



# Forecasting and Yield Sustainability Insights into Potato Production in Madhya Pradesh, India

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## ABSTRACT

**Background:** This study utilized the autoregressive integrated moving average (ARIMA) model, Trend and sustainability approaches to analyze the annual potato area, production and productivity data from 1970 to 2023. The primary focus of this study was the predicted potato production behavior for India and Madhya Pradesh.

**Methods:** The data series was split into two datasets: a training dataset (1970–2020) and a testing dataset (2021–2023) to build and validate a model. The best selected models were used to forecast potato production up to 2030.

**Result:** The production of potatoes in Madhya Pradesh and India in 2023 was 3925.65 and 61250.50 thousand tonnes. Madhya Pradesh and India are predicted 2030 to produce 4559.87 and 63318.26 thousand tonnes. In India and Madhya Pradesh, the area under potato cultivation has changed by 208.76 per cent and 508.32 per cent, respectively, between 1970 to 2023, while production has climbed by 634.06 per cent in India and 1032.30 per cent in Madhya Pradesh.

**Key words:** ARIMA, Production, Sustainability, Trend.

## INTRODUCTION

The potato (*Solanum tuberosum*) is the world's most important food crop. It has long been said that potatoes are poor man's friend crops. As a vegetable, this crop has become very popular in India. A crop with a temperate climate, potatoes thrive in cool weather throughout the growing season. 18 amino acids are present in potato proteins and the overall number of mineral elements accumulated in potatoes surpasses that of many other fruits and vegetables (Li *et al.*, 2024). Because of their high nutritional content, potatoes are a good source of vitamins C, A, group B, K and carotene. They include 20.6% carbs, 2.1% protein, 0.3% fat, 1.1% crude fiber and 0.9% ash by composition (Burgos *et al.*, 2020). Among other essential amino acids, it also contains healthy levels of leucine, isoleucine and tryptophane. Among other things, potatoes are used in the industrial sector to produce alcohol and starch (Kumar *et al.*, 2024). Sustainable agriculture refers to farming practices that improve environmental quality and resource sustainability over time, meet human needs for food and fiber, are economically viable and enhance the quality of life for farmers and society. Given the inherent fluctuations in farming locations, demand and yields, accurate forecasting is crucial for farmers, governments and the agribusiness sector. Recognizing the vital role of food production in national stability, governments are increasingly involved in agricultural forecasting. The area of potato production in India during 2022-23 is 2332 thousand ha, with production of 61250.50 MT (Metric ton) and a yield of 257 q/ha. The total area, production and productivity of potatoes in Madhya Pradesh in 2023 is about 156.39 thousand ha, 451.59 MT and 288.7 q/ha (Ministry of Agriculture and Farmer Welfare, Govt. of India, 2023). Ray *et al.* (2024) In this work, we attempted to develop a

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hybrid machine learning model approach for forecasting the potato volatility price index (Yadav *et al.*, 2024). This research created gradient boosting and state space machine learning approaches in addition to autoregressive integrated moving average (ARIMA) models for the annual output of potato from 1967 to 2020.

Das *et al.* (2024) predicted that non-traditional states like Gujarat, Madhya Pradesh and others have considerably increased to add to the Indian potato basket in addition to traditional potato production. Mishra *et al.* (2023) utilized modern time series and machine learning techniques to examine and predict potato output in eight prominent South Asian nations spanning the years 1961 to 2028. Das *et al.* (2023) investigated the progression of late blight disease in potato in the Terai region of West Bengal during two consecutive years (2014 and 2015).

This research study focused on yield sustainability and enhancing forecasting accuracy in potato production in Madhya Pradesh state and the whole Indian scenario. Given the increasing demand for potatoes as a staple food and industrial raw material, precise forecasting models can help policymakers, farmers and stakeholders make informed decisions regarding production planning, storage and market supply. By integrating time series models, this study aims to improve predictive accuracy in yield estimation, mitigating risks associated with climate variability and market fluctuations. Furthermore, sustainable potato production strategies can optimize resource utilization while maintaining soil health and environmental integrity.

## MATERIALS AND METHODS

### Source of data

In the present investigation, secondary data has been gathered. A glance at Agricultural Statistics (2023) provided the area, production and yield data on potato for the years 1970-2023 for Madhya Pradesh and Whole India.

### Descriptive statistics

Descriptive statistics are frequently used to make numerical data easily understandable. Anyone can make sense of very large datasets by using descriptive statistics. The three categories of descriptive statistics are central tendency (CT), dispersion and association measures.

### Simple annual growth rate (SAGR)

$$\frac{Y_t - Y_0}{Y_0 \times n} \times 100$$

The variables' values are represented by the values of  $Y_t$  at time  $t$  (the most recent data period),  $Y_0$  at the initial time and  $n$  at the number of data periods.

### Trend models

A model is a means of illustrating a system or activity (Mishra *et al.*, 2015). Statistical models often follow the course of the process together with its statistical characteristics and implications. The best model among the competing models is chosen based on the maximum  $R^2$  value.

#### i. Linear model

$$Y_t = b_0 + b_1 t$$

#### ii. Quadratic model

$$Y_t = b_0 + b_1 t + b_2 t^2$$

#### iii. Compound model

$$\ln(Y_t) = \ln(b_0) + t \ln(b_1)$$

#### iv. Cubic model

$$Y_t = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

#### v. Exponential model

$$Y_t = b_0 e^{(b_1 t)}$$

#### vi. Logarithmic model

$$Y_t = b_0 + b_1 \ln(t)$$

#### vii. Growth model

$$\ln(Y_t) = b_0 + b_1 t$$

#### viii. Inverse model

$$Y_t = b_0 + \frac{b_1}{t}$$

#### ix. Power model

$$Y_t = b_0 t^{b_1} +$$

#### x. S type model:

$$Y_t = e^{(b_0 + \frac{b_1}{t})}$$

#### xi. Logistic model:

$$Y_t = \frac{K}{1 + e^{b_0 + b_1 t}}$$

## Measures of sustainability

Vishwajith *et al.* (2018) define sustainability as a complex, multifaceted phenomenon that has been defined in a variety of ways. While highly contentious, it is universally acknowledged that it is difficult and requires numerous examinations. It can be evaluated by taking into account its biophysical, social and economic characteristics in its most basic form.

### Sustainability index (SI)

In this study, we divided the potato productivity data series into two periods to estimate the sustainability index.

• Period-1 (1970-1997)

• Period-2 (1998-2023)

• Whole period (1970-2023)

(a) According to Singh *et al.* (1990). The sustainability measure is as follows:

$$\text{Sustainability index (SI)} = \frac{\bar{Y} - S}{Y_{\max}}$$

(b) According to Sahu *et al.* (2005). A sustainability index value that is closer to zero is a desirable value.

$$SI = \frac{Y_{\max} - \bar{Y}}{\bar{Y}}$$

(c) According to Pal and Sahu (2007) sustainability increases when the sustainability index value decreases.

$$SI = \frac{S_i}{\bar{Y}_i} \cdot \frac{1}{S_{\max}}$$

## Modeling and forecasting

The plan looks like a flowchart for time series analysis-based potato production forecasts. The flow is described as follows (Fig 1):

**1. Planning:** Identify the objective of the study on potato production estimation.

**2. Data on potato production:** Using SPSS23, seems to be the first step in identifying the relevant data on potato production as a process input.

**3. Input potato production data (India and Madhya Pradesh):** This stage indicates that data on potato production will

originate from India and Madhya Pradesh. In this study, we consider the data series of Madhya Pradesh and the whole India production series for interpretation.

**4. Training data:** After the information is acquired, it is categorized as training data, which is what the forecasting models are fitted to.

**5. The training data splits into two routes, signifying the forecasting techniques:** In time series forecasting, the statistical method called autoregressive integrated moving average (ARIMA) is frequently employed (Mishra *et al.*, 2015, Raghav *et al.*, 2022 and Mishra *et al.*, 2023).

**6. Accuracy for training data:** Several accuracy metrics are used in time series analysis. Some of the metrics are as follows:

**MAE:** Mean absolute error, a measure of errors between paired observations expressing the same phenomenon.

**RMSE:** Root mean square error, a measure of the differences between values predicted by a model and the values observed.

**BIC:** Bayesian information criterion, a measure of the relative quality of statistical models for a given set of data.

**Mean absolute error (MAE):** A measurement of inaccuracies between two observations that represent the same occurrence.

**Root mean square error (RMSE):** A measurement of the discrepancies between data observed and values projected by a model.

**Autocorrelation function at lag 1 (ACF1):** A measure of the correlation between time series observations separated by a single time step.

**Mean absolute percentage error (MAPE):** A measure of forecasting model prediction accuracy.

**7. Projecting potato production:** The more accurate forecasting model is probably chosen to project future potato production based on the evaluations.

**8. Finish:** When the procedure is complete.

### Autoregressive moving average (ARMA)

The model containing  $p$  autoregressive terms and  $q$  moving average terms is denoted by the notation ARMA ( $p$ ,  $q$ ). The AR( $p$ ) and MA( $q$ ) models are contained in this model (Mishra *et al.*, 2023).

$$X_t = c + \varepsilon_t + \sum_{i=1}^p p_i X_{t-i} + \sum_{i=1}^q \theta_i \varepsilon_{t-i}$$

### Moving average model

The moving average model of order  $q$  is denoted by the notation MA ( $q$ ):

$$X_t = c + \sum_{i=1}^q \theta_i \varepsilon_{t-i} + \varepsilon_t$$

Where,

$\varepsilon$  = Error term.

$\mu$  = Expectation of (often taken to equal 0), and the model's parameters are  $\theta_1, \dots, \theta_q$ .

## RESULTS AND DISCUSSION

### Performance of potato in India and Madhya Pradesh during 1970-2023

In this section, descriptive statistics such as maximum, minimum, mean, median, skewness and kurtosis are

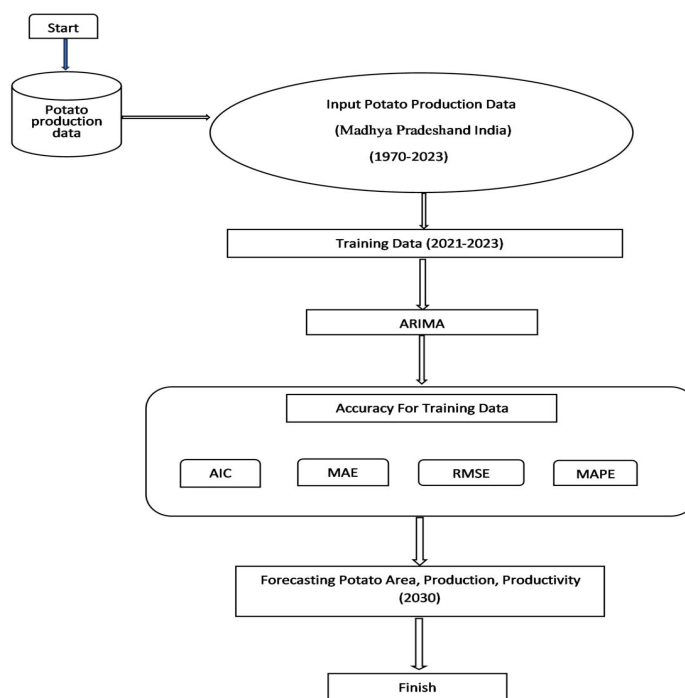


Fig 1: Flow chart of forecasting.

employed to elucidate the series' pattern and generate a consensus that is examined in Table 1. The data Platykurtic structure of potato under area, production and yield in both the series. Madhya Pradesh and India produce an average of 1099.36 and 24714.96 thousand tons of potatoes per year on an average area of 60.49 and 1291.31 thousand hectares. In Madhya Pradesh and India, the average yield produces 147.68 and 172.65 q/ha of potatoes, respectively. Skewness values of 0.41 and 1.18 indicate that Madhya Pradesh and India's potato-growing areas have been shifting over time. Skewed Distribution follows in production and yield in both the population i.e. Madhya Pradesh and India.

#### Trend analysis of potato in India and Madhya Pradesh

There are cubic tendencies in potato output, yield and area across Madhya Pradesh and India, according to the trend study (Table 2). This is problematic since it implies that the series have probably just hit their maximum values and then either stayed steady or declined. The data shows that

**Table 1:** Performance of potato area, production and yield in India and Madhya Pradesh during 1970-2023.

|                       | Area<br>("000 ha) | Production<br>("000 t) | Yield<br>(q/ha) |
|-----------------------|-------------------|------------------------|-----------------|
| <b>India</b>          |                   |                        |                 |
| Mean                  | 1291.319          | 24714.596              | 172.650         |
| Standard error        | 79.023            | 2277.440               | 6.483           |
| Median                | 1206.900          | 20709.060              | 167.700         |
| Kurtosis              | -1.181            | -0.737                 | -0.571          |
| Skewness              | 0.414             | 0.729                  | 0.273           |
| Minimum               | 482.000           | 4451.000               | 88.200          |
| Maximum               | 2345.400          | 61250.500              | 277.460         |
| SGR (%)               | 208.76            | 634.06                 | 96.129          |
| <b>Madhya Pradesh</b> |                   |                        |                 |
| Mean                  | 60.490            | 1099.360               | 147.684         |
| Standard error        | 6.528             | 165.211                | 6.230           |
| Median                | 40.300            | 514.200                | 128.190         |
| Kurtosis              | -0.120            | 0.129                  | -0.753          |
| Skewness              | 1.184             | 1.341                  | 0.904           |
| Minimum               | 15.600            | 165.700                | 91.600          |
| Maximum               | 162.450           | 3925.650               | 231.110         |
| SGR (%)               | 508.32            | 1030.32                | 45.48           |

**Table 2:** Trends of potato in India and Madhya Pradesh.

|                       | Model summary |                |       | Parameter estimates |                |                |                |
|-----------------------|---------------|----------------|-------|---------------------|----------------|----------------|----------------|
|                       | Equation      | R <sup>2</sup> | Sig.  | Constant            | B <sub>1</sub> | B <sub>2</sub> | B <sub>3</sub> |
| <b>India</b>          |               |                |       |                     |                |                |                |
| Area                  | Cubic         | 0.980          | 0.000 | 519.639             | 10.237         | 0.588          | -0.002         |
| Production            | Cubic         | 0.976          | 0.000 | 4046.793            | 504.577        | -5.371         | 0.298          |
| Yield                 | Cubic         | 0.936          | 0.000 | 79.466              | 6.563          | -0.188         | 0.002          |
| <b>Madhya Pradesh</b> |               |                |       |                     |                |                |                |
| Area                  | Cubic         | 0.929          | 0.000 | 12.883              | 1.893          | -0.094         | 0.002          |
| Production            | Cubic         | 0.926          | 0.000 | 78.373              | 47.287         | -3.102         | 0.069          |
| Yield                 | Cubic         | 0.809          | 0.000 | 109.750             | 0.637          | -0.035         | 0.001          |

the area planted for potatoes in Madhya Pradesh and India has increased yearly. The non-linear trends in Madhya Pradesh and India are depicted in Fig 2-7.

#### Sustainability analysis

In Table 3 presents the results of measuring sustainability in the productivity of potatoes in Madhya Pradesh and India using sustainability measurement. According to indexes provided by SI-1 (Singh *et al.*, 1990), SI-2 (Sahu *et al.*, 2005) and SI-3 (Pal and Sahu, 2007), as measured by various formulas for accuracy, it is evident the entire country of India is highly sustainable in yield of potato in period-2 (1998-2023) and Madhya Pradesh is highly sustainable in yield of potato in period-1 (1998-2023).

#### Modeling and forecasting

Based on the objective of the study, We used the Box-Jenkins methodology to estimate the prediction behavior of the series. The model was built using data from 1970 to 2020 and it was validated using data from 2021 to 2023. Future series predictions are made using the models that suit the data the best. None of them are stable in nature, as the ACF and PACF graphs from the original series make abundantly evident and first-order differencing is enough to make them so. It was found that ARIMA models, starting with the model-building procedure given in the material and method section, ranging from (0, 1, 0) to (1, 1, 5) are appropriate for forecasting and predicting the production behavior of potato from 1970 to 2023. The study then uses the differenced series to estimate ARIMA equations for all parameters. It then produces predictions up to 2030. However, ACF and PACF graphs are also used to perform diagnostic checks on residuals. In this case, it is important to convert a non-stationary time series into a stationary one. Instead of requiring multiple transformations and differencing to get the same outcome, stationarity can usually be demonstrated with a single difference.

Fig 8 displays the ACF and PACF plot of the first difference, or the area under potato, for Madhya Pradesh and India. These plots indicate that p=1 and q=5 for Madhya Pradesh and p=1 and q=5 for India would be a reasonable range for the area under potato. Consequently, Table 4 demonstrates the ARIMA (1,1,5) areas under potato have the highest R<sup>2</sup> value and the lowest RMSE, MAPE, MaxAE

and MAE values in India. However, the ARIMA (1,1,5) areas under potato have the highest  $R^2$  value and the lowest RMSE and MaxAE values in Madhya Pradesh. The projected areas for potato in Table 5 demonstrate that Madhya Pradesh and India in 2023 were 163.77 thousand hectares and 2423 thousand hectares, respectively, while the actual areas were 162.45 thousand hectares and 2345.40 thousand hectares. India is predicted to have 2620 thousand hectares and Madhya Pradesh will have 183.71 thousand hectares in 2030 respectively. Fig 9 displays the ACF and PACF plot of the first difference or the value of production under potato in Madhya Pradesh and India. The ARIMA (1,1,2) and ARIMA (0,1,5) were therefore determined to be appropriate for the production

of potato in Madhya Pradesh and India. Table 4 further shows that India has the highest  $R^2$  value along with the lowest values of MAPE, MaxAPE and MAE, however, Madhya Pradesh ARIMA (1,1,2) potato production has the highest value of  $R^2$  along with the lowest values of MAPE, MAE and Normalized BIC. Table 5 contrasts the predicted 3999.89 thousand tones and 63318.26 thousand tones production of potato in Madhya Pradesh and India in 2023, the actual production of 3925.65 thousand tons and 61250.50 thousand tons, respectively. Madhya Pradesh is predicted to produce 4559.87 thousand tons, while India is forecast to produce 69806.76 thousand tons in 2030. The yield under potato in Madhya Pradesh and India, as indicated by the ACF and PACF plot of the first difference

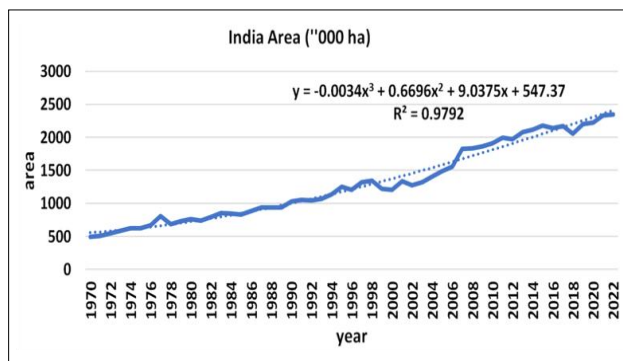


Fig 2: Trends of area under potato in India.

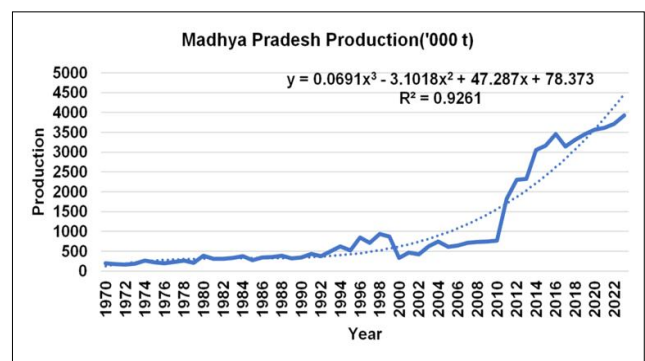


Fig 5: Trends of production under potato in Madhya Pradesh.

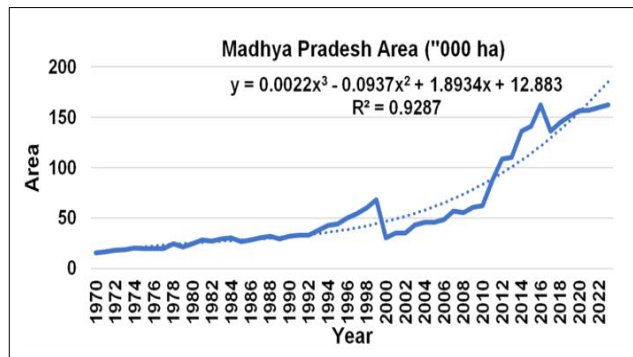


Fig 3: Trends of area under potato in Madhya Pradesh.

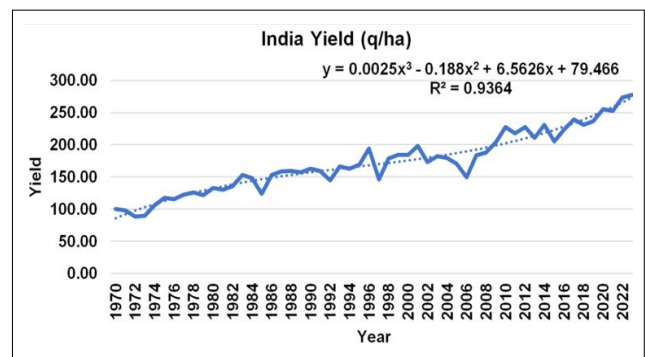


Fig 6: Trends of yield under potato in India.

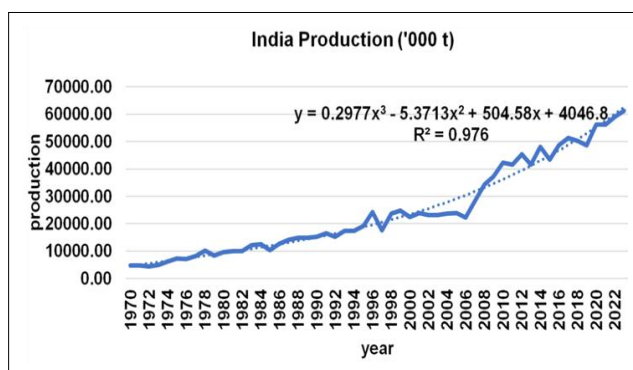


Fig 4: Trends of production under potato in India.

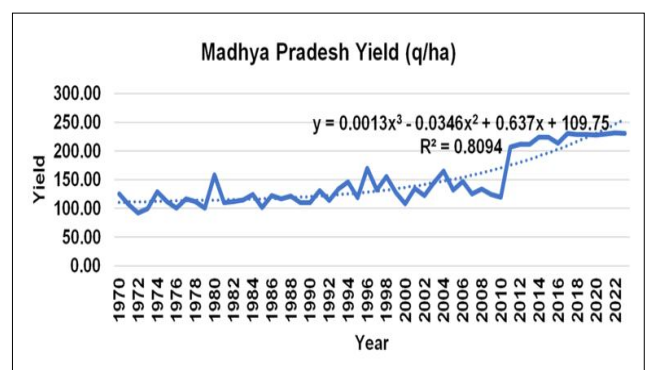


Fig 7: Trends of yield under potato in Madhya Pradesh.

**Table 3:** Sustainability potato yield measurement.

| Sustainability index  | Period 1<br>(1970-1997) | Period 2<br>(1998-2023) | Whole period<br>(1970-2023) |
|-----------------------|-------------------------|-------------------------|-----------------------------|
| <b>India</b>          |                         |                         |                             |
| SI 1                  | 0.570                   | 0.640                   | 0.451                       |
| SI 2                  | 0.414                   | 0.316                   | 0.607                       |
| SI 3                  | 0.004                   | 0.003                   | 0.006                       |
| <b>Madhya Pradesh</b> |                         |                         |                             |
| SI 1                  | 0.600                   | 0.568                   | 0.441                       |
| SI 2                  | 0.421                   | 0.296                   | 0.565                       |
| SI 3                  | 0.003                   | 0.006                   | 0.007                       |

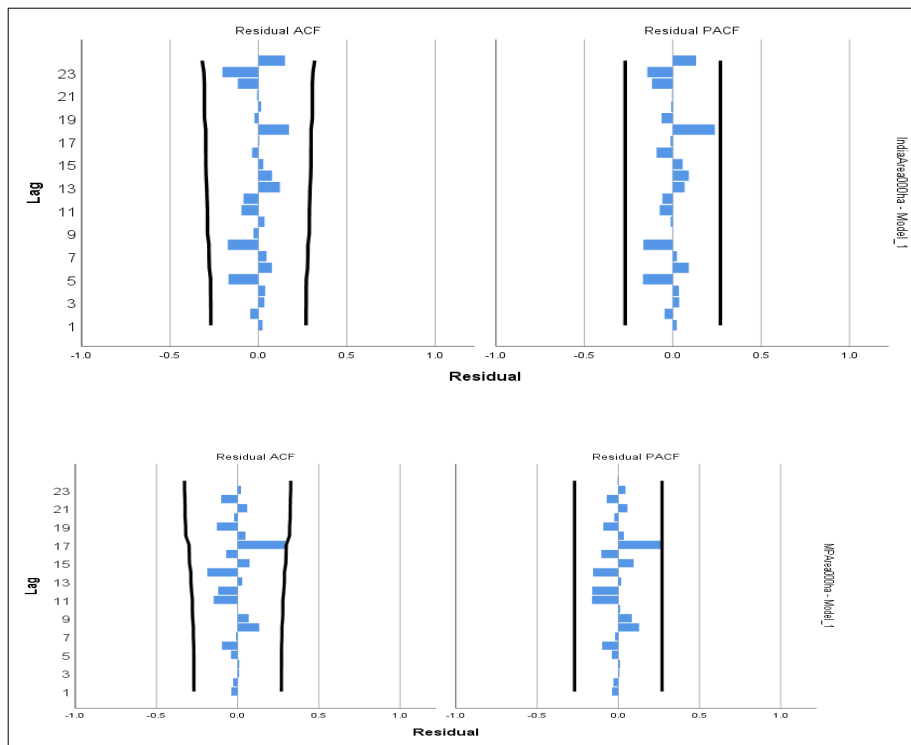
(Fig 10). It may be concluded that ARIMA (0,1,4) and ARIMA (1,1,5) are the ARIMA models that are most suited for yield under potato in Madhya Pradesh and India. Moreover, Table 4 showed that while Madhya Pradesh had the highest  $R^2$  value and the lowest MAPE, MAE, MaxAPE and MaxAE value, India yielded potato highest  $R^2$  and lowest MAPE, MAE and Normalized BIC. In Table 5 contrast to the predicted 264.13 q/ha and 234.63q/ha, the yields of India and Madhya Pradesh in 2023 and yield in 2023 were 277.46 q/ha and 230.85/ha, respectively. Madhya Pradesh is anticipated to receive 250.14 q/ha, while India is expected to receive 274.09 q/ha in 2030.

**Table 4:** Different ARIMA Model for area("000" ha), production ("000" tons) and yield(q/ha)of potato in India and Madhya Pradesh.

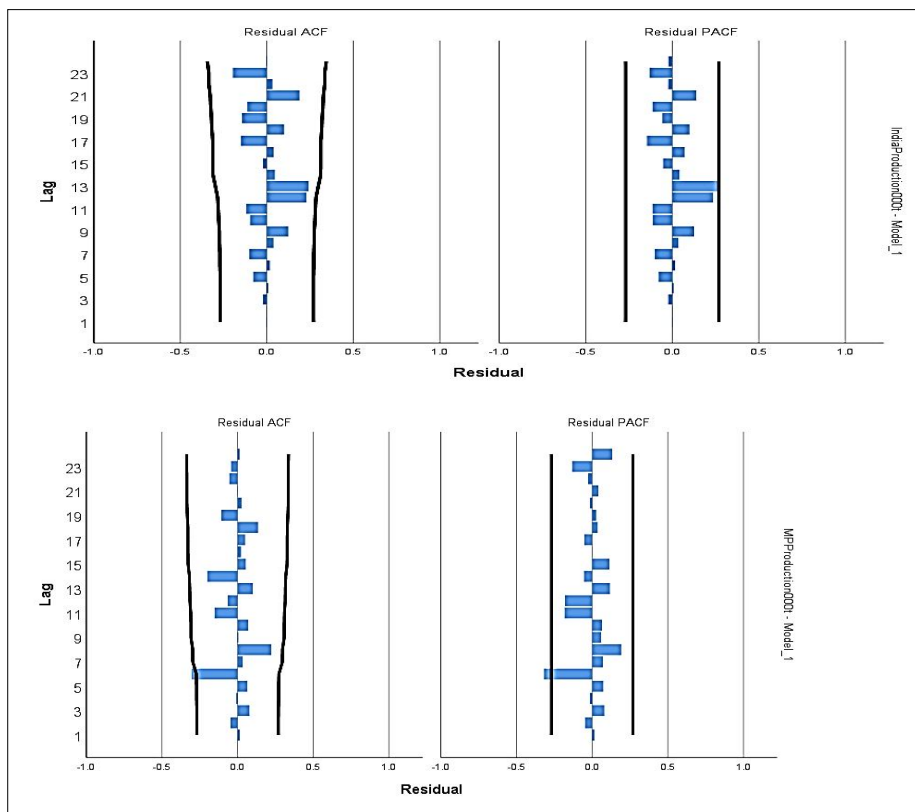
|                       | ARIMA   | $R^2$ | RMSE     | MAPE   | MAE      | MaxAPE  | MaxAE    | Normalized BIC |
|-----------------------|---------|-------|----------|--------|----------|---------|----------|----------------|
| <b>India</b>          |         |       |          |        |          |         |          |                |
| Area                  | (1,1,5) | 0.990 | 62.696   | 3.577  | 42.235   | 16.938  | 189.079  | 8.876          |
| Production            | (0,1,5) | 0.978 | 2600.236 | 9.818  | 1902.447 | 39.111  | 7002.540 | 16.176         |
| Yield                 | (1,1,5) | 0.922 | 13.916   | 5.962  | 9.633    | 27.145  | 40.554   | 5.790          |
| <b>Madhya Pradesh</b> |         |       |          |        |          |         |          |                |
| Area                  | (1,1,5) | 0.966 | 9.360    | 10.466 | 4.976    | 132.986 | 40.011   | 4.997          |
| Production            | (1,1,2) | 0.968 | 224.882  | 20.938 | 129.390  | 190.029 | 988.106  | 10.897         |
| Yield                 | (0,1,4) | 0.807 | 21.088   | 11.118 | 14.904   | 35.613  | 73.504   | 6.472          |

**Table 5:** Model validation and forecasting of area (000'ha), production ('000' tons) and yield (q/ha) under potato in India and Madhya Pradesh.

|                       |          | Area      |                              | Production |           |                              | Yield    |           |                              |
|-----------------------|----------|-----------|------------------------------|------------|-----------|------------------------------|----------|-----------|------------------------------|
| Year                  | Observed | Predicted | Prediction error per centage | Observed   | Predicted | Prediction error per centage | Observed | Predicted | Prediction error per centage |
| <b>India</b>          |          |           |                              |            |           |                              |          |           |                              |
| 2021                  | 2225.75  | 2276.36   | -2.27                        | 56175.75   | 57521.81  | -2.39                        | 252.40   | 249.62    | 1.10                         |
| 2022                  | 2332.05  | 2352.92   | -0.89                        | 59160.34   | 60571.58  | -2.38                        | 273.56   | 265.24    | 3.04                         |
| 2023                  | 2345.41  | 2422.88   | -3.30                        | 61250.50   | 63318.26  | -3.37                        | 277.46   | 264.13    | 4.80                         |
| 2024                  |          | 2413.99   |                              |            | 63527.71  |                              |          | 267.81    |                              |
| 2025                  |          | 2487.86   |                              |            | 65419.16  |                              |          | 261.24    |                              |
| 2026                  |          | 2474.06   |                              |            | 65502.66  |                              |          | 262.94    |                              |
| 2027                  |          | 2559.1    |                              |            | 67459.86  |                              |          | 264.48    |                              |
| 2028                  |          | 2547.16   |                              |            | 67654.86  |                              |          | 268.45    |                              |
| 2029                  |          | 2628.77   |                              |            | 69589.11  |                              |          | 270.55    |                              |
| 2030                  |          | 2620.14   |                              |            | 69806.76  |                              |          | 274.09    |                              |
| <b>Madhya Pradesh</b> |          |           |                              |            |           |                              |          |           |                              |
| 2021                  | 157.11   | 155.17    | 1.23                         | 3611.22    | 3700.83   | -2.48                        | 229.85   | 229.8     | 0.02                         |
| 2022                  | 159.79   | 167.13    | -4.59                        | 3715.71    | 3789.63   | -1.98                        | 231.11   | 232.4     | -0.55                        |
| 2023                  | 162.45   | 163.77    | -0.81                        | 3925.65    | 3999.89   | -1.89                        | 230.85   | 234.63    | -1.63                        |
| 2024                  |          | 167.33    |                              |            | 4099.84   |                              |          | 236.32    |                              |
| 2025                  |          | 168.89    |                              |            | 4187.17   |                              |          | 238.28    |                              |
| 2026                  |          | 173.44    |                              |            | 4267.23   |                              |          | 240.94    |                              |
| 2027                  |          | 173.42    |                              |            | 4343.09   |                              |          | 243.24    |                              |
| 2028                  |          | 178.53    |                              |            | 4416.55   |                              |          | 245.54    |                              |
| 2029                  |          | 179.21    |                              |            | 4488.61   |                              |          | 247.84    |                              |
| 2030                  |          | 183.71    |                              |            | 4559.87   |                              |          | 250.14    |                              |



**Fig 8:** ACF and PACF graphs of residuals for the best-fitted models of area (000'ha) under potato in India and Madhya Pradesh.



**Fig 9:** ACF and PACF graphs of residuals for the best-fitted models of production ('000' tons) under potato in India and Madhya Pradesh.

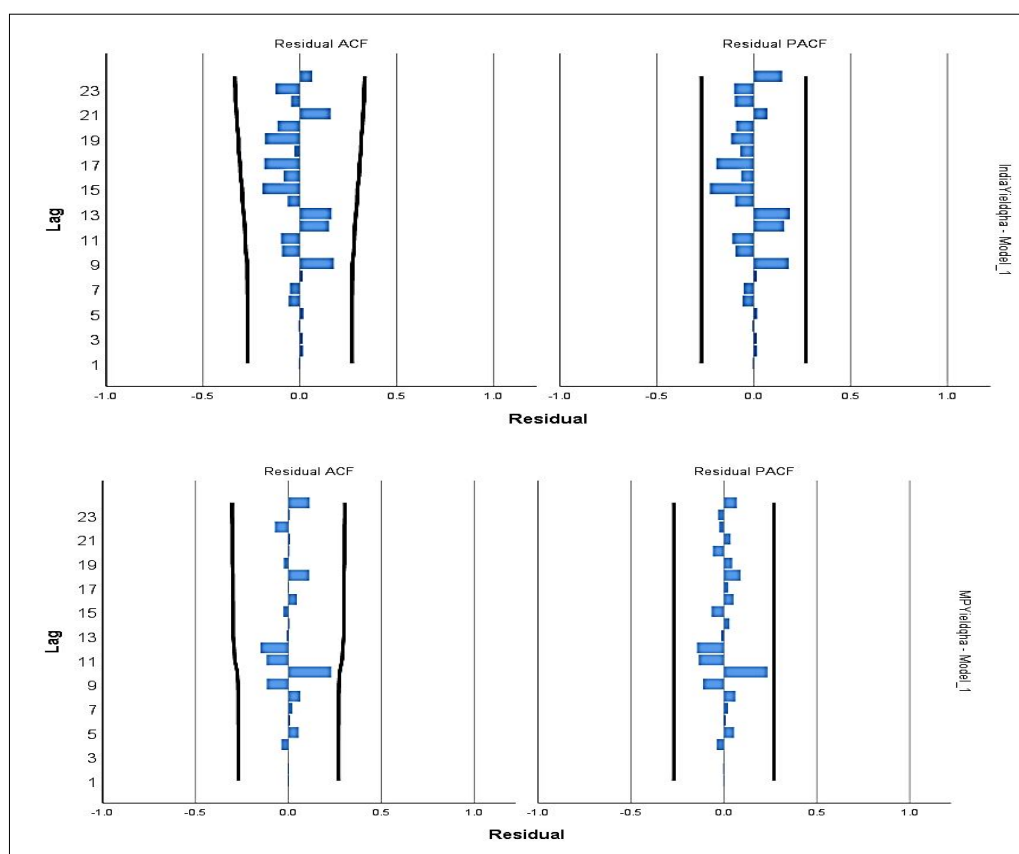


Fig 10: ACF and PACF graphs of residuals for the best-fitted models of yield (q/ha) under potato in India and Madhya Pradesh.

## CONCLUSION

The potato is the world's most important food crop and has become highly popular as a vegetable in India. This study carried out a detailed examination of potato production in India and Madhya Pradesh by applying advanced time series forecasting and machine learning methods. The analysis used annual potato production data from 1970 to 2023 and involved ARIMA models. The ARIMA models, chosen based on various criteria, exhibited strong predictive accuracy. However, the findings indicated that no single model consistently performed the best across all datasets. Overall, ARIMA models had the lowest error rates for both India and Madhya Pradesh. Potato production in India and Madhya Pradesh has experienced notable increases in area, production and productivity. The analysis reveals a cubic trend in these metrics. Additionally, sustainability analysis is employed to guide future crop improvement strategies. For 2030, ARIMA models predict that potato production in Madhya Pradesh will reach approximately 4559.87 thousand tons, while in India overall, it would be expected to be around 69806.76 thousand tons. Future research can explore the integration of remote sensing and geospatial analytics to enhance forecasting precision and assess climate resilience strategies. Additionally, adopting AI-driven decision support systems

can further refine real-time monitoring and intervention mechanisms, ensuring long-term sustainability and profitability in potato cultivation.

## Conflict of interest

All authors declared that there is no conflict of interest.

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