



PREDICTION OF POST-HARVEST SOIL TEST VALUE AFTER SAFFLOWER (*Carthamus tinctorius* L.) CROP IN VERTISOL OF CHHATTISGARH, INDIA

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ABSTRACT

Soil fertility management is cornerstone for sustainable crop production, ensuring nutrient availability for optimal yields. Reliable estimates of post-harvest soil test values (PHSTVs) are crucial for planning nutrient applications for succeeding crops. Conventional soil testing after each crop cycle is costly and time-consuming; hence, predictive models based on initial soil fertility status, applied fertilizer doses, and crop yields provide a practical alternative. The present study was aimed to assess the relationship between observed and predicted PHSTVs and to generate prediction equations after safflower cultivation. Multiple regression analysis was performed, considering PHSTVs as the dependent variable and initial soil test levels, fertilizer inputs, and grain yields as independent variables. Equations developed on the basis of yield and nutrient uptake demonstrated high predictability for $\text{KMnO}_4\text{-N}$, Olsen's P, and NH_4^+ -acetate extractable K. Predicted PHSTVs for N, P, and K were compared with observed values, yielding considerably large R^2 values, confirming strong model performance. Calibration using RMSE and RE showed RMSE values in the order $\text{K} > \text{N} > \text{P}$, while RE values followed $\text{P} > \text{K} > \text{N}$. For safflower, RE values below 10% indicated excellent prediction accuracy. The generated equations for PHSTVs offer a reliable tool for estimating soil test values without repeated laboratory testing. This approach reduces soil testing costs, improves nutrient management efficiency, and supports sustainable crop production.

Keywords: Integrated nutrient management, post-harvest soil test value, safflower, soil test crop response

INTRODUCTION

Sustainable crop production requires efficient nutrient management for soil fertility maintenance and productivity (Kamboj *et al.*, 2024). Continuous cropping, nutrient mining, and imbalanced fertilizer use have contributed to declining soil fertility, reduced crop productivity, and poor nutrient-use efficiency (Shukla *et al.*, 2022; Paramesh *et al.*, 2023). Blanket fertilizer recommendations often overlook the soil nutrient variability and crop demand, causing under- or over-dose of fertilizers (Andualem *et al.*, 2024; Pandit *et al.*, 2025). Thus, soil-test-based nutrient management is essential for sustainable crop production (Murthy *et al.*, 2024; Singh *et al.*, 2025). Regular soil testing is essential for effective nutrient management, but limited laboratory facilities, analytical costs, and

labour make the repeated testing after each harvest a difficult task (Dobermann *et al.*, 2003). This emphasizes on developing reliable methods to predict post-harvest soil test values (PHSTVs). The soil test crop response (STCR) approach integrates soil fertility, crop nutrient requirements, and targeted yield for developing fertilizer recommendations (Ramamoorthy *et al.*, 1967). However, its application requires repeated soil testing, which may be impractical under intensive cropping systems (Kumar *et al.*, 2018; Kirankumar *et al.*, 2019). Multiple linear regression (MLR) models can estimate PHSTVs using initial soil test values, fertilizer inputs, and crop yield, and thus offer a practical viable alternative for nutrient management (Mahajan *et al.*, 2019; Selvam *et al.*, 2021).

Safflower (*Carthamus tinctorius* L.) is an important *rabi* oilseed crop in semi-arid India due to its drought tolerance and ability to utilize residual soil moisture (Manikanta *et al.*, 2023; Ponakala *et al.*, 2024). In India, it covers 46000 ha, with a production of 53000 tonnes and productivity of 537 kg ha⁻¹, while in Chhattisgarh state the crop occupies 270 ha, producing 110 tonnes with a productivity of 407 kg ha⁻¹ (Anonymous, 2018). Safflower is mainly grown under rainfed conditions, particularly on *Vertisols*. Despite the high nutrient-holding capacity of *Vertisols* (Charishma *et al.*, 2023), continuous safflower cultivation under inadequate and imbalanced fertilization may deplete soil nutrients and reduce crop productivity (Arbad and Ismail, 2011; Meshram *et al.*, 2020). Therefore, soil-test-based and precise fertilizer recommendations are essential for sustaining crop productivity. MLR models for predicting PHSTVs in safflower grown on *Vertisols* are limited, as the earlier studies have focused mainly on cereal-based systems (Jatav and Srivastava, 2023). Therefore, this study was aimed to develop and validate MLR models for PHSTV prediction to support soil-test-based fertilizer recommendations and reduce repeated soil testing on safflower based systems.

MATERIALS AND METHODS

Experimental detail

A field experiment was conducted at the Research Farm of IGKV, Raipur, Chhattisgarh (India) in *rabi* season 2019-20 to predict post-harvest soil test values (PHSTVs) of safflower grown on *Vertisols* using multiple linear regression (MLR) models. The field experiment was conducted in two phases viz., fertility gradient and test crop experiment as suggested by Ramamoorthy *et al.* (1967). A test-crop experiment using safflower cv. 'Chhattisgarh Kusum-1' was conducted in a fractional factorial design comprising of 24 treatments, each replicated three times. The experiment included four levels of N (0, 50, 100, and 150 kg ha⁻¹), P₂O₅ (0, 30, 60, and 90 kg ha⁻¹), and K₂O (0, 30, 60, and 90 kg ha⁻¹), with three levels of farmyard manure (FYM) (0, 10, and 20 t ha⁻¹).

Soil and plant analysis

The initial and post-harvest soil samples were collected from each plot and analysed for alkaline KMnO₄-N (Subbiah and Asija, 1956), Olsen-P (Olsen *et al.*, 1954) and NH₄OAc-K (Hanway and Heidel, 1952). Similarly, the safflower plant samples were collected at harvest, processed and analysed for N, P and K contents (Jackson, 1973). Grain and straw yields of safflower crop were recorded plot-wise and converted to q ha⁻¹. Based on nutrient concentrations in grain and straw and their respective yields, total nutrient uptake by safflower was calculated using the following formula:

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient concentration (\%)} \times \text{Yield (kg ha}^{-1}\text{)}}{100}$$

$$\text{Total nutrient uptake} = \text{Grain nutrient uptake} + \text{Straw nutrient uptake}$$

For N, P, and K, the nutrient concentrations were expressed as N, P and K (%), respectively.

Prediction of post-harvest soil test values

Multiple linear regression (MLR) analysis was performed using SPSS 16.0 to develop prediction equations for post-harvest soil test values (PHSTVs) using grain yield or total nutrient uptake, initial

soil test values, and fertilizer application rates for individual plots (Ramamoorthy *et al.*, 1971). The PHSTV was considered a dependent variable, while grain yield or total nutrient uptake, initial soil test value, and fertilizer nutrient dose as independent variables (Luthra *et al.*, 2023). The prediction equation for a post-harvest soil test value was used to make a fertilizer recommendation for succeeding crop. Multiple regression equations were expressed as follows:

$$\text{PHSTV} = \alpha + \beta_1 \text{GY} + \beta_2 \text{ISTV} + \beta_3 \text{FN} \text{ (based on grain yield)}$$

$$\text{PHSTV} = \alpha + \beta_1 \text{TNU} + \beta_2 \text{ISTV} + \beta_3 \text{FN} \text{ (based on total nutrient uptake)}$$

Where α is intercept; β_1 , β_2 and β_3 are regression coefficients; ISTV is initial soil test value; PHSTV is post-harvest soil test value; FN is fertilizer nutrient; GY is grain yield, TNU is total nutrient uptake.

Statistical analysis for calibration of predicted post-harvest soil test values

After experiments, descriptive statistics were used to assess the variations in observed and predicted post-harvest soil test values for available N, P and K across the three strips through paired t-test. Models performance was evaluated by comparing observed PHSTVs with those predicted by MLR equations. It is necessary to calibrate and confirm the prediction of generated model. Following methods were used for the calibration and confirmation of the model generated for the precision of prediction.

Root mean square error (RMSE): RMSE is an indicator of the closeness of observed and predicted values with each other. Better predictability of the model is indicated by lower RMSE values (Mahajan *et al.*, 2019).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (A_i - P_i)^2}{n}}$$

Where, A_i and P_i represent the observed and the predicted post-harvest soil test values of nutrients at the i^{th} data point, and n represents the number of data points.

Relative error: Relative difference between the observed and predicted values is expressed as relative error (RE) in percentage. When RE is less than 10%, the predictions are considered excellent, between 10 and 20% they are considered good, between 20 and 30% they are considered fair, and when greater than 30% they are considered as poor (Jamieson *et al.*, 1991; Zhu *et al.*, 2006).

$$\text{RE} = \sqrt{\frac{\sum_{i=1}^n ((A_i - P_i)/A_i)^2}{n}} \times 100$$

Where, A_i and P_i represent the observed and predicted post-harvest soil test values of nutrients at the i^{th} data point, and n represents the number of data points.

RESULTS AND DISCUSSION

Predicted post-harvest soil test values

The prediction equations for post-harvest soil test values (PHSTVs) of N, P, and K after safflower cultivation in *Vertisol* were developed using multiple regression analysis based on the initial soil test values, fertilizer application rates, and grain yield or nutrient uptake (Table 1). The prediction equations based on grain yield showed good predictive performance with R^2 values of 0.90, 0.85, and 0.68 for $\text{KMnO}_4\text{-N}$, Olsen-P, and NH_4OAc -extractable K, respectively. The equations developed using nutrient uptake also showed R^2 values of 0.90, 0.85, and 0.87 for N, P, and K, respectively. The results revealed that the developed regression equations reliably predict the post-harvest available NPK and may be used for targeted-yield-based fertilizer recommendations for the succeeding crops. Similar predictive relationships have been reported by Bhadhaurya *et al.* (2019) in maize, Arya *et al.* (2019) in cauliflower, Suresh and Santhi (2019) in maize, Singh *et al.* (2020) in soybean, and Mondal *et al.* (2020) in *kharif* rice.

Table 1: Multiple regression prediction equations for post-harvest soil test values of available N, P and K for safflower in two experimental years

Post-harvest prediction equation	R ²
1. Based on yield	
PHSTVN = -13.955 + 0.583*SGY + 1.060*ISTVN - 0.079*FN	0.90
PHSTVP = 3.171 + 0.074*SGY + 0.827*ISTVP - 0.004*FP	0.85
PHSTVK = 176.30 - 0.190*SGY + 0.638*ISTVK + 0.078*FK	0.68
2. Based on nutrient uptake	
PHSTVN = -5.938 + 0.237*TNU + 1.005*ISTVN - 0.095*FN	0.90
PHSTVP = 3.485 + 0.008*TPU + 0.845*ISTVP + 0.003*FP	0.85
PHSTVK = 117.22 + 0.014*TKU + 0.758*ISTVK + 0.024*FK	0.87

Where, PHSTV Post-harvest soil test value; PHSTVN = PHSTV for nitrogen; PHSTVP = PHSTV for phosphorus; PHSTVK = PHSTV for potassium; GY = Grain yield; ISTV = Initial soil test value; ISTVN = ISTV of nitrogen; ISTVP = ISTV of phosphorus; ISTVK = ISTV of potassium; GY = Grain yield; FN = Fertilizer nitrogen; FP = Fertilizer phosphorus; FK = Fertilizer potassium. TNU = Total nitrogen uptake; TPU = Total phosphorus uptake; TKU = Total potassium uptake

values for available N, P, and K under both grain yield- and nutrient uptake-based approaches. The non-significant paired t-test results validate the robustness and reliability of the post-harvest soil test prediction models. These equations can therefore be used to estimate residual soil fertility after crop harvest and provide a scientific basis for soil test-based fertilizer recommendations for succeeding crops in the cropping sequence. Similar post-harvest soil nutrient prediction models have been successfully developed by Coumaravel *et al.*, 2016 for maize, Kumar *et al.* 2018 for turmeric, and Arya *et al.*, 2019 for cauliflower.

Variation in observed and predicted PHSTV

The strip-wise mean observed and predicted post-harvest soil test values for available nitrogen (N), phosphorus (P), and potassium (K), estimated based on grain yield and nutrient uptake, are given in Table 2. The agreement between the observed and predicted soil test values were evaluated using a paired *t*-test. The analysis revealed no significant differences ($p > 0.05$) between the observed and predicted

Table 2: Observed and predicted post-harvest soil test value based on grain yield and nutrient uptake

Particulars	Strip I			Strip II			Strip III		
	Observed	Predicted, based on Yield	Predicted, based on uptake	Observed	Predicted, based on yield	Predicted, based on Uptake	Observed	Predicted, based on Yield	Predicted, based on Uptake
Available N (kg N ha ⁻¹)	192.88-225.58 (212.22)	196.94-225.80 (212.25)	197.54-224.97 (211.98)	196.32-236.85 (218.90)	201.88-239.45 (219.86)	202.65-238.69 (219.65)	197.71-239.98 (225.61)	203.60-242.10 (227.44)	205.52-241.38 (227.03)
Available P (kg P ha ⁻¹)	8.93-27.27 (20.00)	12.08-26.40 (20.15)	12.24-26.50 (20.19)	13.55-33.32 (25.28)	16.19-31.06 (24.60)	16.38-31.26 (24.69)	16.48-35.28 (26.84)	19.79-32.63 (26.68)	19.82-32.69 (26.78)
Available K (kg K ha ⁻¹)	443.76-503.76 (479.70)	455.10-510.20 (482.83)	449.6-515.8 (483.4)	450.13-517.70 (481.66)	464.99-515.78 (484.49)	462.0-520.9 (485.5)	457.36-532.90 (496.26)	464.85-538.45 (499.48)	462.0-548.2 (503.6)

Note: The values in parentheses indicate the mean of respective observed or predicted post-harvest soil test values. Predicted PHSTVs were estimated using multiple linear regression (MLR) equations, with initial soil test values and fertilizer application rates along with grain yield or nutrient uptake as explanatory variables, following STCR approach.

Calibration of predicted post-harvest soil test values

The developed prediction equations were used to estimate the post-harvest soil test values (PHSTVs) of N, P, and K and the predicted values were compared with the corresponding observed values. The prediction models were calibrated using root mean square error (RMSE) and relative error (RE, %) as measures of prediction accuracy (Table 3). Based on both grain yield and nutrient uptake approaches, the RMSE values followed the order K > N > P, whereas the RE values followed the order P > N > K. The RMSE and RE values obtained from the grain yield and nutrient uptake based

approaches were comparable, with only minor differences, indicating good agreement between the two prediction approaches. Since an RE value < 10% is considered indicative of excellent prediction

Table 3: Regression model between predicted and observed value along with their calibrated values

Nutrients	Regression model	R ²	RMSE (kg)	RE (%)
<u>Based on grain yield</u>				
N	$Y = 20.43 + 0.91X$	0.935	3.12	0.18
P	$Y = 4.85 + 0.79X$	0.930	1.82	1.13
K	$Y = 76.60 + 0.85X$	0.870	7.49	0.19
<u>Based on nutrient uptake</u>				
N	$Y = 26.48 + 0.88X$	0.921	3.33	0.18
P	$Y = 5.13 + 0.77X$	0.924	1.92	1.2
K	$Y = 2.34 + 1.01X$	0.872	8.79	0.21

Note: R², coefficient of determination; RMSE, root mean square error (kg); RE, relative error (%); X denotes the measured (observed) value, whereas Y denotes the predicted/calibrated value.

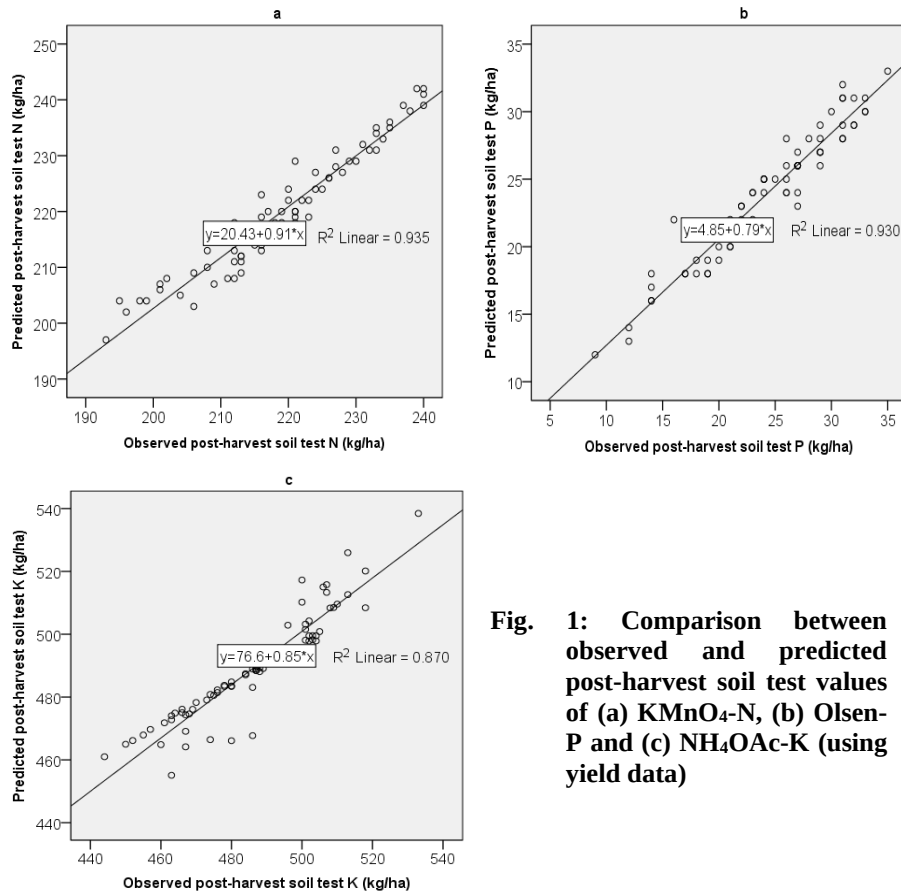


Fig. 1: Comparison between observed and predicted post-harvest soil test values of (a) KMnO₄-N, (b) Olsen-P and (c) NH₄OAc-K (using yield data)

accuracy, the developed equations showed excellent predictive performance for N, P, and K. Similar approaches for predicting and validating post-harvest soil test values reported by Selvam *et al.* (2021) for barnyard millet and Mahajan *et al.* (2019) for rice–wheat cropping systems.

The relationship between the observed and predicted soil test values for N, P and K are given in Fig. 1 & 2 (a, b and c) based on grain yield and nutrient uptake,

respectively. Model performance was further evaluated by comparing the observed and predicted post-harvest soil N, P, and K values. The regression trends closely followed 1:1 line, indicating strong agreement between observed and predicted values. Moreover, the predicted values were distributed close to 1:1 line for all the three nutrients, revealing the predictive accuracy and reliability of the developed MLR models. Similar method of comparison between the observed and predicted data has been reported by Coumarave*et al.* (2016) for maize, Abishek *et al.* (2022) for hybrid

castor and Spoorthishankar *et al.* (2025) for green gram.

Correlation (r) between observed and predicted soil test values

A strong positive correlation was observed between the actual and predicted post-harvest soil test values of N, P and K (Fig. 3). Under the grain yield-based approach, the correlation coefficients (r) were 0.97, 0.97, and 0.93 for N, P, and K, respectively. Corresponding r values under the nutrient uptake-based approach were 0.96, 0.96, and 0.93, respectively. The high correlation coefficients

indicate close agreement between observed and predicted post-harvest soil test values, with the grain yield-based equations showing marginally higher correlations for N and P than the nutrient uptake-based equations. Similarly, Selvam *et al.* (2021) reported strong correlations between observed and predicted post-harvest soil test values of N, P, and K after barnyard millet.

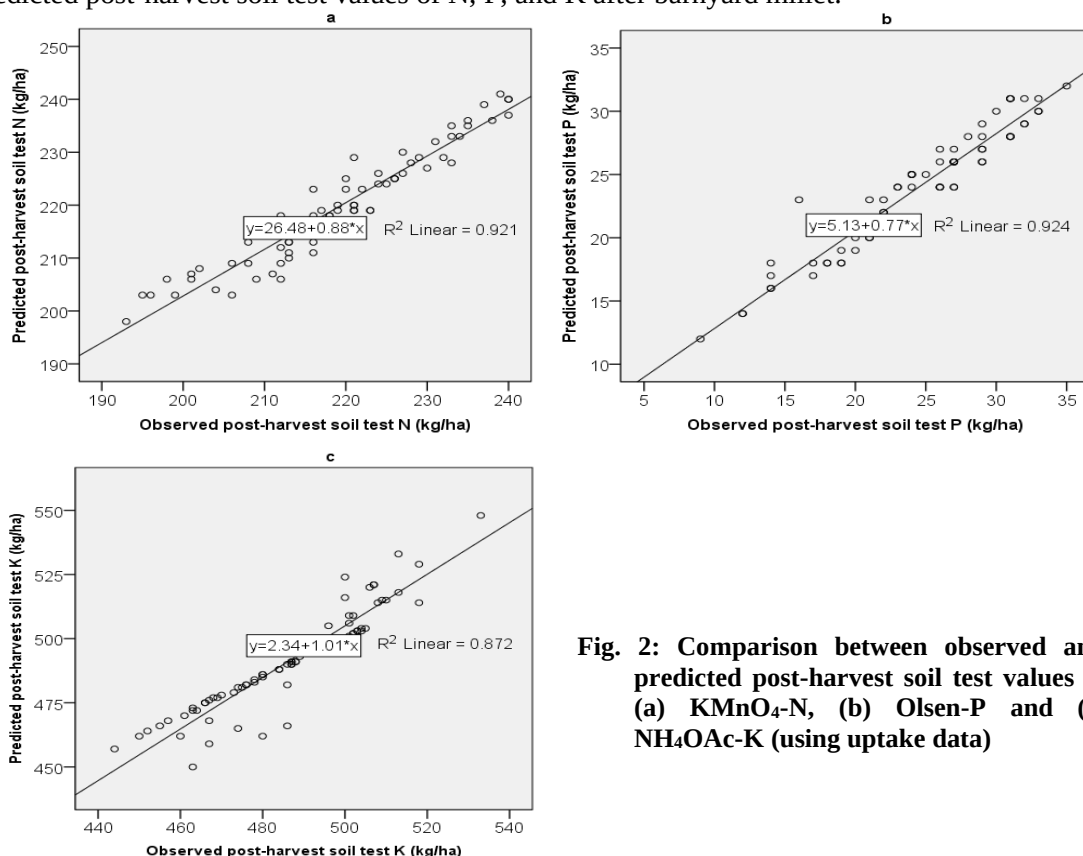


Fig. 2: Comparison between observed and predicted post-harvest soil test values of (a) KMnO₄-N, (b) Olsen-P and (c) NH₄OAc-K (using uptake data)

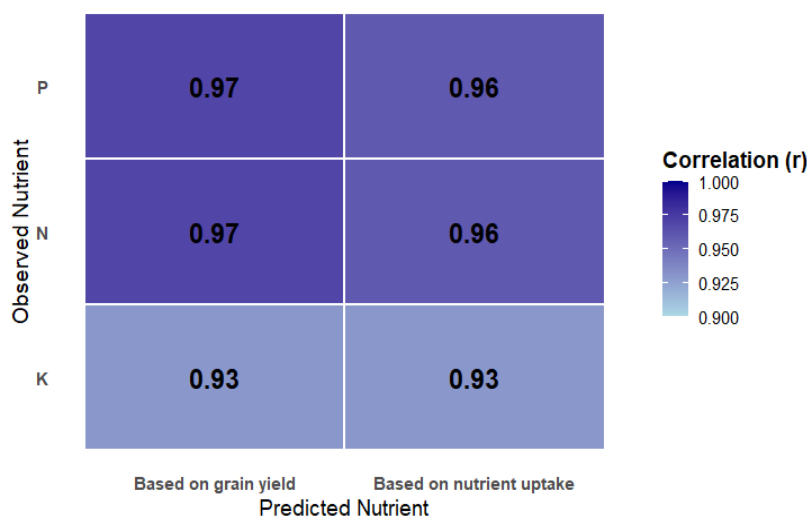


Fig. 3: Heatmap of correlation coefficients (r) between observed and predicted post-harvest soil test values of N, P, and K

Conclusion: In this study post-harvest soil test values were estimated using equations that were established to anticipate the availability of nitrogen, phosphorus, and potassium. These equations clearly showed the possibility for their application in useful fertilizer recommendations for subsequent crop reducing the dependence on soil testing costs after each harvest.

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Conflict of interest: The authors declare that they have no competing interests.

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