Research Article

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Advanced Predictive Models and Their Role in Decision Support Systems for Managing the COVID-19 Pandemic: A Case Study of the Kingdom of Saudi Arabia

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Abstract

Background. The recent global pandemic created unique difficulties for healthcare systems all around the world that required accurate predictions to make decisions about resources management and other factors. For Saudi Arabia, an essential component for managing a crisis like this includes analyzing the dynamics of changes within case numbers. **Aims.** This paper seeks to improve healthcare decision-making by conducting a comparative assessment of the prediction accuracy of various machine learning models used for forecasting COVID-19 cases in Saudi Arabia. **Methodology.** Five ML models will be considered in this study – Decision Tree Regressor, Random Forest Regressor, LSTM, CNN, and SARIMAX. The selected models will be trained using the series of time-related data concerning the number of patients confirmed with coronavirus in Saudi Arabia. Models' performance will be assessed based on MAE, RMSE, and R^2 metrics. **Results.** The results revealed Random Forest as the most accurate model with a set of metrics being (MAE: 0.214106, RMSE: 0.809336, R^2: 0.999997). The second place went to Decision Tree with MAE equaling 0.466465, RMSE equaling 1.168835, and R^2 equaling 0.999976. As for the third and fourth places, both deep learning models achieved comparable metrics and significantly outperformed ARIMA and SARIMAX. **Conclusion.** Machine learning models have proven their efficiency in such applications. The study identified a need for region-specific predictive models. It also pointed to a necessity to integrate data and create a model with greater accuracy and speed of processing.

Keywords: COVID-19 prediction, machine learning, random forest, decision tree, SARIMAX, healthcare, decision-support systems, time series forecasting

ABBREVIATIONS

AI is an artificial intelligence;
AR is an autoregressive;
ARIMA is an autoregressive integrated moving average;
CDMOs is a chief district medical officers;
CDSS is a clinical decision support system;
CNN is a convolutional neural network;
COVID-19 is a coronavirus disease 2019;
DDMA is a district disaster management authority;
DSO is a district surveillance officer;
HESN is a health electronic surveillance network;
LSTM is a long short-term memory;MA is a moving average;
MAE is a mean absolute error;
ML is a machine learning;
PHIS is a public health information system;
RMSE is a root mean squared error;
RNN is a recurrent neural network;
SARIMAX is a seasonal autoregressive integrated moving average with eXogenous variables;
WHO is a world health organization

NOMENCLATURE

$\beta$is a backward shift operator;
$B$is a number of trees in random forest;
$R^2$is a coefficient of determination;
$X$is an input data matrix (e.g., image or time-series grid);
$\beta X_t$is a contribution of exogenous variables in SARIMAX;
$b$is a bias term in CNN layer;
$c_i$is a Predicted value in region R_i;
d, D are an orders of differencing (regular and seasonal) in SARIMAX;
$\varepsilon_t$is an error term at time t;
$\hat{f}\left(x\right)$ is a final prediction from the random forest model;
$f\left(x\right)$is a prediction function for decision tree regressor;
$f_\beta\left(x\right)$ is a prediction from the b-th tree in random forest;
$I\left(x \in\ R_i\right)$ is an indicator function (1 if x is in regionR_i, else 0);
K_{mn} is a kernel (filter) used in CNN;
$p, q$is an orders of the AR and MA components respectively;
$R_i$is a region associated with leaf node i;
$s$is a length of seasonal cycle in SARIMAX;
$x$is an input feature vector;
$\gamma_t$is an observed value at time t;
$Z_{ij}$is an output feature map element in CNN;
$\phi\left(B^s\right)$ is a seasonal AR polynomial in SARIMAX;
$\Theta\left(B^s\right)$ is a seasonal MA polynomial in SARIMAX;
$\varphi$is an autoregressive (AR) coefficient;
θ is a moving average (MA) coefficient;

1. INTRODUCTION

COVID-19, which is caused by the SARS-CoV-2 virus, has been identified in Wuhan, China, at the end of 2019 [1]. On March 11, 2020, the World Health Organization (WHO) announced the COVID-19 outbreak as a pandemic because of the rapid spread worldwide [2]. From there on, the coronavirus had an immense effect on global health, economic, and cultural sectors, including the Kingdom of Saudi Arabia [3].

The rapidly spreading nature of this outbreak meant that patients, healthcare practitioners, and officials had to make quick and often challenging decisions with insufficient information available. Thus, early and accurate pre-dictions of COVID-19 case numbers were identified as essential components in allocating healthcare resources efficiently [4]. Clinical Decision Support Systems (CDSS) became powerful instruments to facilitate early diagnosis, screening, and treatment choices. Such systems provide personalized solutions based on unique patients' data from different sources, including imaging, clinical tests, and medical history [1].

As part of its response to the pandemic, Saudi Arabia used various digital systems, such as the COVID Patient and Facility Management Information System, which helped coordinate district-level actions that were largely taken by institutions, such as DSOs, CDMOs, and DDMA [6]. Nevertheless, the rapid growth of mHealth and digital technologies contributed to the accumulation of a great amount of structured and unstructured data [7]. The digital revolution in the healthcare industry enabled government agencies and companies to use big data and analyze it quickly and effectively [8].

Big data analytics play a crucial role in detecting epidemic trends, helping with diagnosing, and providing preventive measures through mining insights from massive and complicated datasets [9]. Moreover, these analytical methods, together with data science, computer science, and computational biology, can be employed to assist with epidemiological research, medication development, and diagnostics [9]. Predictive analytics, algorithmic approaches, and mathematical models are often applied in order to forecast the number of COVID-19 cases; investigate spread and potential risks [10].

As part of their efforts to monitor public health activities throughout the pandemic, Saudi Arabia established several digital health projects, including the Health Electronic Surveillance Network (HESN) and the Public Health Information System (PHIS). Nevertheless, there are only a few studies from Saudi Arabia applying machine learning techniques to forecast the mortality rate and risk factors for this disease [11]. In general, conventional statistics does not always consider the complicated relationship between different variables, thereby being inefficient in dealing with pandemic situations [12].

One such study revealed that machine learning algorithms, namely Random Forest, Decision Trees, Linear Regression, and SARIMAX performed effectively in predicting COVID-19-related metrics, including hospitalizations and recoveries. Moreover, the paper stressed the importance of having high-quality data, proper feature selection, and thorough model validation for accurate predictions. Such models serve as a basis for evidence-based policymaking and efficient treatment of patients in case of pandemics. This study aims at enhancing decision-support systems in healthcare by testing the predictive capabilities of various machine learning (ML) models in forecasting COVID-19 cases in the Kingdom of Saudi Arabia [13].

The object of study is the examination of machine learning models and big data analytics in managing the COVID-19 pandemic, taking into account their rare application in the Kingdom of Saudi Arabia. Almost all models used internationally operate under general assumptions, without accounting for the specificity of health infrastructure and demography in certain regions.

The subject of study is the Kingdom of Saudi Arabia's health system along with its unique features, including centralization and rapid adoption of digital solutions in the health sector. Moreover, there is a notable absence of regionally-targeted studies that limit practitioners in implementing predictive tools to improve healthcare services.

The purpose of the work is to cover the gap that appears due to the lack of comparative research that evaluates the performance of ML models by utilizing COVID-19 data of the Kingdom.

2. PROBLEM STATEMENT

The experience with management of the coronavirus outbreak revealed the critical significance of precise forecasting technologies for assisting decision making in the healthcare sector. Machine learning models and data science approaches were actively implemented throughout the world to predict the spread of the pathogen and inform further steps of the authorities. Nevertheless, it is essential to note that most of these predictive solutions are based predominantly on global parameters, generalizations, and assumptions that are not completely reflective of the specifics of each nation's healthcare infrastructure, demographics, or socio-cultural context. For instance, in case of the Kingdom of Saudi Arabia, it is critical to acknowledge the existence of distinctive features related to healthcare decisions, population dynamics, and government policies, which make current predictive models inaccurate and unreliable.

The peculiarities of the local healthcare system consist in centralized decision-making, along with rapid integration of advanced tools, including digital health platforms, electronic health records (EHR), and telehealth services. In spite of these positive aspects, one cannot ignore the absence of adequate research on the development and application of region-specific machine learning models that would take into consideration local socio-epidemiological circumstances. As a result, healthcare specialists can hardly apply these algorithms to forecast epidemics and develop proper response measures. Thus, without the development of local predictive solutions, the decision-making process can be compromised, which can negatively affect public health.

Thus, there is a need to conduct a comparative analysis of the application of several predictive machine learning models in Saudi Arabia. This research should focus on assessing models such as ARIMA, SARIMAX, Random Forest, Decision Tree, LSTM, and CNN. It is expected that these analyses will allow for determining the most effective and sustainable predictive technologies. Importantly, the results can become instrumental in developing and refining decision support systems, allocating healthcare resources efficiently, and informing public health policies in Saudi Arabia.

3. REVIEWS OF THE LITERATURE

The onset of the novel coronavirus in early 2020 has spurred increased interest in research involving predictive modeling and decision support systems for health emergencies. Initial research was primarily concerned with virus detection and characteristics [1]. Moreover, the outbreak has been declared a global pandemic by the World Health Organization [2], hence spurring the adoption of artificial intelligence (AI) technology in global healthcare. Researchers later turned their attention to exploring patient recovery outcomes [3] as well as developing predictive models of infection trajectories [5, 7]. Although deep learning approaches, similar to those employed in [5], appear efficient at forecasting patient trajectory trends, their reliability in actual health emergency settings remains under question [14].

In the Kingdom of Saudi Arabia, there have been several important initiatives in digital health involving the Health Electronic Surveillance Network (HESN) and the Public Health Information System (PHIS). However, only a few studies in the area of predicting COVID-19 mortality and risk factors have emerged from the country, despite the existence of many machine learning approaches to the problem [11]. Indeed, traditional statistical models often fail to account for complex interactions among multiple variables in a dataset, rendering them less effective at predicting future developments in a pandemic [12].

A recently conducted study revealed that machine learning models based on Random Forest, Decision Trees, Linear Regression, and SARIMAX proved to be effective at predicting various aspects of patient recovery and mortality due to COVID-19. In this instance, Random Forest performed better than the other models [13]. Overall, high quality of input data, proper feature selection, and model validation played an instrumental role in accurate predictions. Such machine learning models pave the way for evidence-based policymaking as well as better patient care [13]. The present study seeks to improve existing healthcare decision-support systems through comparative assessment of predictive performance of various machine learning models in predicting COVID-19 cases in Saudi Arabia.

Machine learning models have also been incorporated into CDSS and applied to diagnosing diseases and performing patient triaging during pandemics [6, 11]. A number of studies demonstrate the importance of big data analytics in improving epidemic response efficiency, especially when applied in dynamically changing environments such as Saudi Arabia [8, 9, 10]. In this regard, Alsunaidi et al. [10] show how sensor-based big data analytics could be used for monitoring patients during the pandemic. On the other hand, Awotunde et al. [9] provide a review of scalable data management platforms for pandemic management based on artificial intelligence. Also, expert systems for clinical decision making tailored to specific environments have been shown to be crucial for disease diagnostics under regional constraints [11, 13].

A comparative evaluation of the machine learning models demonstrates that ensemble models such as Random Forest perform better compared to traditional statistical models owing to the ability of former to capture nonlinear features of disease development. At the same time, models such as SARIMAX and ARIMA appear inferior because their reliance on time series analysis makes them less efficient in capturing fast and unpredictable developments typical of pandemic [14]. Therefore, it appears imperative to develop models that would combine domain-specific knowledge and adaptability through advanced machine learning. Also, the incorporation of data on non-pharmaceutical interventions, demographics, and ICU treatment outcomes enhanced model training and prediction precision [4, 12].

Notwithstanding these achievements, there remains a gap in the adaptation of models to specific environments of different countries. Indeed, while studies make extensive use of global databases, there are relatively few studies focused specifically on Saudi Arabia [13]. Consequently, there remains a gap in utilizing AI-powered technologies for national healthcare systems, which require specialized modeling owing to unique features of the local environment [11, 13].

4. MATERIALS AND METHODS

Several reliable models that had been used repeatedly for COVID-19 case predictions globally were reviewed comparatively. The models in question are diverse and include not only basic statistical models but also various advanced machine learning architectures that can be successfully applied for epidemics' forecasts. The Decision Tree Regressor model relies on the rule-like construction that is straightforward for reading and interpreting; however, it tends to overfit, especially on highly complex datasets. The Random Forest Regressor is another machine learning model that constructs a large number of decision trees and combines their output values to increase the accuracy rate and prevent overfitting.

Furthermore, two other models, which involve classical statistical approaches to forecasting, were included in the analysis – the ARIMA and SARIMAX. They represent sophisticated yet well-known frameworks for working with temporal data that are widely used for different forecasting purposes. Finally, one model of a deep learning architecture was implemented, namely, Convolutional Neural Networks (CNNs). Although CNNs are commonly used for spatial data analysis, their applicability was extended to sequence modeling as well since CNNs demonstrated their efficiency in time series forecasting.

Data for this study was collected from open-access sources that can be regarded as credible within the scope of Saudi Arabia. Thus, it includes daily counts of new cases, recoveries, and deaths caused by the novel coronavirus, as well as such additional information as demographics and records of policies introduced during the pandemic period.

Ensuring the high-quality data is essential for achieving accurate results when developing models; thus, the obtained dataset was carefully checked for completeness, precision, and reliability, forming the background for further analysis and predictions.

To evaluate the studied models, three main criteria were defined. First, the Mean Absolute Error (MAE) was used for calculating the arithmetic mean of absolute errors that gives a general idea of how precise the model is at predicting values. Second, the root-mean squared error (RMSE) criterion was calculated, allowing the model to emphasize larger errors since all differences between expected and actual values are squared. Finally, the coefficient of determination or R^2 was used for estimating how well a certain model captures the data patterns.

The process of model comparison was organized based on the following stages. At first, an extensive literature review was carried out to collect relevant performance metrics (MAE, RMSE, and R^2) of each model from previous research on COVID-19 forecasting. Then, a systematic comparison was conducted with the help of a matrix outlining the advantages and disadvantages of each model.

Mathematically, the models can be described as follows. Decision Tree Regressor predicts outcome values depending on the division of the input space on several regions, where the prediction is a weighted sum over these regions. Random Forest model involves constructing an aggregation of decision tree predictors, resulting in an enhanced performance of the model. ARIMA predicts time series by using its autoregressive and moving averages components along with integrated differencing. SARIMAX builds upon ARIMA adding the seasonal component and external variables to model time series. As for CNN, its prediction is performed via performing convolution operations on input data.

The mathematical representations of models used for predictions in this study are shown below.

$$f(x) = \sum_{i=1}^{M} c_i 1_{\{x \in R_i\}}, \tag{1}$$

where R_i denotes the i-th partition of the feature space, c_i is the predicted value assigned to that region, and $\mathbf{1}_{\{x \in R_i\}}$ is an indicator function.

For the random forest regressor, the final prediction is obtained by averaging the outputs of B individual decision trees:

$$\hat{f}(x) = \frac{1}{B} \sum_{b=1}^{B} f_b(x), \tag{2}$$

where $f_b(x)$ represents the prediction of the b-th tree and B is the total number of trees in the ensemble.

For the autoregressive integrated moving average model, ARIMA(p, d, q), the general autoregressive and moving-average structure can be written as:

$$y_t = c + \sum_{i=1}^{p} \varphi_i y_{t-i} + \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} + \varepsilon_t, \tag{3}$$

where y_t is the observed value at time t, c is a constant term, φ_i denotes the autoregressive coefficients, θ_j denotes the moving-average coefficients, and ε_t is the error term.

For the seasonal autoregressive integrated moving average model with exogenous variables, SARIMAX, the model can be expressed as:

$$\varphi(B)\Phi(B^s)(1-B)^d(1-B^s)^D y_t = c + \theta(B)\Theta(B^s)\varepsilon_t + \beta^T X_t, \tag{4}$$

where B is the backshift operator, s is the seasonal period, d and D denote the non-seasonal and seasonal differencing orders, respectively, X_t represents the vector of exogenous variables, and β is the corresponding coefficient vector.

For the convolutional neural network, the convolution operation at position (i, j) is defined as:

$$Z_{ij} = \sum_{m} \sum_{n} X_{i+m, j+n} K_{mn} + b, \tag{5}$$

where X denotes the input matrix, K is the convolution kernel, b is the bias term, and Z_{ij} represents the resulting feature value at position (i, j).

5. EXPERIMENTS

The experiment comprised training and testing of the selected prediction models on a time series of data related to the course of COVID-19 in Saudi Arabia. This database contains information about the daily numbers of infections, recovered patients, and deaths associated with coronavirus, as well as demographic data and interventions made in relation to them, which underwent meticulous quality assurance. In order to make it ready for effective learning, the data was pre-processed. Models were created using widely known software packages with a fine tuning of hyperparameters based on the method of cross-validation.

Decision Tree Regressor and Random Forest Regressor utilize their inherent capacity to forecast nonlinear dependencies and, hence, could be used without changes. On the other hand, ensemble averaging allows Random Forest to avoid overfitting and decrease its variance. SARIMAX is a seasonal ARIMA model with external regression variables, which can help capture dependencies and impacts on the disease development in the context of COVID-19. The two neural network architectures LSTM and CNN, were implemented with an adequate number of layers and units and trained on numerous epochs until convergence.

Three key metrics were used to evaluate the models' effectiveness. They are mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2). This set of measures allowed conducting a thorough check of prediction accuracy, sensitivity to gross errors, and the level of variance explained by models. Experimentation was performed in multiple iterations to obtain reliable results, accompanied by systematic documentation and comparison of the results. It has been found out that Random Forest Regressor is the optimal choice in terms of prediction accuracy and stability ($R^2 > 0.95$) and, hence, lowest prediction errors. At the same time, statistical models such as SARIMAX proved to be unable to capture non-linearities in data, while deep learning models showed intermediate performance and required considerable computer power and fine tuning.

The results presented above show the practical significance of the use of ensemble machine learning approaches in predicting epidemics in a limited area. The results indicate the importance of creating a regionally adapted predictive model to assist decision-making and resource allocation during public health emergencies.

6. RESULTS

This section presents a detailed overview of the performance of several machine learning models used for COVID-19 prediction in Saudi Arabia. The analysis employs three key error metrics (MAE, RMSE, and R^2) used both in the present research and in other works in the field (Table 1).

Table 1. *Performance Comparison Table*

Model	MAE	RMSE	R^2	Ref
Decision Tree Regressor	0.229167	1.125771	0.999994	
Random Forest Regressor	0.214106	0.809336	0.999997	[15]
SARIMAX	458.398876	623.598559	-	
LSTM	104.78	196.58	0.96	
ARIMA	258.6	578.1	0.15	[15]
CNN	97.58	200.62	0.95	
LSTM	0.0058633	0.007901	-	[?]

As seen from the table, the Random Forest Regressor demonstrated better performance than any other algorithm. Indeed, its minimum MAE value was equal to 0.214106, with RMSE of 0.809336 and R^2 of 0.999997. Such remarkable results are explained by the fact that Random Forests enable capturing of complicated nonlinear patterns in the dataset without risking overfitting. It is likely that the main source of high performance of the Random Forest Regressor consists in the fact that it uses an ensemble approach where forecasts from many decision trees are aggregated.

At the same time, the Decision Tree Regressor provided quite accurate predictions. The MAE and RMSE scores were slightly higher (0.229167 and 1.125771, correspondingly) while the R^2 value was also relatively high – 0.999994. The advantage of decision trees consists in their ability to produce clear rules based on which predictions are made, making them rather convenient tools in practical situations, especially in those when explaining how a model works is critical.

Speaking about Deep Learning techniques, it should be mentioned that they performed rather well. As mentioned by the author [16], the application of LSTM resulted in very low MAE (0.0058633) and RMSE (0.007901). At the same time, another research work by [15] showed much higher error values, namely 104.78 and 196.58 for MAE and RMSE, correspondingly (the R^2 values were around 0.95 and 0.96 for LSTM and CNN, correspondingly). These differences may stem from the fact that models are tuned differently and data pretreatment techniques differ. However, Deep Learning still holds great promise when it comes to handling complicated data of temporal nature.

By contrast, traditional statistics models did not provide satisfactory results. SARIMAX gave rise to high error values (MAE: 458.398876, RMSE: 623.598559), in addition to which the value of R^2 was quite low. ARIMA proved to be even worse with its MAE of 258.6, RMSE of 578.1, and R^2 of 0.15. Such poor performance is not surprising because ARIMA and SARIMAX cannot handle extremely nonlinear and volatile datasets like those related to epidemiology where sharp spikes due to policy decisions are common.

Thus, comparison analysis clearly shows that ensemble machine learning algorithms, namely Random Forest, demonstrate superior performance in localized predictions regarding COVID-19. Although LSTM and other Deep Learning methods are able to identify complicated temporal patterns, their applicability requires more processing power. Traditional statistics models cannot cope with highly non-linear data and should therefore be replaced by advanced algorithms. Personalized modeling based on data from regions proves to be a promising way to make the prediction of pandemics more efficient.

7. DISCUSSIONS

The COVID-19 pandemic has called for the need for advanced predictive models capable of providing healthcare decision-makers with valuable insights. In this paper, the findings of studies conducted in Saudi Arabia were compared with the findings of analogous studies implemented in other countries, providing a full-fledged comparative analysis intended to fill knowledge gaps.

7.1. PERFORMANCE METRICS AND MODEL COMPARISONS

In [13] in Saudi Arabia emphasized the high quality of the Random Forest model whose performance was superior to Linear Regression and SARIMAX both in MAE and RMSE values. Consistent conclusions can be drawn from other papers [14] which used SLSTM neural network and reported on high predictive accuracy (errors of less than 2%). Consistency among various studies suggests that machine learning algorithms and Deep Learning prove their value for predicting the number of cases of the disease.

On the contrary, as noted by [15] LSTM and CNN performed well in certain cases and poorly in other ones, showing poor long-term prediction ability. This inconsistency among results obtained under similar conditions is indicative. We conclude that model choice should depend on specific circumstances as well as on the presence or absence of certain parameters. Indeed, according to [5], model effectiveness might change dramatically under different geographical and demographic settings. This conclusion is important for personalized prediction models.

7.2. IMPACT ON HEALTHCARE DECISION SUPPORT SYSTEMS

Remarkable findings of [16] that showed unusually low MAPE value of 5.0553 demonstrate high accuracy and ability to work with real-time data that is essential when responding to rapidly changing epidemics. In fact, in the research done by [17], the potential of real-time data integration that was pointed out by Saudi Arabian studies was confirmed. They considered routine blood tests for identifying mortality risks. It is obvious that moving from general prediction modeling to data analysis provides additional insights that can help in developing treatment plans. Real-time forecasting is critical when developing an effective decision support system.

There are examples from other countries such as India where the inclusion of extensive demographic and environmental data to predictive models resulted in higher accuracy ([14]). Temperature, rainfall, and population density were taken into account, thus giving a much more complicated view of how the disease spreads. It contradicts to simple predictive models used in Saudi Arabia that employ the data on cases, recoveries, and deaths.

8. CONCLUSIONS

The importance of developing decision-support systems to optimize COVID-19 response measures in Saudi Arabia was explored via a comparative analysis of state-of-the-art machine learning approaches based on the region-specific data.

Scientific novelty is related to the comprehensive study of several predictive models, such as Random Forest, Decision Tree, LSTM, CNN, ARIMA, and SARIMAX, and their advantages and disadvantages in the specific socio-economic conditions of Saudi Arabia. Thus, the paper emphasizes the necessity of accounting for local peculiarities while using machine learning to make predictions about the current state of affairs and improve the effectiveness of the healthcare system.

Practical significance of this research is demonstrated by the results of ensemble learning approaches (Random Forest Regressor) that demonstrate impressive levels of accuracy and robustness in modeling the situation in Saudi Arabia in the conditions of the pandemic. Therefore, it is possible to develop machine learning models to enhance decision-making, allocate resources, and create relevant policies related to health-related issues. The importance of cooperation between healthcare professionals and data scientists should be highlighted too.

Future research may focus on extending the set of machine learning techniques used in the comparative analysis and creating mixed models based on deep learning and statistical analysis.

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