



Forecasting pre-harvest rice (*Oryza sativa*) yield: A regression analysis of meteorological factors and climate change impacts on food security

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ABSTRACT

In order to arrive at the findings, different statistical models have been developed as a result to examine how climate change may affect rice yield at various phases of the crop as well as it has been attempted to forecast its output for Karnal district. Time series data on rice yield for the past 37 years on crop and weather variables have been used in the Karnal district of Haryana from 1985–1986 through 2021–22. The relationship between rice (*Oryza sativa* L.) crop and various models was investigated. A boost in yield can be obtained by creating fresh weather indices from weekly data. The model takes various weather variables into account. It was discovered that the best models (models 1, 2, and 7, 8) for assessing the impact of specific weather variables were linear functions across weekly data, meteorological factors, and adjusted crop production for the trend impact are the independent variables. A forecast model was also built and the findings revealed that forecasting at the 15th week of the crop period or one and a half months before harvest was found reliable.

Keywords: Crop production, Pre-harvest forecast, Statistical model, Weather indices

India has experienced remarkable economic growth in recent years and remains one of the fastest growing economies in the world. However, poverty and food insecurity in India are still areas of concern in spite of many strides. Food is considered as a basic amenity essential for the sustenance, development and growth of an individual. India has ranked 101 among the 116 countries on the Global Hunger Index, 2021. According to the Food and Agriculture Organization, the food price index has increased by 30% in the year 2021–22. Although the Government of India has been actively addressing food security at households for a long time through the public distribution system. Climate change has a significant impact on food availability, accessibility, and quality. For instance, agricultural productivity may be affected by rising temperatures, altered precipitation patterns, increased frequency of extreme weather events, and reduced water availability. The variability and changes in

climate have a major influence on agricultural productivity, especially in India, where agriculture is highly dependent on the performance of the southwest monsoon and favourable weather conditions. Unpredictable weather patterns raise concerns for both policymakers and farmers. In recent years, the average global temperature has risen, and hydrological patterns have been altered due to several factors, including the burning of fossil fuels for transportation, coal combustion in energy production, and the release of greenhouse gases from industrial activities, as well as extensive deforestation. As the world progresses rapidly, food security has become an increasing challenge to ensure that all people have consistent access to sufficient, nutritious, and safe food. This issue is complex, influenced by agricultural production, climate change, supply chains, and economic access.

Achieving food security requires stable crop yields and efficient food production systems. Climate variability, natural disasters, and economic inequalities can all negatively impact food security. Therefore, sustainable farming practices, better resource management, and advancements in agricultural technology are critical to ensuring that everyone has access to adequate food. Food security is closely linked to yield forecasting, as reliable predictions of agricultural production help ensure a stable food supply (George and McKay 2019). Various studies, such as those by Agrawal *et al.* (1980, 1983, 1986), Jain *et al.* (1980), Yadav *et al.* (2014)

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and Sisodia *et al.* (2014), have explored the relationship between crop yields and weather variables. In this context, the present research aims to assess the individual effects of weather conditions on rice yield and forecast rice production in the Karnal district of Haryana.

MATERIALS AND METHODS

The research was conducted in the Karnal district, located in the north-central region of Haryana (latitudes 26°47' and 82°12'), Karnal, Haryana's north-central plain zone (EPZ). Rice cultivation thrives in humid to sub-humid climates with subtropical and temperate conditions, as well as soils with good water-holding capacity. Rice grows best in soils with a pH range of 5.5–6.5, with clay, silty clay, and silty clay loam being the most suitable soil types. Medium to medium-heavy textured deep alluvial soils are easily cultivable. Rice crops require between 1400 and 1800 mm of water. Given the favorable soil, climate, and available irrigation resources, the region is highly suitable for rice production. Rice (*Oryza sativa* L.) is typically cultivated during the *kharif* season, when atmospheric conditions, including water availability, are most favorable for its growth. The study examined weekly weather data, including maximum and minimum temperatures, morning and evening relative humidity, rainfall, and sunshine hours, spanning from 1985–86 to 2021–22. This weather data was obtained from the Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana. Time series data on rice yield for the Karnal district for the time period 1985–86 to 2021–22 was obtained from the statistical abstract of Haryana. By utilizing yield forecasting techniques such as remote sensing, statistical models, and weather-based predictions, policymakers and farmers can anticipate crop yields and plan accordingly. As we know accurate forecasts can help in better decision-making regarding resource allocation, market strategies, and emergency measures in the event of low production. This helps mitigate risks such as food shortages, price volatility, and malnutrition, ensuring the resilience of food systems in the face of challenges like climate change and population growth.

Crop season: Rice is commonly grown in Karnal district in the third week of June, when the average daily temperature is around 41°C. Rice is sown at a lower temperature, which causes poor germination, limited tillering, and early flowering, exposing the floral components to heat damage. All of these variables lower agricultural yields. Vegetative, reproductive, and ripening stages are the three stages of crop growth. The early growth stage encompasses the time from sowing to emergence, as well as the crop's vegetative stage, which lasts for eight weeks from June 18 (25th SMW) to August 12 (32th SMW). The reproductive and ripening stages of the crop are included in the maturity phase, which lasts 9 weeks from August 13 (33rd SMW) until October (41st SMW). As a result, present study includes data from 17 weeks (25th SMW to 41st SMW) for each weather variable under consideration.

Statistical analysis: The impact of weather conditions

on yield was examined using weekly meteorological data from June 1 (approximately 14 days prior to sowing through the harvest period), while forecast models were developed using data from the half crop season. Data from a fortnight before to sowing were included because it is thought that this time period affects crop establishment.

Statistical models studied: Agrawal *et al.* (1986) established statistical models that represent the impact of weekly variations in meteorological factors on crop yield can be expressed as a linear function, utilizing the correlation coefficient to quantify the relationship between yield and the corresponding weekly weather data. We tested a total of eight models.

Model 1: The initial Agrawal *et al.* (1986) model

$$Y = a + b_0 \sum_{w=1}^n X_w + b_1 \sum_{w=1}^n r_{xy(w)} X_w + b_2 \sum_{w=1}^n r_{xy(w)}^2 X_w + cT + \mu$$

$$= a + b_0 Z_0 + b_1 Z_1 + b_2 Z_2 + cT + e$$

a, b_j (j = 0, 1, 2), and C are model parameters. N is the number of weeks before harvest. W is the week identification. Y is rice yield (kg/ha). The yield has a correlation coefficient of r_{xy} with the weather variable being studied in the current week of X_w , and vice versa (w). It is anticipated that the error Terms will have a and a zero mean in a normal distribution. Constant variance σ^2 where T refers for the trend variable (time index) and ϵ stands for the error terms.

Model 2: The model changes to the following when the phrase $b_2 Z_2$ is dropped: $Y = a + b_0 Z_0 + b_1 Z_1 + cT + e$

Model 3 and 4: The only difference between these models and models 1 and 2 is that $r_{xy(w)}$ is calculated utilizing yield corrected for trend impact.

Model 5: The following model are produced by inserting 2nd terms of meteorological parameters and correlation coefficients into model 1:

$$Y = a + b_0 \sum_{w=1}^n X_w + b_1 \sum_{w=1}^n r_{xy(w)} X_w + b_2 \sum_{w=1}^n r_{xy(w)}^2 X_w + b_{00} \sum_{w=1}^n X_w^2 + b_{11} \sum_{w=1}^n r_{x^2y(w)} X_w^2 + b_{22} \sum_{w=1}^n r_{x^2y(w)}^2 X_w^2 + cT + \mu$$

$$= a + b_0 Z_0 + b_1 Z_1 + b_2 Z_2 + b_{00} Z_{00} + b_{11} Z_{11} + b_{22} Z_{22} + cT + \mu$$

Model 6: The quadratic terms $b_2 Z_2$ and $b_{22} Z_{22}$ are eliminated from model 5 to achieve this, leaving the following model:

$$Y = a + b_0 Z_0 + b_1 Z_1 + b_{00} Z_{00} + b_{11} Z_{11} + cT + e$$

Model 7 and 8: Models 5 and 6 are identical with the exception that adjusted yield for trend influence is used to determine correlation coefficients.

Relative humidity data, which were previously expressed in percentages, have been transformed to arc-sine root proportions. Stepwise regression was used to select significant generated weather indicators (independent variables in the models). The effects of unit changes in weather variables on yield for the wth week have been quantified by deriving the models in relation to X_w .

Forecast model and time of forecast: The subsequent

model including single and various combinations of weather variables to exhibits their interaction effects on crop yield was fitted using partial crop season data.

$$Y = a + \sum_{i=1}^p \sum_{j=0}^1 b_{ij} Z_{ij} + \sum_{i'=1}^p \sum_{j=0}^1 b_{i'j} Z_{i'j} + cT + e$$

$$Z_{ij} = \sum_{w=1}^m r_{iw}^j X_{iw}, Z_{i'j} = \sum_{w=1}^m r_{i'w}^j X_{i'w} X_{i'w}$$

Where Y represent yield; p, Number of meteorological variables utilized, and m, signify the number of weeks considered in the model development. Yield and the i^{th} weather variable (X_i)/the sum of the two weather variables (and) in the week are correlated. The symbol T stands for the temporal trend variable. The variables in the model are a, b_{ij} , $b_{i'j}$, j and c. The error terms e is presumptively distributed normally, with a mean of zero and variance. To fit the model, various values of m ($m = 12, 13 \dots 15$) were employed. As production was to be predicted well in advance of harvest, the data collected after the 15th week were not used. The coefficient of determination is calculated using the following formula (R^2).

Accuracy measures of developed model: Several accuracy parameters, including as R^2 (coefficient of determination), per cent deviation, per cent standard error (CV), and root mean square error (RMSE) were employed to verify the suitability of the developed model.

RESULTS AND DISCUSSION

To determine the ideal correlation between crop output and various meteorological variables, we looked at eight different models. An overview of the fitted models is shown in (Table 1) along with their coefficient of determination (R^2) values. It demonstrates that model 1 that used yield-adjusted correlations outperformed models that utilized simple correlations, and (ii) the incorporation of quadratic terms for meteorological variables, as well as the square of the correlation coefficient, did not substantially improve the model's performance. Nonetheless, models 1, 2, 7, and 8 demonstrated comparable characteristics after being fitted to the data using stepwise regression analysis. In order to look into how weather factors, affect rice production. we adopted model 7. The all stages of rice crop growth are given in (Fig. 1). The annual rice yield (kg/ha) of Karnal district are given in (Fig. 2). These figures represent the yield increase as well as decrease with year.

Climate-related factors' impact on rice yield: The impact of a meteorological variable increase of one unit on average yield at various crop growth stages have been explored in this section. lists the effects of climatic variable on rice yield are given in (Table 2). When the vertical scale is inverted, the effect of a one-unit change is insufficient relative to the mean

Impact of T_{max} : The following expression represents the multiple regression equation for the maximum temperature, designated as Model I.

$$Y = -38.8951 + 0.095Z_0 + 1.393Z_1 + 0.900T \quad (R^2=0.73)$$

The results were derived from

$$\frac{\partial Y}{\partial X_{xy(w)}} = 0.095 + 1.393r_{xy(w)}$$

A 1°C increase over the average weekly maximum temperature benefited rice yield during the crop's early growth and vegetative growth stages (Table 2). An increase in the maximum temperature during the reproductive stage had the opposite effect on rice output. It has been discovered that during the ripening and maturity stages, increases in the maximum temperature are often beneficial.

Impact of T_{min} : "The equation for the multiple regression analysis of minimum temperature (Model I) is defined as follows:"

$$Y = -23.552 + 1.144Z_1 + 0.881T \quad (R^2=0.65)$$

The results were derived from

$$\frac{\partial Y}{\partial X_{xy(w)}} = 1.144r_{xy(w)}$$

Table 2 demonstrates that during the vegetative growth stage, a minimum temperature increase of 1°C above the average has a detrimental impact. All during the reproductive stage, nevertheless, the effect was beneficial. It has been found that the impacts are generally detrimental to the crop during the ripening and maturity stages.

Impact of RH at morning: The Multiple predictor model (Model-V) for morning RH is provided below:

$$Y = -86.354 + 0.886Z_{11} + 0.943T \quad (R^2=0.74)$$

The findings were obtained from:

$$\frac{\partial Y}{\partial X_{xy(w)}} = 0.886 \times 2X_w r_{x^2y(w)}$$

Table 1 The coefficient of determination (R^2) for various models

Climatic variables	Model							
	1	2	3	4	5	6	7	8
Max temperature (°C)	0.73	0.73	0.65	0.65	0.72	0.72	0.66	0.66
Min temperature (°C)	0.65	0.65	0.61	0.61	0.64	0.64	0.62	0.62
RH at morning (%)	0.64	0.64	0.60	0.60	0.74	0.74	0.73	0.73
RH at evening (%)	0.67	0.67	0.63	0.63	0.77	0.77	0.76	0.76
Precipitation (mm)	0.76	0.76	0.65	0.65	0.75	0.75	0.74	0.74
SSH	0.69	0.69	0.66	0.66	0.73	0.73	0.72	0.72

RH, Relative humidity; SSH, Sunshine hours.

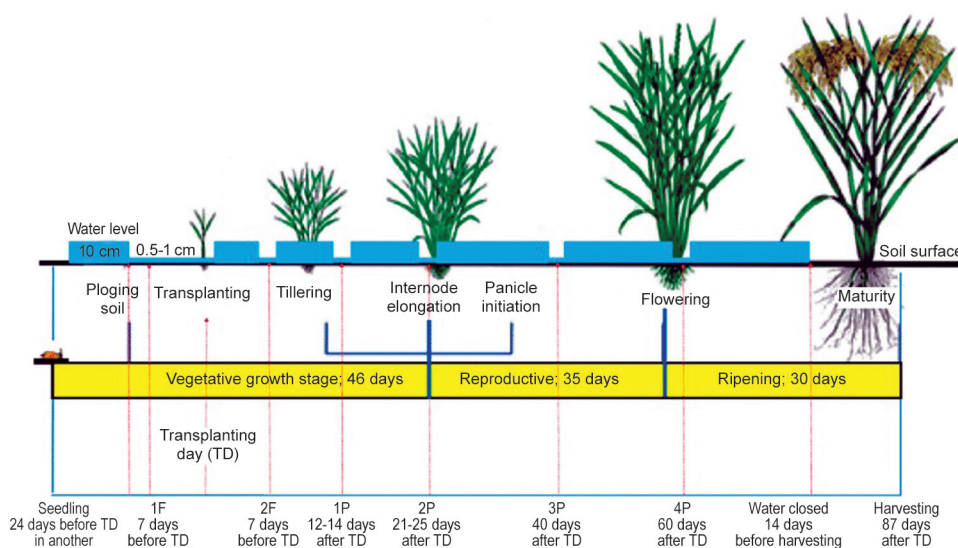


Fig. 1 Stages of rice crop growth.

A one per cent increase in humidity above average each week has, aside from the final stages of crop growth, generally had a positive impact on rice yield i.e. ripening and maturity period. Hence, rise in humidity during last 4–5 weeks before the harvest could be detrimental to the rice yield.

Influence of RH at evening: The multiple predictor model (Model-V) for evening RH is provided below:

$$Y = -46.177 + 0.001Z_{11} + 1.068T \quad (R^2=0.74)$$

The findings were obtained from

$$\frac{\partial Y}{\partial X_{xy(w)}} = 0.001 \times 2X_w r_{x^2 y(w)}$$

Throughout the entire crop growing phase, the effects were mainly detrimental on rice yields, with the exception of the harvesting stage. As a result, a slight increase in humidity in the evening during the harvesting stage may be helpful to rice yield. However, the 20th week has no impact.

Influence of precipitation: The model-1 multiple predictor model for Precipitation is as follows:

$$Y = -6.993 - 0.002Z_1 + 0.752T \quad (R^2=0.76)$$

The findings were obtained from

$$\frac{\partial Y}{\partial X_{xy(w)}} = -0.002 \times 2X_w r_{x^2 y(w)}$$

Up until the vegetative growth stage, a 1 mm increase in precipitation above the average weekly rainfall has frequently demonstrated beneficial effects. However, the effects were negative during the reproductive, ripening, and maturity stages of crop development. It is also common knowledge that increased rainfall during the ripening and harvesting stages reduces rice production. With rise in temperature, rain

becomes deciding factor in regulating crop production. It is envisaged that the increase in temperature, if any, may be compensated by increase in rainfall.

Effect of sunshine hours: The multiple predictor model (Model-V) for sunshine hours (SSH) may be found below.

$$Y = 7.090 - 0.002Z_1 - 0.003Z_{00} + 0.750T \quad (R^2 = 0.73)$$

The results were derived from:

$$\frac{\partial Y}{\partial X_{xy(w)}} = -0.002r_{xy(w)} - 0.003 \times 2X_w$$

Generally, during the planting and vegetative development phases of the crop, an increment of one unit in solar exposure above the mean weekly levels has shown to confer advantageous effects (Table 2). Conversely, a detrimental effect has been recorded during the flowering, ripening, and maturation phases of the crop as a result of increased solar radiation exposure. Table 2 presents findings indicating that during the eighth week of the crop, a one-hour increase in sun shine hours over the weekly sunshine hours led to a 1.3% increase in rice output.

Agnolucci and De (2020), Shammi and Meng (2021),

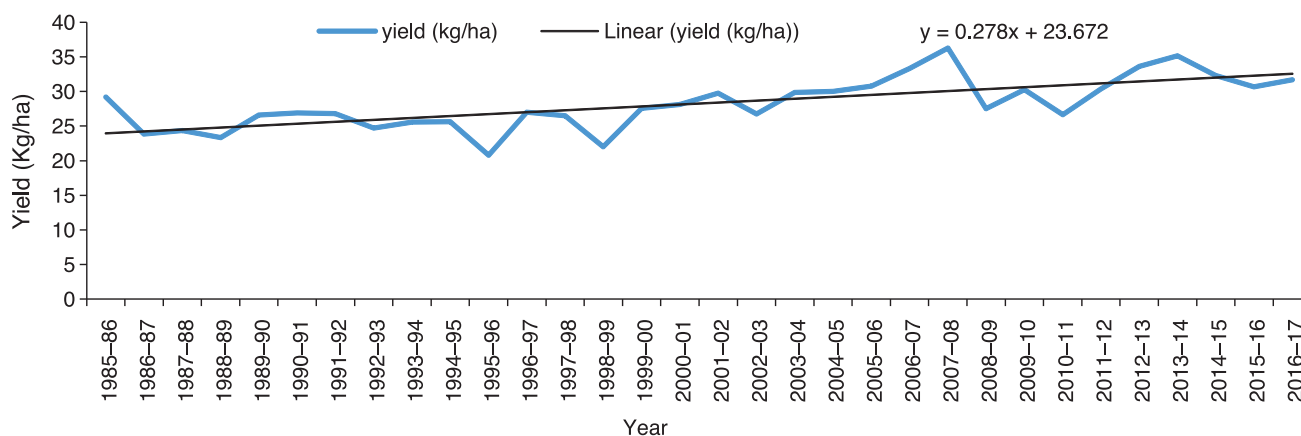


Fig. 2 Annual rice yield (kg /ha) of Karnal district.

Table 2 Per cent change in yield with per unit increase in weather variable over its average value

Growth phases	Week no.	SMW	Weather variables					
			Max. temp. (°C)	Min. temp. (°C)	RH at morning (%)	RH at evening (%)	Precipitation (mm)	Sunshine hours
Preparation	1	22	0.021	-0.073	0.234	-0.000	2.900	0.094
	2	23	0.011	0.220	0.350	-0.000	-0.000	0.167
	3	24	0.121	-0.061	0.163	-5.900	8.180	0.159
Sowing	4	25	0.224	-0.054	0.119	3.040	0.000	0.028
Vegetative growth stage	5	26	0.168	0.233	0.047	-1.250	0.000	0.070
	6	27	0.015	0.087	0.156	-8.500	9.600	0.162
	7	28	0.067	0.238	0.078	-4.800	0.000	0.045
	8	29	0.072	-0.032	0.198	-3.500	0.000	1.345
	9	30	0.008	-0.123	0.203	-0.000	0.000	0.111
	10	31	0.014	0.169	0.206	6.920	0.000	0.055
	11	32	0.011	-0.086	0.261	-6.100	0.000	0.188
	12	33	0.109	0.280	0.123	-6.110	0.000	0.034
Reproductive stage	13	34	0.181	0.062	0.165	-0.000	6.320	-0.062
	14	35	0.499	0.261	0.405	-0.000	-0.000	-0.005
	15	36	0.085	0.049	0.307	-7.400	-1.100	-0.034
	16	37	0.187	0.194	-0.361	-7.260	-0.000	0.001
Ripening stage	17	38	0.083	-0.139	-0.356	1.440	-0.000	-0.078
	18	39	0.032	0.042	-0.416	6.300	-9.700	-0.020
	19	40	0.123	-0.022	-0.560	8.240	-6.800	-0.059
	20	41	0.110	-0.130	-0.504	0.000	-0.000	-0.033

SMW, Standard meteorological week; temp, Temperature; RH, Relative humidity.

Cao *et al.* (2022), and Pham *et al.* (2022) have also studied the impact of climate change on crop yield using various statistical approaches.

An examination of Table 3 reveals that the 15th week (corresponding to the second week of September) represents the optimal period for predicting rice yield in the Karnal region, as the coefficient of determination R^2 does not significantly increase when incorporating data from subsequent periods. Consequently, the model developed for $m = 15$ is affirmed.

$$Y = 13.420 - 1.088Z_{40} - 0.045Z_{451} + 0.019Z_{241} + 0.810T (R^2 = 0.84)$$

The regression diagnostics of the selected zonal model

(follow one pattern for all, either below or above figure are given in Fig. 3.

The analysis indicates that the weighted interactions of rainfall and sunshine hours unweighted indices of precipitation and the weighted interactions of minimum temperature with precipitation, in conjunction with the time trend variable (T), serve as significant explanatory variables within the model. The fitted forecasting model has been developed to capture these relationships. as previously described has been used to generate the yield forecasts for the years 2017–18, 2018–19, 2019–20, and 2021–22 (Supplementary Table 1). The findings demonstrate how

Table 3 Models fitted for Karnal district at $m = 12, 13, 14, 15$ and 16

m	MODEL	R^2	Adj. R^2
12	$Y = 14.220 - 1.085Z_{40} - 0.048Z_{451} + 0.023Z_{241} + 0.811T$ (7.784) (0.407) (0.018) (0.004) (0.145)	81.0	79.6
13	$Y = 14.420 - 1.025Z_{40} - 0.041Z_{451} + 0.020Z_{241} + 0.815T$ (7.782) (0.403) (0.016) (0.006) (0.148)	82.1	78.0
14	$Y = 14.420 - 1.080Z_{40} - 0.041Z_{451} + 0.020Z_{241} + 0.815T$ (7.783) (0.402) (0.012) (0.008) (0.147)	83.9	79.7
15	$Y = 13.420 - 1.088Z_{40} - 0.045Z_{451} + 0.018Z_{241} + 0.810T$ (7.780) (0.406) (0.013) (0.001) (0.141)	84.0	79.8
16	$Y = 14.423 - 1.080Z_{40} - 0.042Z_{451} + 0.021Z_{241} + 0.810T$ (7.779) (0.402) (0.012) (0.004) (0.144)	79.9	78.2

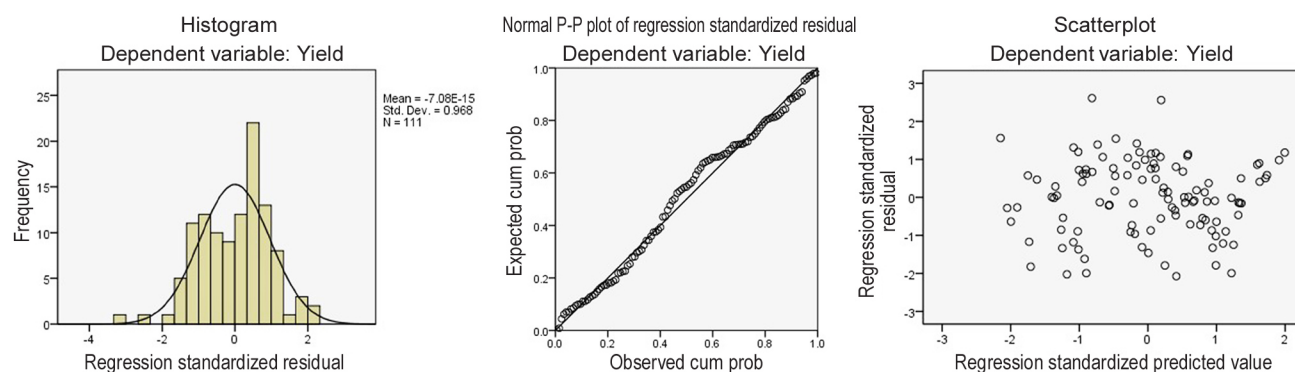


Fig. 3 Regression diagnostics of the selected zonal model (follow one pattern for all, either below or above figure)

closely the predicted yield and the observed yield matched. The per cent variation of the projection varied from 1.70–5.66. Thus, it can be concluded that the previously indicated model is capable of precisely forecasting rice production up to 1.5 months ahead of harvest.

The study reveals that most weather variables negatively impact rice yield throughout the crop season, except during specific stages. Rice production increases by 1°C above the average weekly maximum temperature during early growth and vegetative growth stages. A 1 mm increase in rainfall has a positive effect up to vegetative growth. During the sowing and vegetative growth stages, an increase of one unit above the normal weekly sunshine hours is advantageous. During the vegetative growth stage, a minimum temperature increase of 1°C over the average has a negative impact. All during the reproductive stage, nevertheless, the effect was beneficial. During the harvest stage, a small rise in relative humidity in the evening could benefit rice productivity. The 20th week, however, has no bearing. The 15th week (2nd week of September) is the ideal time to forecast rice output in the Karnal area because the value of R^2 does not substantially rise when data from subsequent periods are included.

The findings of a critical examination point to the preference for utilizing model-15 based on trend yield and weather variables. Trend yield has been noted as a significant parameter that appears in all the models, suggesting that Tr, an indicator of technological advancement, improved use of pesticides, weed killers, fertilizers, and insecticides, and increased use of high yielding varieties, accounts for the majority of yield variability. The utilization of created models for district-level rice yield estimation in Haryana is supported by the average absolute percent deviations of the post-sample period forecasts, which range from 1.70–5.66%. The yield model's ability to predict district-level yield is the subject of the other query. The approach has shown to greatly enhance district-level rice yield forecasting, according to the results. Furthermore, the created model can reliably predict rice yield(s) at least one month before the crop is

harvested; in contrast, Department of Agriculture (DOA) yield predictions are derived much later after the crop is actually harvested. Forecasting yield can help in various different measures like: risk management, efficient resource allocation, improved crop management, climate change adaptation and policy formulation and support.

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