Bioscene

Bioscene
Volume- 22 Number- 01
ISSN: 1539-2422 (P) 2055-1583 (O)
www.explorebioscene.com

A Computational Framework for Trend Pattern Analysis of Pearl Millet Production using Linear and Non-Linear Models

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Abstract
This paper deals with trend pattern analysis of pearl millet production in three pearl millet growing states of India, namely, Uttar Pradesh, Maharashtra and Gujarat. The secondary time series data on production of pearl millet during 2002-2022 is utilized for the investigation. Some well known models viz., linear, quadratic, cubic and exponential models are fitted to the concerned time series data, and trend values have been obtained. The precision of the fitted models have been evaluated using coefficient of determination (R^2), root mean square error (RMSE) and relative mean absolute percentage error (RMAPE). The findings of the investigation reveal that the cubic model is appropriate for forecasting of future trend of pearl millet production in the concerned states.

Keywords: Time series; coefficient of determination; root mean square error; relative mean absolute percentage error.

1. Introduction

India is the largest producer of millets in the world and also the 5th largest exporter of millets globally. Millets provide food security to millions of households and contribute to the economic efficiency of farming in India. Important millet crops grown in India are Sorghum (Great millet), Bajra (Pearl millet), Maize, Ragi (Finger millet) and small millets viz., Korra (Foxtail millet), Little millet, Kodo millet, Proso millet and Barnyard millet (Rani et al., 2023).

Pearl millet (Pennisetum glaucum) belongs to the Poaceae family and is commonly known as Bajra. It is a most widely grown type of millet in India (Basavraj et al., 2010). Pearl millet is well adapted to production systems characterized by low rainfall (200-600 mm), low soil fertility, and high temperature, and thus can be grown in areas where other cereal crops, such as wheat or maize, would not survive (Nambiar et al., 2011).Saleh et al. (2013) reviewed millet's nutritional benefits, health potential, and processing advancements, highlighting its role in food security for arid regions. It addressed challenges and future prospects for promoting millet as a sustainable food for growing populations. India produced 9.74 Million tons of Pearl millet in 2022-23 [Source: Agricultural and Processed Food Products Export Development Authority (APEDA)]. India continues to be the single largest producer of pearl millet in the world, although the area has been declining in the traditional growing states of Gujarat, Rajasthan and Haryana. Pearl millet is usually grown as a dry land dual purpose grain and fodder crop. It is grown in about 7.1 million hectare yielding 10.3 million tons, followed by sorghum (5.7 million hectare, yielding 4.4 million tons) and finger millet (1.1 million hectare, yielding 1.82 million tons) and other millets (0.7 million hectare yielding 0.4 million tons) (Shankar and Pushpa, 2023). Pearl millet production is concentrated in the developing countries which account for over 95% of the production and acreage. Pearl millet is nutritious, non-glutinous (non-sticky) and are not acid forming foods, thus making them very easy to digest, and low in simple carbohydrates and higher in complex carbohydrates, making it a low-glycemic index (GI) food. It contains about 11.6% protein, 5% fat, 67% carbohydrates and 2.7% minerals. The health benefits and nutritional value of pearl millet is rich in minerals like calcium, copper, iron, magnesium, phosphorus, potassium and selenium as well as essential vitamins like folate, pantothenic acid, niacin, riboflavin and Vitamins B6, C, E and K.

India stands as the largest producer of pearl millet, accounting for 50% of the global output. In the year 2023-24, India's total pearl millet production reached 10.72 million tons, witnessing an yield of 1.45 tons per hectare [DES, 2024].

In the past as well as in recent times, statistical analysis of pearl millet as well as other millet crops have been made by various scientists and researchers, for instance, Varmora and Rankja (2010) developed a multiple linear regression model to forecast pearl millet yield by using 47 years of Rajkot's rainfall data and explained 91% yield variation. Validation over six years showed 2-20% deviations due to erratic rainfall and irregular sowing. Despite high errors, the model proved useful for early yield forecasting. Tripathi et. al. (2013) analyzed trends in area, production, and productivity of pearl millet in India using time series data from 1950-2010. It forecasted future trends using the ARIMA model and found significant growth rates. Parametric models like compound, power, and compound trends effectively depicted the trends in pearl millet. Vijay and Mishra (2018) compared the effectiveness of Artificial Neural Network (ANN) and ARIMA models for forecasting time series data on pearl millet area and production in Karnataka (1955-2015). Results showed that the ANN model outperformed ARIMA based on RMSE, MAPE, and MSE. Chaudhary et al. (2023) analyzed 11 years of pearl millet price data from Rajasthan's APMCs revealed an overall increasing trend despite irregular fluctuations. Seasonal price patterns were similar in Alwar and Barmer, with higher variability in Jaipur. Prices peaked post-harvest and declined thereafter. Barmer showed high price variability, while Jaipur had the highest coefficient of variation.

Dwivedi et al. (2024) analyzed growth trends of small millets in Madhya Pradesh pertaining to the period 1966-2021. Millet cultivation area and production declined by 5.34% and 3.44% annually, while productivity rose by 2% due to improved practices. Low awareness hindered consumption, exacerbating nutritional deficiencies.

Some other noteworthy contributions towards statistical modeling and time series analysis of crops, other than millets, have been made by Kumar and Menon (2022), Rana and Kumar (2022), Kumar et al. (2024), Mishra et al. (2025), Prakash et al. (2025),Singh and Kumar (2025), and Singh et al. (2025).

The objective of the present paper is to analyze the trend pattern in production of pearl millet for selected states of India. The analysis is carried out by fitting well-known statistical models (viz., linear, quadratic, cubic and exponential models) to the time series data on pearl millet pertaining to the period 2002-2022, and estimating the trend values. The precision of the concerned fitted models have been evaluated using coefficient of determination (R^2), root mean square error (RMSE) and relative mean absolute percentage error (RMAPE).

2. Materials and Methods

2.1 Source of Data

The secondary time series data on pearl millet production in some selected states of India pertaining to the period 2002-2022 is collected from the records of Directorate of Economics & Statistics, DAC&FW, Govt. of India.

2.2 Terminologies and Notations

In the present analysis, three pearl millet growing states of India viz., Uttar Pradesh (S1), Maharashtra (S2), and Gujarat (S3) are considered. These states exhibit various trends of pearl millet production during the concerned period of investigation.

2.3 Fitting of Trend Models to the Data

For analyzing the trend patterns of pearl millet production in the concerned states S1, S2 and S3, the trend values are computed by fitting linear, quadratic, cubic and exponential models to the time series data on pearl millet production as follows:

(a) Linear Model:

$$y_t = a + bt \ldots\ldots\ldots(1)$$

where y_t denotes the time series value at time t.The values of constants ‘a’ and ‘b’ are estimated on solving the following normal equations:

$$\sum y_t = na + b\sum t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$\sum ty_t = a\sum t + b\sum t^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where 'n' represents the number of observed values.

(b) Quadratic Model:

$y_t = a + bt + ct^2$......................(4)

The values of constants 'a', 'b' and 'c' are obtained on using the principles of least squares as follows:

$\sum y_t = na + b\sum t + c\sum t^2$...............(5)

$\sum ty_t = a\sum t + b\sum t^2 + c\sum t^3$..........(6)

$\sum t^2y_t = a\sum t^2 + b\sum t^3 + c\sum t^4$.......(7)

(c) Cubic Model:

$y_t = a + bt + ct^2 + dt^3$...............(8)

The values of constants 'a', 'b','c' and 'd' are computed on solving the following normal equations:

$\sum y_t = na + b\Sigma t + c\Sigma t^2 + d\Sigma t^3$............(9)

$\sum ty_t = a\Sigma t + b\Sigma t^2 + c\Sigma t^3 + d\Sigma t^4$.........(10)

$\sum t^2y_t = a\Sigma t^2 + b\Sigma t^3 + c\Sigma t^4 + d\Sigma t^5$......(11)

$\sum t^3y_t = a\Sigma t^3 + b\Sigma t^4 + c\Sigma t^5 + d\Sigma t^6$......(12)

(d) Exponential Model:

$y_t = ae^{bt}$.......................................(13)

Taking natural log on both sides of equation (13), we have

$$log_e y_t = log_e a + btlog_e e$$

i.e., $Y_t = A + bt$.................................(14)

where $Y_t = log_e y_t$, $A = log_e a$, and$log_e e = 1$.

The normal equations for estimating 'A' and 'b' are as follows:

$\sum Y_t = nA + b\sum t$.............................. (15)

$\sum tY_t = A\sum t + b\sum t^2$......................... (16)

Finally, the value of 'a' is obtained as follows:

$$a = antilog\ (A)$$

The precision of the concerned fitted models have been evaluated using various statistical measures viz., coefficient of determination (R^2), root mean square error (RMSE) and relative mean absolute percentage error (RMAPE)using the following formulae:

$$\mathrm{R}^2 = 1 - \frac{\Sigma_{t=1}^{n}(y_t - \hat{y}_t)^2}{\Sigma_{t=1}^{n}(y_t - \bar{y})^2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}$$

and

$$RMAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y_t - \hat{y}_t}{y_t}\right| \times 100$$

where $\bar{y}$ denotes the mean value of variable Y, i.e., production of pearl millet. Also,$\hat{y}_t$ represents the trend value of variable Y, which is obtained on fitting the concerned models (such as linear model, quadratic model, cubic model, or exponential model) to the variable Y.

3. Results and Discussion

The time series data on pearl millet production in states S1, S2 and S3 is presented in Table 1. The trend values are obtained on fitting linear, quadratic, cubic and exponential models to the data in the concerned statesS1, S2 and S3, and the findings are depicted in Tables 2, 3 and 4, respectively. Moreover, the model equations for linear, quadratic, cubic and exponential trends in the respective states are summarized in Table 5.

Table 1. Time series data on pearl millet production in selected states of India

Year	*Production (in '000 Tons) for the States		
	S1	S2	S3
2002	1072.50	1146.00	907.00
2003	1119.90	896.00	1599.90
2004	1223.90	1126.00	1084.70
2005	1246.30	1032.00	1072.00
2006	1286.00	1059.00	1019.00
2007	1336.40	1127.00	1307.00
2008	1302.00	662.00	961.00
2009	1389.00	766.00	828.00
2010	1557.00	1123.00	1091.25
2011	1633.00	823.00	1230.27
2012	1758.00	502.00	1044.00
2013	1870.00	379.80	1210.00
2014	1810.00	445.00	770.00
2015	1780.00	618.00	790.00
2016	1740.00	680.61	930.00

2017	1790.00	755.00	960.00
2018	1780.00	310.00	830.00
2019	1940.00	510.00	910.00
2020	2010.00	660.00	1010.00
2021	1950.00	480.00	1060.00
2022	2050.00	470.00	1290.00

(*Source: Directorate of Economics & Statistics, DAC&FW, Govt. of India)

Table 2. Trend values for linear, quadratic, cubic and exponential models in state S1

Year (t)	Production (y_t)	Trend Values for S1			
		Linear Model (L_t)	Quadratic Model (Q_t)	Cubic Model (C_t)	Exponential Model (E_t)
2002	1072.50	1117.81	1041.88	1056.39	1146.79
2003	1119.90	1166.24	1113.10	1118.90	1183.49
2004	1223.90	1214.67	1181.91	1181.31	1221.36
2005	1246.30	1263.10	1248.33	1243.35	1260.45
2006	1286.00	1311.53	1312.35	1304.78	1300.78
2007	1336.40	1359.96	1373.97	1365.33	1342.41
2008	1302.00	1408.38	1433.20	1424.75	1385.37
2009	1389.00	1456.81	1490.02	1482.80	1429.70
2010	1557.00	1505.24	1544.44	1539.21	1475.46
2011	1633.00	1553.67	1596.47	1593.73	1522.67
2012	1758.00	1602.10	1646.10	1646.10	1571.40
2013	1870.00	1650.53	1693.33	1696.08	1621.69
2014	1810.00	1698.96	1738.16	1743.40	1673.58
2015	1780.00	1747.39	1780.59	1787.82	1727.14
2016	1740.00	1795.82	1820.63	1829.07	1782.41
2017	1790.00	1844.25	1858.26	1866.91	1839.45
2018	1780.00	1892.67	1893.50	1901.07	1898.32
2019	1940.00	1941.10	1926.34	1931.32	1959.06
2020	2010.00	1989.53	1956.78	1957.38	2021.76
2021	1950.00	2037.96	1984.82	1979.01	2086.46
2022	2050.00	2086.39	2010.46	1995.95	2153.23

Table 3. Trend values for linear, quadratic, cubic and exponential models in state S2

Year (t)	Production (y_t)	Trend Values for S2			
		Linear Model (L_t)	Quadratic Model (Q_t)	Cubic Model (C_t)	Exponential Model (E_t)
2002	1146.00	1084.42	1168.41	1100.41	1105.31
2003	896.00	1050.12	1108.92	1081.71	1054.56
2004	1126.00	1015.83	1052.07	1054.93	1006.14
2005	1032.00	981.53	997.88	1021.25	959.95
2006	1059.00	947.23	946.35	981.88	915.87
2007	1127.00	912.94	897.46	938.01	873.82
2008	662.00	878.64	851.23	890.82	833.70
2009	766.00	844.34	807.65	841.52	795.43
2010	1123.00	810.04	766.72	791.29	758.91
2011	823.00	775.75	728.44	741.32	724.06
2012	502.00	741.45	692.82	692.82	690.82
2013	379.80	707.15	659.85	646.97	659.10
2014	445.00	672.86	629.53	604.96	628.84
2015	618.00	638.56	601.86	567.99	599.97
2016	680.61	604.26	576.85	537.25	572.42
2017	755.00	569.97	554.49	513.94	546.14
2018	310.00	535.67	534.78	499.24	521.07
2019	510.00	501.37	517.72	494.35	497.14
2020	660.00	467.07	503.32	500.47	474.32
2021	480.00	432.78	491.57	518.77	452.54
2022	470.00	398.48	482.47	550.47	431.76

Table 4. Trend values for linear, quadratic, cubic and exponential models in state S3

Year (t)	Production (y_t)	Trend Values for S3			
		Linear Model (L_t)	Quadratic Model (Q_t)	Cubic Model (C_t)	Exponential Model (E_t)
2002	907.00	1127.91	1243.96	913.06	1100.50
2003	1599.90	1119.43	1200.65	983.98	1092.82
2004	1084.70	1110.95	1161.01	1034.48	1085.20
2005	1072.00	1102.47	1125.03	1066.84	1077.63
2006	1019.00	1093.99	1092.72	1083.32	1070.11
2007	1307.00	1085.51	1064.07	1086.20	1062.65

2008	961.00	1077.02	1039.09	1077.74	1055.24
2009	828.00	1068.54	1017.78	1060.20	1047.88
2010	1091.25	1060.06	1000.13	1035.86	1040.57
2011	1230.27	1051.58	986.15	1006.98	1033.31
2012	1044.00	1043.10	975.84	975.84	1026.10
2013	1210.00	1034.62	969.19	944.70	1018.94
2014	770.00	1026.14	966.21	915.82	1011.83
2015	790.00	1017.66	966.89	891.48	1004.78
2016	930.00	1009.18	971.25	873.94	997.77
2017	960.00	1000.69	979.26	865.48	990.81
2018	830.00	992.21	990.95	868.36	983.90
2019	910.00	983.73	1006.29	884.84	977.03
2020	1010.00	975.25	1025.31	917.20	970.22
2021	1060.00	966.77	1047.99	967.70	963.45
2022	1290.00	958.29	1074.34	1038.62	956.73

In Tables 2, 3, and 4, the term 'y_t' represents the actual pearl millet production (in thousand tons) for the year 't' (where $t$ranges from 2002 to 2022). Also, the term 'L_t' denotes the linear trend value for the year 't'. Moreover, 'Q_t' denotes the quadratic trend value, 'C_t' refers to the cubic trend value, and 'E_t' denotes the exponential trend value for pearl millet production.

Table 5. Model equations for linear, quadratic, cubic and exponential trends in selected states of India

Models	**States**		
	S1	**S2**	**S3**
Linear	$y_t' = 48.429t' + 1602.1$	$y_t' = -34.297t' + 741.45$	$y_t' = -8.4811t' + 1043.1$
Quadratic	$y_t' = -1.1993t'^2 + 48.429t' + 1646.1$	$y_t' = 1.3262t'^2 - 34.297t' + 692.82$	$y_t' = 1.8331t'^2 - 8.4811t' + 975.84$
Cubic	$y_t' = -0.0424t'^3 - 1.1993t'^2 + 51.218t' + 1646.1$	$y_t' = 0.1988t'^3 + 1.3262t'^2 - 47.377t' + 692.82$	$y_t' = 0.378t'^3 + 1.8331t'^2 - 33.355t' + 975.84$
Exponential	$y_t' = 1571.4e^{0.0315t'}$	$y_t' = 690.82e^{-0.047t'}$	$y_t' = 1026.1e^{-0.007t'}$

(Note: $t' = t - 2012$)

The relative performances of the concerned fitted models on pearl millet production in the states S1, S2, and S3 are illustrated graphically in Figs. 1 to 12.

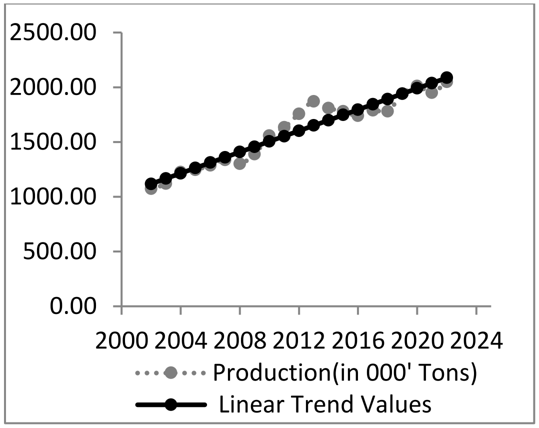

Fig. 1. Linear trend values for state S1

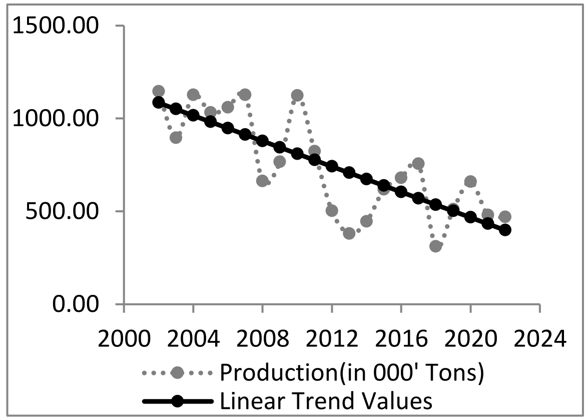

Fig. 2. Linear trend values for state S2

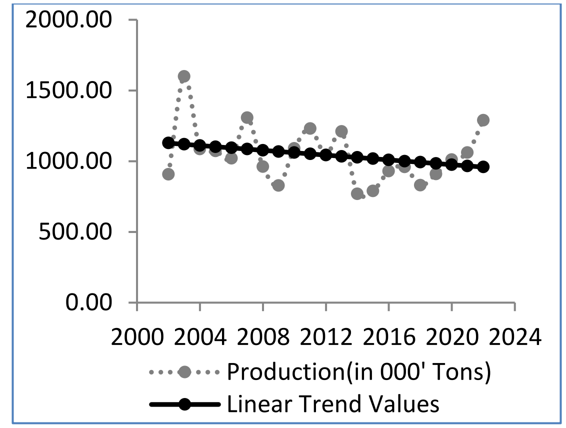

Fig. 3. Linear trend values for state S3

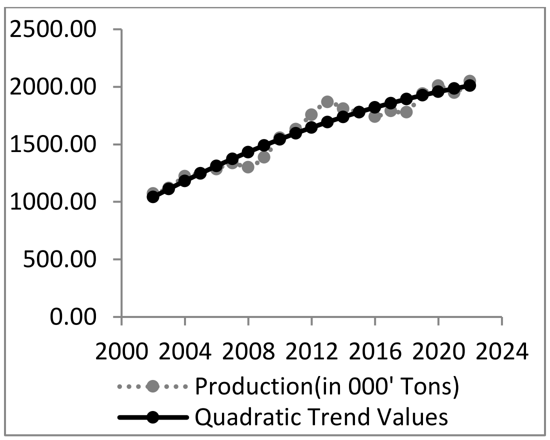

Fig. 4. Quadratic trend values for state S1

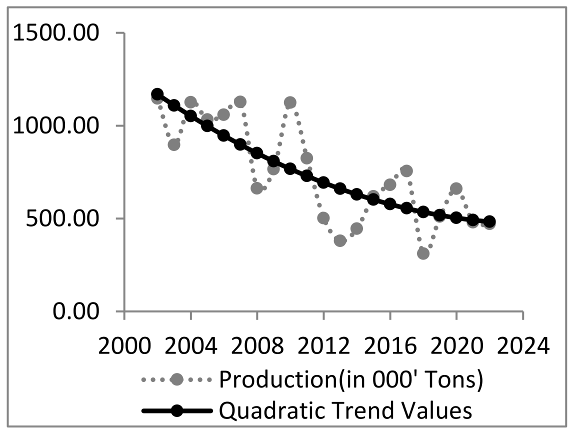

Fig. 5. Quadratic trend values for state S2

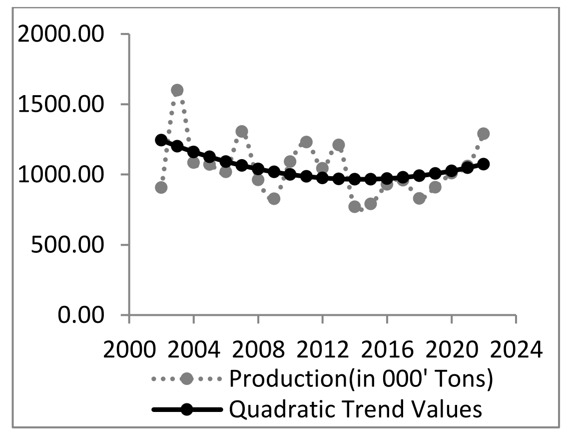

Fig. 6. Quadratic trend values for state S3

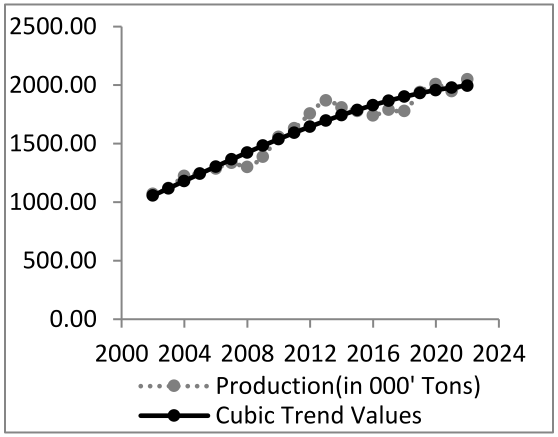

Fig. 7. Cubic trend values for state S1

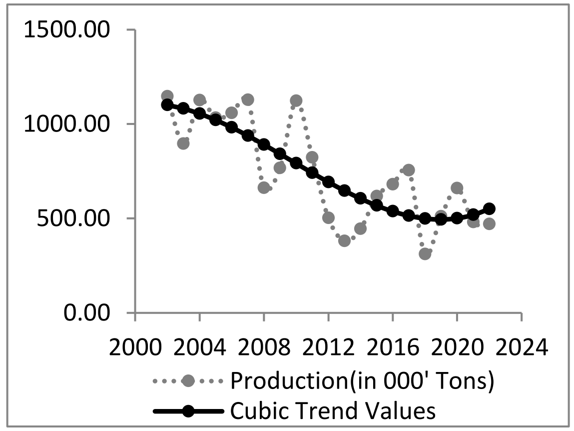

Fig. 8. Cubic trend values for state S2

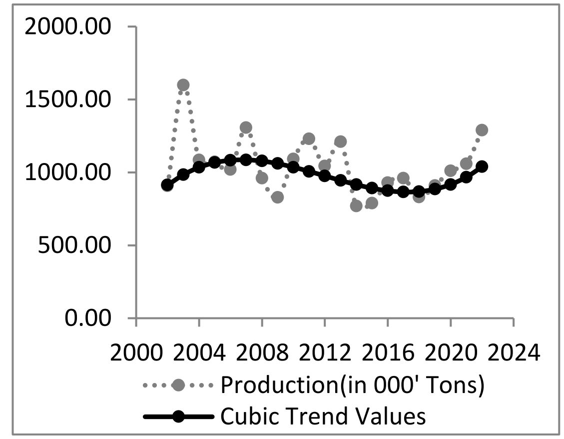

Fig. 9. Cubic trend values for state S3

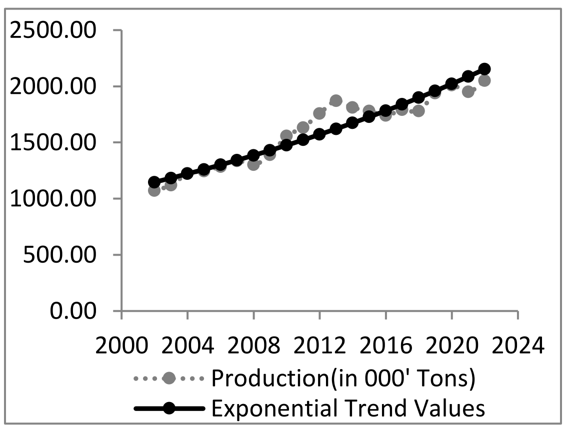

Fig. 10. Exponential trend values for state S1

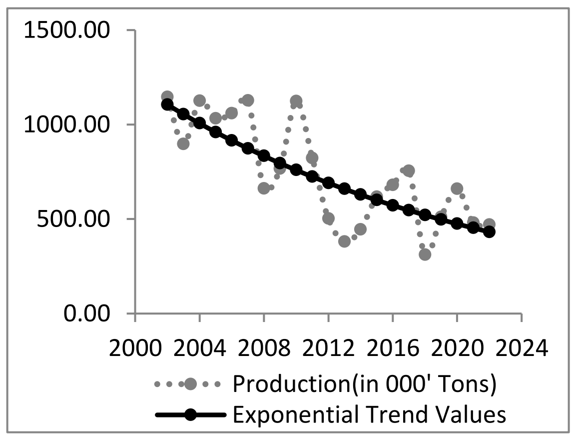

Fig. 11. Exponential trend values for state S2

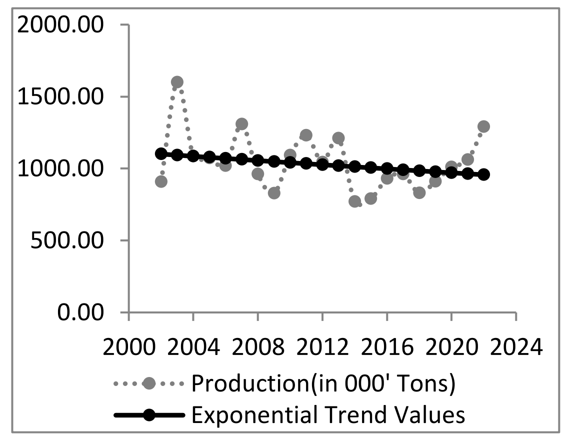

Fig. 12. Exponential trend values for state S3

The values of statistical measures viz., R^2, RMSE and RMAPE for the concerned fitted models in the respective states S1, S2, and S3, are computed and the findings are summarized in Table 6.

Table 6. Model evaluation for pearl millet production in selected states of India

States	Models	R^2	RMSE	RMAPE
S1	Linear	0.926	83.03	4.00
	Quadratic	0.942	73.19	3.53
	Cubic	0.943	72.83	3.42
	Exponential	0.913	98.41	4.61
S2	Linear	0.599	169.91	23.63
	Quadratic	0.625	164.29	21.16
	Cubic	0.641	160.68	21.85
	Exponential	0.548	167.35	21.93
S3	Linear	0.069	188.73	14.17
	Quadratic	0.163	178.96	13.77
	Cubic	0.274	189.79	11.99
	Exponential	0.062	189.31	13.61

The Table 6 reveals the following results:

i. In the states S1 and S2, the values of R^2 are greater than 0.5 for all the fitted models, which exhibit that the fitted models are appropriate for trend pattern analysis of pearl millet production in the states S1 and S2.

ii. In the state S3, the values of R^2 are infinitesimally small due to consistent trend pattern of pearl millet production.

iii. In the states S1 and S2, the cubic model reported least values of RMSE and RMAPE in production of pearl millet, as compared to the other fitted models.

iv. In the state S3, cubic model reported least RMAPE as compared to other fitted other models.

Hence, taking into account the above mentioned points, it can be concluded that the concerned fitted models are suitable for analyzing the trend pattern of pearl millet production in the selected states of India. Furthermore, the cubic model appears to be more accurate than the other fitted models in examining the trend pattern of pearl millet production.

4. Conclusion

The present investigation deals with the trend pattern analysis of pearl millet production in some pearl millet growing states of India viz., S1 (Uttar Pradesh), S2 (Maharashtra), and S3 (Gujarat) utilizing secondary time series data pertaining to the period 2002-2022. The trend values were estimated by fitting linear, quadratic, cubic and exponential models to the relevant time series data on pearl millet production. Additionally, the precision of the concerned fitted models was evaluated using various measures viz., coefficient of determination (R^2), root mean square error (RMSE) and relative mean absolute percentage error (RMAPE).

The state Uttar Pradesh exhibited rapid increase in growth pattern of pearl millet production during the period of investigation, whereas the state Maharashtra reported rapid decline in growth pattern of pearl millet production. Furthermore, a consistent growth pattern of pearl millet production was observed in Gujarat. In the year 2022, the state Uttar Pradesh witnessed highest production of pearl millet, followed by Gujarat and Maharashtra.

The empirical results of investigation reveal that the fitted models were suitable for exploring the trend patterns of pearl millet production in the concerned states. Moreover, on the basis of values ofR^2, RMSE and RMAPE, it can be concluded that the cubic model is more precise as compared to the other fitted models, and can be used for forecasting of pearl millet production in the concerned states of India.

The findings of investigation offer valuable insights for policy development aimed at increasing pearl millet production to address global food demand and enhance nutritional security. In order to enhance pearl millet production, the farmers should be incentivized for its cultivation.

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