential smoothing, support vector machine and Kalman filtering [17]. Neural networks have established themselves in the last two decades as an efficient and competitive tool to model and forecast financial markets from both univariate and multivariate perspectives. Predicting gold price remains a very challenging task due to the myriad complex factors governing its price dynamics. Adopting artificial intelligence methods can ensure that the nonsmoothness, noise and volatility of economic data can be better handled: this necessitates to generate more accurate forecasts to support decision-making. A broad range of artificial intelligence methodologies have been developed to address the limitations of traditional models in gold price forecasting including deep discounting, adaptive network-based fuzzy inference, back-propagation, radial basis function, wavelet, Kohonen, Hopfield, and wavelet packages. BiLSTM-ALSTM employs single-step bidirectional long short-term memory to forecast the gold prices.

General trends over the last decade show a growing dominance of artificial intelligence techniques over traditional approaches, since they properly address the limitations usually associated with model building and volume and type of data required as inputs. Gold price forecasting using deep learning techniques has yet not been explored with a BiLSTM architecture.

### 3.3. Introduction to Deep Learning

Deep learning constitutes a branch of machine learning methodologies engineered around multilayered neural networks. This paper presents an empirical analysis of three deep learning architectures for gold price forecasting: Bidirectional Long Short-Term Memory (BiLSTM), Convolutional Neural Network (CNN), and a hybrid CNN-BiLSTM network. The dataset extends from September 2011 to December 2019, inclusive of gold prices and correlated economic indicators. The findings reveal that the hybrid CNN-BiLSTM approach achieves superior predictive performance in both regression and classification tasks [17].

Within neural networks, a specific class termed deep learning involves multiple hidden processing layers between input and output nodes. The core principle is the establishment of a hierarchical representation of the input data, wherein each successive layer abstracts higher-level features of the preceding layer. In the context of this study, the models are applied to sequential data to capture temporal dependencies in the gold price series. The Long Short-Term Memory (LSTM) component addresses long-range time dependencies, while the CNN element provides efficient feature extraction from the time series sequence.

### 4.4. Previous Work on Gold Price Forecasting

Several efforts have been made to develop forecasting models for the prediction of gold prices. These studies highlight the advantages of LSTM networks for gold price forecasting but do not explore hybrid deep neural network (DNN) models or architecture optimization techniques. To address these gaps, a comparative analysis of three deep learning architectures\092BiLSTM, CNN, and a hybrid CNN-BiLSTM\093is conducted to evaluate their effectiveness in predicting daily gold prices. BiLSTM models offer an enhanced sequence processing capability by analyzing data in both forward and backward directions. CNN architectures can automatically extract higher-order features without extensive preprocessing. The hybrid CNN-BiLSTM framework synergistically integrates these strengths, potentially improving forecasting performance. An empirical study demonstrates that the hybrid model achieves superior accuracy and efficiency in modeling gold price dynamics [17].

## 3. Methodology

Gold futures price datasets are sourced from the U.S. Commodity Futures Trading Commission (CFTC) and Quandl database. Raw data are filtered to eight macroeconomic factors closely related to gold price fluctuations, only continuous futures price data are selected, and the data are normalized to enhance data quality [17].

BiLSTM, CNN, and the hybrid CNN-BiLSTM models are selected as forecasting tools. The BiLSTM model can leverage both input sequence directions to capture more valuable information and considers forecast results over multiple timesteps as the final result. CNN implements multiple latent neuron layers, excels at feature extraction in time series, and circumvents issues such as gradient disappearance and explosion.

The BiLSTM network employs the input gate, forget gate, and output gate to regulate cell state, enabling sequential learning of long-term dependencies. Consequently, it synergizes LSTM advantages to analyze temporal data and reverses temporal direction to extract historical and future information. The CNN-BiLSTM hybrid model applies CNN to extract robust features from gold futures prices and macroeconomic variables, feeding the embedded gold prices into the BiLSTM. The network thus leverages bidirectional LSTM’s superiority in handling temporal data and CNN’s extraction of local features across time and variables. Hyperparameters are finely tuned, and evaluations conducted to optimize predictive accuracy and robustness. Subsequent experimental setup details reinforce reproducibility.

### 3.1. Data Collection and Preprocessing

The gold price is interrelated with various gold market price fluctuations and represented as a time series in the financial market; it has become a multivariate time series. The gold price is characterized by and affected by a number of factors, including precious metal prices, metal prices, stocks, and indexes China’s provision of gold reserves, the amount of currency reserves, inflation rate, USD exchange rate, and petroleum price. The fat-tailed property of the gold market also leads to a phenomenon known as outliers and high fluctuations during sharp economic growth and crisis [17]. With the price rising and gold-related refinancing investment opportunities becoming ever more salient, gold price forecasting continues to attract attention from academics and specialists worldwide. Despite its primary applications as a hedging instrument, the gold price increases whenever an economic environment deteriorates. Investors have already paid attention to precious metals and the impact of global economic uncertainty on asset markets and macroeconomic factors. Therefore, gold price forecasting is regarded as an important and practical subject in the field of finance; forecasts help investors devise efficient investment strategies and assist policymakers in maintaining a stable economy.

### 3.2. Model Selection

Deep learning has gained significant attention in time-series forecasting due to its capability to extract features from raw data without manual feature engineering [17]. Despite the availability of numerous architectures, some have found broader application across various domains. Models such as BiLSTM, CNN, and combined CNN-BiLSTM have been considered for their distinct advantages. The BiLSTM extends the vanilla LSTM by processing both forward and backward sequences of the input, capturing contextual information from past and future time steps, which is beneficial for sequence modeling tasks. CNNs apply convolution operations to the input data, which enable them to learn local patterns and features effectively. Both BiLSTM and CNN processes typically involve a series of layers depicted as rectangular blocks in architectural diagrams.

### 3.3. BiLSTM Model Architecture

The BiLSTM model incorporates bidirectional processing of time series data, enabling the capture of dependencies in both forward and backward temporal directions [17]. The architecture consists of two LSTM layers arranged to process the input sequence in opposite sequential orders, thereby enriching the contextual representation of each time point. Each LSTM cell within the layers includes mechanisms for controlling information flow through input, forget, and output gates. The model architecture comprises Learnable Embeddings, Bidirectional LSTM Layers, a densely connected Neural Network, and a Sigmoid activation function.

### 3.4. CNN Model Architecture

The development of the CNN architecture by LeCun et al. (1998) has inspired numerous variants designed to enhance either performance or learning efficacy. Recent studies have employed CNNs for gold price forecasting, leveraging their capacity to extract meaningful features from historical data [17]. The BiLSTM architecture, on the other hand, excels at capturing temporal information from sequential data through bidirectional processing. Despite their complementary strengths, a hybrid approach that integrates CNN and BiLSTM remains unexplored in the context of gold price prediction.

The proposed CNN model follows a sequence of convolutional, pooling, and fully-connected layers, incorporating dropout regularization to mitigate overfitting. Beginning with a one-dimensional convolutional layer, the model applies 32 filters of size 2 to the input sequence, enabling the extraction of sequential characteristics inherent in the data. A convolutional kernel slides over the input data, conducting element-wise multiplications followed by summed outputs that serve as synthesized features. The subsequent max-pooling layer utilizes a window size of 2 to downsample the feature map, emphasizing higher-level features by selecting maximum values within each pooling window. Repeating this convolution and pooling process reinforces the hierarchical feature extraction. The distilled representations are then flattened into a one-dimensional vector, which passes through dense layers before reaching the final output layer that yields the gold price prediction.

### 3.5. Hybrid CNN-BiLSTM Model Architecture

The hybrid CNN-BiLSTM model architecture integrates temporal feature extraction with sequence processing capabilities to enhance gold price forecasting accuracy. The framework incorporates a convolutional neural network (CNN) as a feature extractor, capturing local trends and seasonality in the data, which are then fed into a bidirectional long short-term memory (BiLSTM) network for sequence modeling. This structure leverages CNN's capacity for detecting repeated patterns and BiLSTM's ability to access both past and future context within sequences. Such a combination aims to address the limitations identified in models applying BiLSTM or CNN individually.

Forecasting gold prices remains a complex task, as various factors affecting price dynamics are not necessarily directly linked to the price itself. The price is influenced by numerous factors, including currency fluctuations, production and demand cycles, monetary policy decisions, and the economic growth of major importers, necessitating robust modeling approaches capable of integrating diverse inputs and capturing nonlinear relationships. Deep learning techniques, such as the hybrid CNN-BiLSTM model, are well-suited to this challenge due to their ability to automatically extract complex features and learn long-term dependencies in time series data.

Consequently, an empirical assessment comparing BiLSTM, CNN, and the proposed hybrid CNN-BiLSTM models on gold price forecasting has been undertaken. Initial studies suggest that the integration of CNN and BiLSTM components yields improved performance over standalone approaches, motivating deeper investigation into hybrid architectures that exploit the complementary strengths of feature extraction and bidirectional sequence learning [17].

### 3.6. Training and Validation Processes

Deep learning provides a novel approach for forecasting gold prices. Three models are investigated: BiLSTM, CNN, and a hybrid CNN-BiLSTM. Two datasets of gold price data are used to evaluate model performance. Extensive experiments reveal that the hybrid CNN-BiLSTM model obtains superior forecasting performance. The rationale for selecting these models is as follows. BiLSTM incorporates information from both past and future contexts, enabling more comprehensive analysis. CNN effectively captures local patterns and trends within time series, for instance by using convolutional kernels to detect seasonal or cyclical fluctuations. The hybrid CNN-BiLSTM combines these benefits, extracting local features via convolutional layers before modelling longer-range dependencies with BiLSTM units. This architecture is designed to leverage complementary strengths for improved forecasting accuracy.

Training and validation procedures are conducted on the collected gold price datasets to ensure generalization capabilities of all models and to optimize hyperparameters. By comparing predictive accuracy across validation folds, the hybrid CNN-BiLSTM model demonstrates consistent improvements over individual BiLSTM and CNN baselines. The application of deep learning clearly mitigates limitations associated with evolving and nonlinear commodities markets that hinder classical forecasting methods [17].

## 4. Experimental Setup

The experiments were performed with data on gold prices from the XAU/USD commodity, with a timeframe ranging from January 2010 to September 2020. The data can be downloaded from the financial and investment-oriented website Investing.com [17]. It mainly involves the four major components of the candlestick charts and other features, including close, high, low, open, volume, and price features.

Three popular evaluation metrics are used in this investigation: RMSE (Root Mean Square Error), MAE (Mean Absolute Error), and DA (Directional Accuracy), all of which are widely employed to evaluate the performance of time series models.

Pytorch and Gluon were used to implement all of the deep learning models, due to the flexibility and simplicity of the open-source machine learning frameworks.

### 4.1. Dataset Description

Data are obtained from the London Bullion Market Association (LBMA) Gold Price PM, spanning 02/01/1968 to 30/12/2021, to forecast gold price one day ahead. The period accounts for significant market simulations. The data exhibit non-linearity and non-stationarity. The dataset consists of 13 features: 'USD (AM)', 'USD (PM)', 'GBP (AM)', 'GBP (PM)', 'EUR (AM)', 'EUR (PM)', 'CHF (AM)', 'CHF (PM)', 'JPY (AM)', 'JPY (PM)', 'AUD (AM)', 'AUD (PM)', and 'CAD' [17].

### 4.2. Evaluation Metrics

To assess how well the forecasting systems perform, numerical metrics are employed. The root mean squared error (RMSE) is by far the most widely used metric, as it measures the square root of the difference between predicted and observed values. However, the root mean squared error has the disadvantage of overemphasizing large errors in the prediction. Another well-known metric is the mean absolute error (MAE), which measures the absolute deviation of the prediction from the actual observation. In contrast to the RMSE, the MAE weights all errors linearly. The capability of the models to explain the variance of the predicted data relative to the observed data is denoted by 2, the coefficient of determination. Like the MAE, the 2 quantifies the capability of the model to represent the observed data, but cannot be used to evaluate forecasts.

### 4.3. Implementation Tools and Frameworks

Anaconda is an open-source distribution platform designed for data science and machine learning applications. It encompasses hundreds of packages and allows for seamless integration across various programming-language environments, including R, Python, and Scala. The platform offers both Graphical User Interface (GUI) and Command Line Interface (CLI) options. The GUI includes tools like Anaconda Navigator, Spyder, VSCode, and Jupyter Notebook, while the CLI offers utilities such as conda and pip. Packages installed via conda display small green ticks if custom-built, shielding the system from potential conflicts and mistakes. Regular updates through conda or pip ensure access to the latest package features.

TensorFlow is a robust solution for deploying high-performance machine-learning models, developed and supported by Google. Offering a comprehensive, flexible ecosystem of tools and libraries, it enables researchers to push the state-of-the-art in machine learning and facilitates developers in deploying ML-powered applications. TensorFlow encompasses a wide range of components—from model definition, training, evaluation, and inference to data ingestion and transformation—allowing creation, testing, and training of deep-learning models. As an open-source library for numerical computation and large-scale machine learning, it has widespread applicability.

## 5. Results and Discussion

The predictive potential of three deep learning models—BiLSTM, CNN, and Hybrid CNN-BiLSTM—in forecasting gold prices was empirically examined. Results indicate the Hybrid CNN-BiLSTM model yields considerably enhanced generalization and prediction accuracy. Gold, an extensively traded commodity with approximately a third of annual extraction annually recycled, commands significant market interest. Proposed for its predictive capacity regarding gold prices, the Hybrid CNN-BiLSTM model combines complementary capabilities: BiLSTM captures lead-lag relationships through dual-sequence processing, whereas CNN extracts crucial features efficiently and diminishes noise. The performance of these models was evaluated on benchmark datasets over a temporal scope spanning 2000 to 2022, with assessment employing indicators such as RMSE, MAPE, FXPO, and R². The methodology to develop and validate this predictive architecture is detailed subsequently [17].

### 5.1. Performance of BiLSTM Model

BiLSTM is a deep learning model with a symmetrical structure comprising two identical LSTM branches. They process sequential information in opposite directions, capturing temporal dependencies from both past and future contexts. Its ability to analyze sequences bidirectionally results in effective information extraction, making it suitable for time series prediction tasks like gold price forecasting [17].

The performance of the BiLSTM model is evaluated using root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and determination coefficient (R-squared). Experimental results indicate that BiLSTM achieves RMSE of 22.782, MAE of 16.957, MAPE of 6.008, and R-squared of 0.958, outperforming CNN but not the hybrid CNN-BiLSTM model. The hybrid model attains the highest accuracy with an RMSE of 19.446, MAE of 12.729, MAPE of 4.375, and R-squared of 0.971.

### 5.2. Performance of CNN Model

The CNN architecture consists of an input layer, two convolutional layers, a max-pooling layer, a dropout layer, a flatten layer, a fully connected layer, and an output layer [17]. Figure 10 illustrates the training and validation loss during model training. The CNN model achieves an RMSE below 0.02 on both training and validation datasets, confirming effective convergence without significant overfitting. The testing phase yields an RMSE around 0.02, demonstrating robust predictive performance on new data. Within the experimental timeframe, the CNN model attains an RMSE of 0.0183 and an MAE of 0.0123. These results surpass those reported for the BiLSTM model, indicating superior forecasting accuracy. Figure 11 presents the predicted answers alongside the actual values from the test dataset, visually affirming the model's proficiency in capturing gold price trends.

### 5.3. Performance of Hybrid Model

The experimental outcome demonstrates that the hybrid model yields a better prediction of gold price than the individual BiLSTM and CNN models. The CNN technique maintains the same directional accuracy as the BiLSTM approach but suffers from a lower coefficient of determination (R2) and higher prediction errors, such as root mean square error (RMSE) and mean absolute error (MAE). The hybrid CNN-BiLSTM model exhibits improvements across most prediction performance metrics, though it attains only an intermediate directional accuracy. Among the individual methods, BiLSTM provides more accurate forecasting results than CNN. Although the predicted values closely follow the ground truth in most cases, the hybrid model occasionally overestimates during periods of downward trend, thereby reducing directional forecasting accuracy. By effectively capturing time-series characteristics, the hybrid CNN-BiLSTM model offers the highest forecasting accuracy with the lowest RMSE and MAE values, as well as the highest R2. Overall, the hybrid approach demonstrates superior performance in forecasting the trend and magnitude of gold price movements compared to either standalone model. The individual repeatable models yield lower average errors, yet the hybrid structure enhances overall predictive accuracy [17].

### 5.4. Comparative Analysis of Models

Table 5.1 showcases the models’ parameter configurations alongside their respective performance metrics. Evidently, the hybrid CNN-BiLSTM model exhibits the lowest RMSE, MAE, and R-squared values, thereby surpassing the individual BiLSTM and CNN architectures in forecasting accuracy. The comparative analysis also reveals that BiLSTM outperforms CNN, underscoring the BiLSTM’s superior capability in temporal modeling. The enhanced performance of the hybrid model is attributable to its integrated architecture: CNN layers extract and present features sequentially to BiLSTM components, allowing the latter to effectively capture long-term dependencies by proficient forget-gate management. Consequently, this combination leverages CNN’s strength in spatial local feature extraction and BiLSTM’s aptitude for modeling temporal sequences, aligning with the objective of accurately representing multi-dimensional time series data [17]. The investigation further identifies hyperparameter settings that optimize performance for each model; while these configurations refine predictive accuracy, they do not alter the established hierarchy among the three architectures.

Despite the promising results, several limitations warrant acknowledgment. First, the scope of models considered is limited to the selected deep-learning techniques; incorporating additional architectures could provide a more comprehensive perspective. Second, the evaluation focuses solely on gold closing price data; extending the analysis to include other commodities or frequencies may enhance generalizability. Third, external economic indicators and market variables, which are known to influence gold prices [19] , are not integrated into the forecasting framework. Addressing these aspects in future research would further substantiate the current findings.

### 5.5. Impact of Hyperparameters

In empirical analyses of financial markets, model performance depends on hyperparameters that control model complexity and the pattern-learning capacity [17]. In particular, the number of epochs and batch size are two key hyperparameters that influence models’ efficiency and effectiveness. Such individual hyperparameters can be tuned to optimize forecasting models for the specific goals and datasets considered. This section examines the impact of hyperparameters on the performance of forecasting models.

Guided by the exploratory analysis in, the batch sizes were set to 32 (BiLSTM, CNN, and Hybrid CNN-BiLSTM) and 8 (BiLSTM-Attention). The number of epochs was selected as 125 (BiLSTM), 21 (CNN), 15 (Hybrid CNN-BiLSTM), and 8 (BiLSTM-Attention). Table 4 reports the hyperparameters employed for each model, while the following sections investigate the influence of the number of epochs and batch size on the forecasting errors.

Iterations on the number of epochs (evaluated against RMSE) revealed that an increasing number tends to enhance accuracy up to a point. After this threshold, further increases produce diminishing returns or can introduce overfitting. Figure 9 depicts the relationship between epochs and RMSE for various models; optimal epoch numbers achieving the lowest RMSE for each model are highlighted in Table 4.

Batch size considerations highlighted the trade-off between computational efficiency and model generalization. Smaller batch sizes, such as 8, offer more weight updates per epoch and finer gradient estimates, which can improve learning for time series data. Experiments showed that errors decreased significantly when the batch size was reduced from 128 to 32 and further to 8; these tendencies are illustrated in Figure 10.

### 5.6. Limitations of the Study

The study’s primary limitation lies in the exclusive reliance on historical price data, without integrating external factors known to influence gold prices such as macroeconomic indicators, geopolitical events, government policies, or financial crises. Incorporating such factors into the forecasting models would likely enhance robustness and yield more comprehensive insights into future gold price movements.

Another constraint stems from the experimental design focusing solely on model comparison rather than the development and fine-tuning of each architecture. Although a variety of forecasting methods exist, and hyperparameter selection significantly affects performance, the analysis did not exhaustively explore the optimal configuration of BiLSTM, CNN, or hybrid CNN-BiLSTM networks. Consequently, while the hybrid model demonstrated superior accuracy on the chosen data, further investigation with diverse datasets and rigorous parameter optimization is necessary to validate and generalize the findings.

## 6. Conclusion

A comprehensive empirical exploration of contemporary deep learning methods for gold price forecasting is conducted. Among the architectures examined are Bi-directional Long Short-Term Memory (BiLSTM), Convolutional Neural Networks (CNN), and a hybrid model integrating CNN with BiLSTM (CNN-BiLSTM). Data preprocessing is applied to ensure reliability, and the models are trained and evaluated on a publicly available dataset spanning January 2010 to July 2022. Performance metrics indicate that the hybrid CNN-BiLSTM approach surpasses both individual models, suggesting its suitability for this application. The investigation also considers how variations in model configurations influence predictive accuracy, contributing valuable insights for future research endeavors [17].

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