



Productivity and Soil Health Evaluation of Cropping Systems with Hey Won NPK Fertilizers: A Predictive Modeling and Performance Analysis Approach Through Python

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ABSTRACT

Background: With the intensification of agriculture, optimizing fertilizer use is critical for enhancing crop yields while maintaining soil health. This study evaluates the impact of three NPK fertilizer grades-Hey Won NPK 14-14-14, 14-5-21 and 20-8-12-on the productivity of maize-based cropping systems and their influence on soil properties.

Methods: A two-year field experiment (2022-2024) was conducted at the research farm of the Department of Soil Science, Punjab Agricultural University (PAU), Ludhiana, India, using a split-plot design. Four maize-based cropping systems were assigned to the main plots and five fertilizer treatments to the sub-plots. Key parameters such as grain yield, plant nutrient levels (N, P, K) and soil nutrient status (pre- and post-fertilization) were assessed.

Result: Preliminary results demonstrated significant differences in crop yields, system productivity and equivalent yields due to varying fertilizer treatments. The findings highlight the benefits of targeted NPK applications in boosting crop performance and improving soil nutrient profiles, supporting sustainable agriculture. Additionally, predictive modeling and performance analysis using Python identified key nutrient-yield relationships and the pivotal role of specific crops in enhancing nutrient-use efficiency. The study underscores the value of data-driven strategies for optimizing fertilizer management, offering actionable insights for farmers, agronomists and policymakers to improve productivity while preserving soil health across diverse cropping systems.

Key words: Cropping system, Macronutrients, Productivity, Regression equation, Soil, Treatments.

INTRODUCTION

The rapidly growing population across the globe is estimated to reach over 9 billion by 2050, affecting sustainable agriculture development and food security. According to United Nations Food and Agricultural Organization, 99.7% of human food is fulfilled by terrestrial environment (Singh and Ryan, 2015). Therefore, it is essential to increase global agricultural production by 60%-110% for the coming 20 years (Grafton *et al.*, 2015). Currently, the overall cropland area covers 11% out of 13 billion ha total land area which delivers about 78% of average per capita calorie consumption (Brevik, 2013).

Hence, increasing crop yields is the most suitable way rather than extending arable lands, for ensuring food security. In addition, utilizing balanced and complete fertilizers provides more than 50% increase in crop yields. Thus, the use of fertilizers has been become very evident (Selassie, 2020). There is a well-established significant relationship between food grain production and fertilizer consumption (Sunil *et al.*, 2014). The cereals account for approximately 50.8% of the total world NPK requirement (Heffer, 2013). The present fertilizer strategy is to increase agricultural production through its efficient and balanced use (Nadeem *et al.*, 2022).

The nutrients play an important role in crop growth and development. Crop nutrients are elements which are essential in providing healthy and vigorous plants ultimately

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leading to higher yields. The secret to good nutrient management is to ensure that crops are receiving the right quantity of nutrients exactly when they need them most for sustainable growth and productivity of different cropping systems (Toor, 2021). As nutrients can be supplied by the soil, they should also be supplemented with organic manures and fertilizers. The nutrients that are required by crops in the largest amounts are N, P and K (Zewide and Melash, 2021). The use of fertilizers efficiently is an important strategy for increasing crop production. The organic matter application significantly and strongly affects the soil health

even in small concentration. This keeps the optimum soil microbial population and also balances the nutrient cycling (Singh and Ryan, 2015). In the present study, Hey Won NPK fertilizers have been introduced by Taiwan Fertilizer Company (TFC) with the addition of humic acid, to explore the beneficial effects on crop production and soil health.

Complete NPK fertilizer out of the total nutrient composition supply is a major constrain in the country. However, there is limited information available on the effects of complex fertilizers on different crops. The present study investigated the effects of various NPK-grade (Hey Won) fertilizers on maize based cropping system and soil health along with identifying boosting cropping system yield through following Python based prediction and performance evaluation approach.

MATERIALS AND METHODS

Site description

A field experiment was conducted for two years (2022-2024) at the research farm (Latitude- 30°56' N, Longitude- 75° 52' E, Climate- semi-arid subtropical and Annual Rainfall-

700-800 mm), Department of Soil Science, Punjab Agricultural University (PAU), Ludhiana, India.

Experimental plan

The experiment followed a split plot design (plot size: 27 m²) with four maize-based cropping systems as main plots: Maize-potato-summer moong (CS1), Maize-cabbage-spring potato (CS2), Maize-potato-onion (CS3) and Maize-peas-eggplant (CS4). Sub-plots included five NPK treatments: control (T1), 14-14-14 (T2), 14-5-21 (T3), 20-8-12 (T4) and PAU conventional fertilizer (T5). Each treatment was replicated thrice in a fixed layout, totaling 15 treatments (Fig 1). Irrigation was applied as per crop and weather conditions. Baseline soil physico-chemical properties like soil texture (sandy-loamy), pH (7.14), electrical conductivity (0.147 dS/m), organic carbon (0.65%), nitrogen (150.5 kg/ha), phosphorous (29.6 kg/ha) and potassium (161.25 kg/ha) were measured.

Material and crop description

Taiwan Fertilizer Company supplied Hey Won NPK fertilizers, transformed nitrophosphate blends enriched with humic acid to enhance soil properties and nutrient

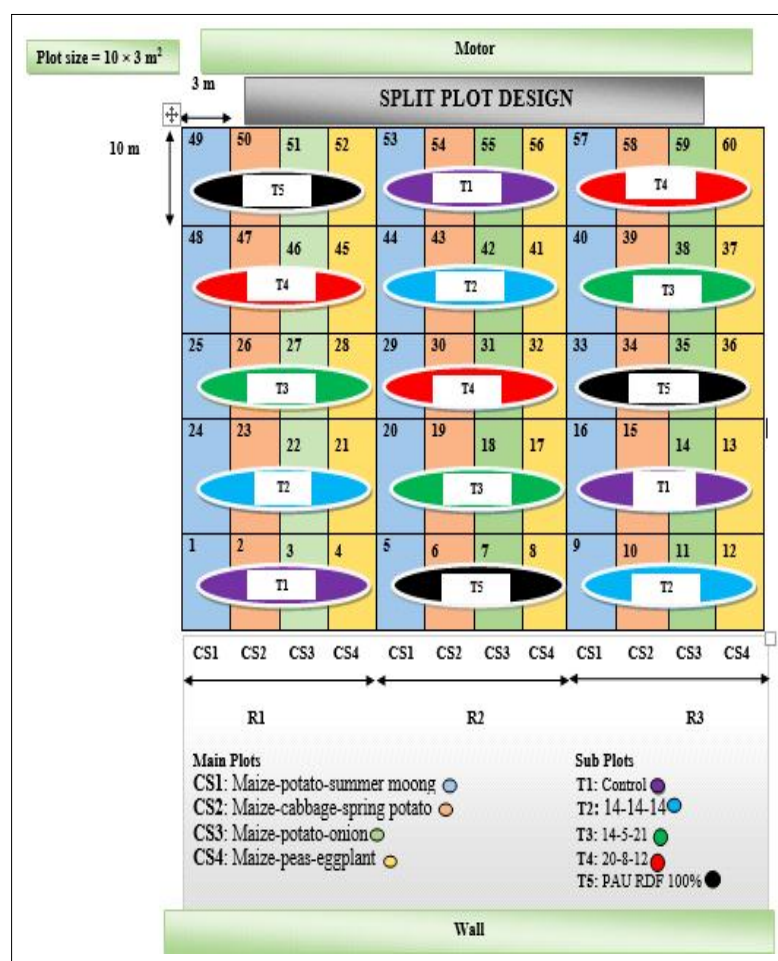


Fig 1: Split plot experimental layout.

uptake (Bhatt *et al.*, 2022). The tested grades included 14-14-14 (T2), 14-5-21 (T3) and 20-8-12 (T4), each supplying nitrogen (ammonical and nitrate), available phosphorus (P_2O_5) and water-soluble potassium (K_2O). The PAU conventional fertilizer (T5) used urea (N source), SSP - single super phosphate (P source) and MOP-muriate of potash (K source) based on crop-specific recommended doses (RDF). Control (T1) plots received no fertilizer. With maize (PMH2) other crops such as summer moong (SML 1827), onion (Punjab Naroya), peas (Punjab 89), cabbage (Indian), eggplant (Punjab Bharpour), potato and spring potato (Kufri Pukhraj) were cultivated as cropping system. Details of each crop variety specific spacing and RDF are provided in Thind and Mahal (2021).

Crop yield and cropping system use efficiency

Grain yields (q/ha) from maize-based cropping systems were recorded over two years and converted to maize equivalent yield (MEY) using minimum support prices

(Uddin *et al.*, 2009). System productivity (SP) was calculated as MEY (kg/ha) divided by the system duration (days) and expressed as kg/ha/day (Tomar and Tiwari, 1990). Land use efficiency (LUE) was derived by dividing total crop duration by 365 and expressed as a percentage (Kumar *et al.*, 2014).

Plant macronutrient analysis

At harvest, grains and fruits were separated, dried and 0.5 g samples were ground. Nitrogen was determined via the Kjeldahl method (Jackson, 1967) after digestion with selenium dioxide-sulfuric acid. Phosphorus and potassium were analyzed from nitric-perchloric acid (3:1) digests using colorimetric and flame photometric methods, respectively (Jackson, 1967). Crop NPK concentrations (%) were summed by system to represent total NPK content per cropping system.

Soil analysis

Surface soil was taken from 0-15 cm depth and sieved (2 mm) for physico-chemical analysis. Soil pH and EC (1:2 soil:water) were measured using a pH meter and

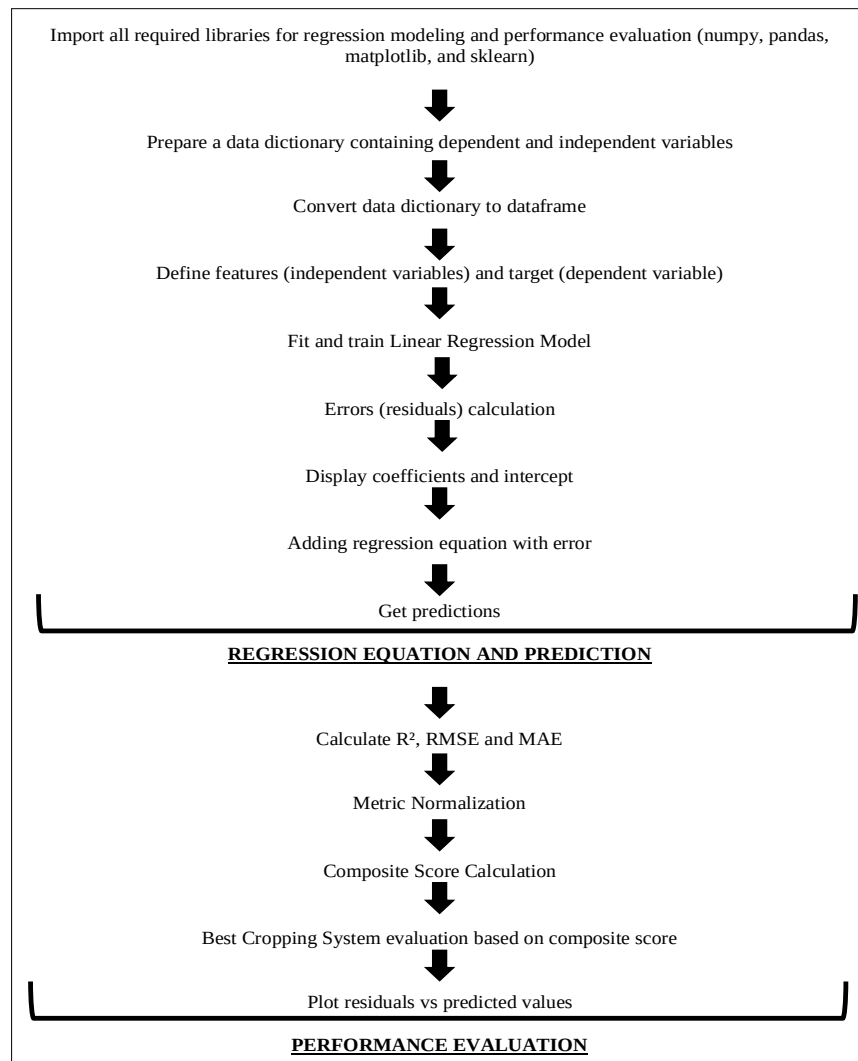


Fig 2: Prediction modeling and performance evaluation flowchart of maize-based cropping systems performed by PYTHON.

conductivity meter (dS/m). Available nitrogen, organic carbon, phosphorous and potassium were determined using standard methods (Sikka *et al.*, 2024).

Statistical analysis

ANOVA was performed (GenStat 10th ed.) to assess plant and soil data, with significance tested via LSD ($p \leq 0.05$) and Duncan's post hoc test for pairwise yield comparisons. Polynomial modeling was applied to evaluate cropping system yield dynamics under Hey Won fertilizers. Correlation analysis (SPSS 30.0) identified key plant and soil factors influencing yields, with multicollinearity excluded before final regression modeling. Python streamlined feature selection, regression diagnostics and visualizations (actual vs. predicted and residual plots) to ensure model robustness.

Regression equations were developed for each system using significant ($p \leq 0.05$ and 0.01) variables. Model performance was assessed using R^2 , RMSE and MAE. All prediction modeling and evaluation were conducted in Google Colab using Python libraries (scikit-learn, Pandas, NumPy, Matplotlib, Seaborn). Fig 2 outlines the complete workflow from data preparation to model refinement. Future studies may apply advanced models (e.g., decision trees, neural networks) for improved predictions.

RESULTS AND DISCUSSION

Crop and cropping system yield

Hey Won fertilizers (14:14:14, 14:5:21 and 20:8:12) significantly ($p < 0.05$) improved yields in maize-based systems over two years, with the most notable increases in spring potato, potato, cabbage, eggplant and maize (Table 1). Maximum yields were crop-specific: potato, eggplant and onion under T2; spring potato and cabbage under T3; pea, maize and summer moong under T4. This variability reflects crop genetic differences and fertilizer-crop compatibility (Setiawati *et al.*, 2020). Control (T1) consistently yielded the lowest, while RDF (T5) outperformed control but underperformed compared to Hey Won treatments.

Yields under T2, T3 and T4 surpassed T5, with eggplant (T2 and T3, +77.01%) and summer moong (T2, +1.27%) showing the highest and lowest percentage increases, respectively. T3 notably boosted yields in four crops, likely due to improved nutrient synergy, root development and humic acid-enhanced soil health (Kolage *et al.*, 2018; Bhatt and Singh, 2022).

System-wise, M-C-Sp (570.33 q/ha) and M-P-O (466.42 q/ha) under T3 outperformed M-Pe-E (411.40 q/ha).

Table 1: Effect of 14:14:14, 14:5:21 and 20:8:12 application on average grain yield (q/ha) of different crops grown in maize-based cropping system.

Fertilizer treatments	Maize	Potato	Summer moong	Spring potato	Onion	Pea	Cabbage	Eggplant
Control	32.90 ^a	78.31 ^a	10.56 ^a	112.18 ^a	106.00 ^a	31.48 ^a	105.95 ^a	135.06 ^a
14% N, 14% P ₂ O ₅ and 14% K ₂ O	56.80 ^b	262.85 ^c	13.77 ^b	260.67 ^c	149.17 ^b	72.52 ^b	168.05 ^c	282.09 ^e
14% N, 5% P ₂ O ₅ and 21% K ₂ O	58.63 ^c	251.80 ^{bc}	13.68 ^b	286.31 ^d	148.41 ^b	74.06 ^b	225.39 ^e	250.54 ^d
20% N, 8% P ₂ O ₅ and 12% K ₂ O	60.53 ^d	249.23 ^{bc}	13.80 ^b	258.86 ^c	141.38 ^b	76.34 ^b	189.07 ^d	200.09 ^c
100% NPK provided by RDF	54.70 ^b	225.51 ^b	13.15 ^{ab}	236.73 ^b	128.42 ^b	64.13 ^b	149.23 ^b	156.31 ^b
Mean	52.71	213.54	12.99	230.95	134.67	63.71	167.54	204.82
LSD (5%)	3.537	29.260	1.950	23.065	20.131	25.993	10.311	18.570

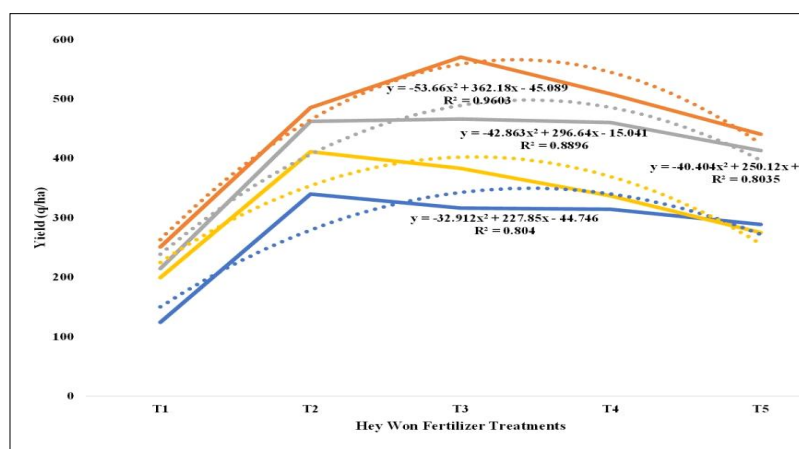


Fig 3: Line graph presenting different Hey Won fertilizer treatment application on maize-based cropping system yield (q/ha) with polynomial regression analysis.

ha) and M-P-Sm (339.71 q/ha) under T2. The M-C-Sp system's superior yield suggests enhanced nutrient and resource use efficiency. Regression analysis ($R^2 = 0.80-0.96$) confirms strong model-data fit (Fig 3). This approach allows us to observe how changes in fertilizer types and application rates can interact with the specific components of each cropping system, leading to varying yield outcomes (Shi *et al.*, 2021).

Overall, Hey Won fertilizers improved crop and system yields, aligning with Chimonyo *et al.* (2019) and Abid *et al.* (2020), who emphasized integrated nutrient management benefits. Vegetable-based systems may also offer better economic returns depending on crop and conditions. Walder *et al.* (2023) and this study highlight higher yields under organic-based fertilizers versus pure chemical inputs. Intercropping (e.g., maize-potato) further enhances yield and water efficiency, reducing water use by 3-13% (Xie *et al.*, 2021).

Equivalent yield and resource use efficiency

Table 2 and 3 show significant differences in MEY and SP across cropping systems. The maize-potato-onion (M-P-O) system recorded the highest MEY (324.28 q/ha) and SP

(117.49 kg/ha/day), while maize-potato-summer moong (M-P-Sm) had the lowest MEY (225.60 q/ha) and SP (80.00 kg/ha/day), likely due to poor maize-summer moong compatibility (Xie *et al.*, 2021). M-Pe-E and M-C-Sp outperformed M-P-Sm in MEY, with onion inclusion boosting nutrient uptake (Singh and Sikka, 2007).

Fertilizer treatments significantly affected MEY and SP, with T3 (14:5:21) consistently outperforming other treatments, while the control (T1) yielded the least (Xie *et al.*, 2021). Also, the M-Pe-E system showed the highest LUE (79.18%), while M-C-Sp had the lowest (71.51%), Fig 4, suggesting longer land utilization but potentially lower productivity due to factors like soil nutrient depletion (Walder *et al.*, 2023). Similar patterns were noted by Kumar *et al.* (2014) in jute-based and by Sammauria *et al.* (2020) in pearl-millet based cropping systems. Ali *et al.* (2021) described the maximum pearl millet EY and SP in cotton-summer pearl millet cropping system under 75% RDN-inorganic fertilizer + 25% RDN-FYM, an integrated fertilization approach.

Other studies confirm the benefits of intercropping: Maize-soybean systems improved yield, water use and land productivity (Liu *et al.*, 2018; Xu *et al.*, 2020). Islam *et al.*

Table 2: Effect of 14:14:14, 14:5:21 and 20:8:12 application on maize equivalent yield.

Fertilizer treatments	Maize equivalent yield (q/ha)				
	M-P-Sm	M-C-Sp	M-P-O	M-Pe-E	Mean
Control	121.34	141.06	191.48	181.07	158.74
14% N, 14% P ₂ O ₅ and 14% K ₂ O	265.27	276.90	369.35	378.41	322.48
14% N, 5% P ₂ O ₅ and 21% K ₂ O	250.65	319.48	372.61	364.54	326.82
20% N, 8% P ₂ O ₅ and 12% K ₂ O	251.82	289.72	363.31	344.20	312.26
100% NPK provided by RDF	238.95	257.67	324.65	285.66	276.73
Mean	225.60	256.97	324.28	310.78	
LSD (5%)					
CS (Main)	105.901				
NL (Sub)	24.143				
CS × NL (Main × Sub)	48.287				

*CS= Cropping system; NL= Nutrient levels.

Table 3: Effect of 14:14:14, 14:5:21 and 20:8:12 application on system productivity.

Fertilizer treatments	System productivity (kg/ha/day)				
	M-P-Sm	M-C-Sp	M-P-O	M-Pe-E	Mean
Control	43.03	54.05	69.38	62.65	57.28
14% N, 14% P ₂ O ₅ and 14% K ₂ O	94.07	106.09	133.82	130.94	116.23
14% N, 5% P ₂ O ₅ and 21% K ₂ O	88.88	122.41	135.00	126.14	118.11
20% N, 8% P ₂ O ₅ and 12% K ₂ O	89.30	111.00	131.63	119.10	112.76
100% NPK provided by RDF	84.73	98.72	117.63	98.84	99.98
Mean	80.00	98.45	117.49	107.54	
LSD (5%)					
CS	36.650				
NL	8.401				
CS × NL	16.803				

*CS= Cropping system; NL= Nutrient levels.

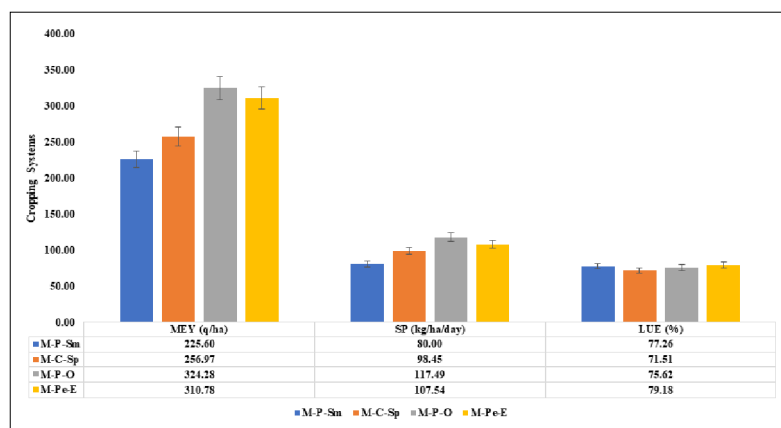


Fig 4: MEY, SP and LUE levels on different maize-based cropping system.

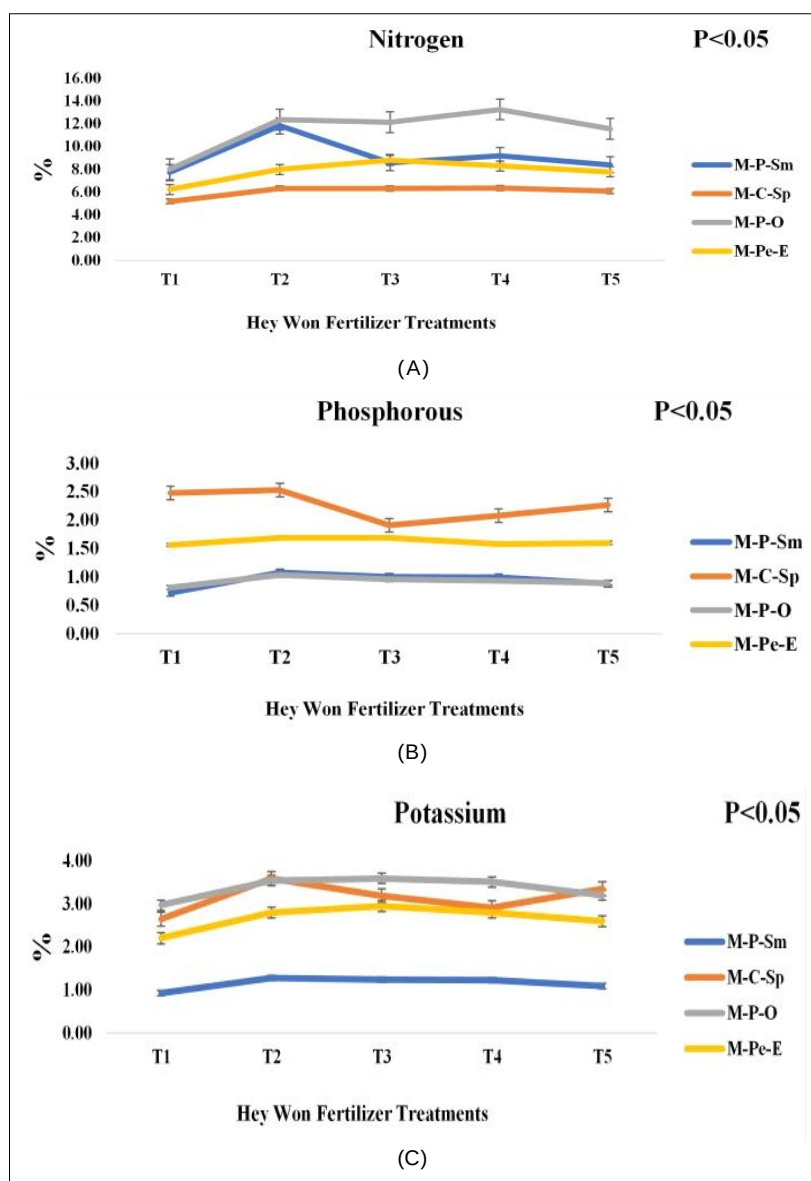


Fig 5: (A) Nitrogen (B) Phosphorous (C) Potassium levels under different maize-based cropping system and Hey Won fertilizer treatments.

(2020) reported maximum system productivity, profitability, sustainable yield index, production efficiency and relative economic efficiency but least land use efficiency in Maize + Green gram(1:2)- green gram + maize (1:1)-tomato, cropping system indicating that the sustainable production might not linked with the efficiently utilization of land cover. Sikka *et al.* (2024) also reported significant yield and MEY improvements with Sardar amin granules and Bentonite Sulphur in maize-based systems. The highest production efficiency was observed in soybean-onion cropping system than soybean-potato under 100% RDN (Recommended Dose Nutrient) applied with FYM@ 5 t per ha and biofertilizer suggesting the important role of onion and nutrient fertilizer amendments in improving the cropping system (CS3) performance (Patil *et al.*, 2024).

Plant macronutrient status

Nitrogen (N), phosphorus (P) and potassium (K) levels varied significantly under different cropping systems and Hey Won fertilizer treatments (Fig 5). The M-P-O system recorded the highest N (11.46%) and K (3.36%) levels, likely due to the synergistic interaction of maize, potato and onion (Xie *et al.*, 2021). Conversely, N (6.05%) and K (1.16%) were lowest in M-C-Sp and M-P-Sm, respectively. P content peaked in M-C-Sp (2.25%) and was lowest in M-P-O (0.93%), suggesting cabbage with spring potato may enhance P uptake under certain conditions, but may limit N and K due to competition (Thummanatsakun and Yampracha, 2018).

Macronutrients spiked under T2, slightly declined at T3, stabilized at T4 and dropped at T5, with T1 showing the lowest levels. Despite lower nutrient levels under T3, yield and productivity were highest, indicating that efficient nutrient use and agronomic practices also drive yield (Xie *et al.*, 2021). Nitrogen was generally dominant across all systems and treatments. Notably, P exceeded K in M-C-Sp, reflecting the plant's ability to manage limiting factors.

Previous studies (Kumar *et al.*, 2014; Ghosh *et al.*, 2020; Jiang *et al.*, 2024) support these findings, highlighting the importance of balanced NPK fertilization for enhanced nutrient uptake and yield. Our highest yield under T3 and strong M-P-O system performance align with Luitel *et al.* (2024), who reported optimal onion bulb yield under medium organic matter and high K₂O in maize-based systems.

Soil health status

The root-nutrient uptake association is very strong at 0-15 cm as crops roots are highly concentrated at this depth. No significant changes were observed in soil pH, EC and K after two cropping cycles, indicating soil stability and balanced K dynamics (Table 4). However, fertilizer treatments significantly influenced soil OC, N and P levels. T3 (14% N, 5% P₂O₅, 21% K₂O) showed the highest OC (at par with T2) and N, along with elevated P. Fertilization likely boosted microbial activity, enhancing nutrient cycling and soil fertility (Dinca *et al.*, 2022). Available P peaked under T4, while K remained stable across T2, T3 and T4,

Table 4: Effect of 14:14:14, 14:5:21 and 20:8:12 fertilizers on soil health of maize-based cropping system.

Fertilizer treatments	pH	EC (μS cm ⁻¹)	OC(%)	N (kg/ha)	P (kg/ha)	K (kg/ha)
Control	7.28	140.23	0.49	70.04	106.79	398.30
14% N, 14% P ₂ O ₅ and 14% K ₂ O	6.88	150.00	0.57	78.40	116.41	426.39
14% N, 5% P ₂ O ₅ and 21% K ₂ O	6.70	125.84	0.57	94.08	118.11	426.77
20% N, 8% P ₂ O ₅ and 12% K ₂ O	6.76	155.66	0.54	83.63	127.80	424.34
100% NPK provided by RDF	7.13	148.16	0.51	77.35	116.31	397.88
Mean	6.95	143.98	0.54	80.70	117.08	414.74
LSD (5%)	NS	NS	0.041	15.314	10.243	NS

Table 5: Correlation matrix among several plant and soil variables for M-P-Sm (CS1) cropping system.

	Yield	MEY	SP	PN	PP	P.K	S.OC	S.N	S.P
Yield	1.000								
MEY	0.999	1.000							
SP	0.999	1.000	1.000						
PN	0.644	0.618	0.619	1.000					
PP	0.949	0.931	0.931	0.788	1.000				
P.K	0.952	0.935	0.935	0.713	0.992	1.000			
S.OC	0.782	0.756	0.756	0.469	0.848	0.878	1.000		
S.N	0.157	0.125	0.125	-0.080	0.299	0.385	0.632	1.000	
S.P	0.609	0.613	0.613	0.056	0.549	0.635	0.513	0.569	1.000

Yield- cropping system yield; MEY- equivalent yield; SP- system productivity; P.N- plant nitrogen; P.P- plant phosphorous; P.K- potassium; S.OC- soil organic carbon; S.N- soil nitrogen; S.P- phosphorous. Green = 1.00-0.90 (Very high correlation), Yellow = 0.90- 0.70 (High correlation) and Red = <0.70 (Moderate and low correlation).

suggesting no nutrient imbalance. T5 (100% RDF) improved soil parameters over control but was less effective than Hey Won fertilizers. Cropping systems had no notable effect on soil properties.

Organic amendments with fertilizers significantly improve soil health and productivity (Dhaliwal *et al.*, 2019). The humic acid in Hey Won fertilizers appears beneficial for sustaining soil quality (Sikka *et al.*, 2024). Similarly, integrating organic and inorganic sources enhances soil fertility and yield (Bangre *et al.*, 2024). Singh *et al.* (2021) also reported increased OC and N under high NPK doses

in maize-vegetable pea systems, boosting yield and profitability.

Correlation, regression analysis (Prediction modeling) and Performance evaluation

Pearson correlation analysis was conducted for four cropping systems (CS1-CS4) using key variables: yield, MEY, SP, plant NPK and soil OC, N and P (Tables 5-8). Yield correlated significantly ($p \leq 0.05/0.01$) with P.P and P.K in CS1; P.N in CS2; P.N, P.K and S.OC in CS3 and P.K in CS4. This highlights system-specific nutrient-yield dynamics

Table 6: Correlation matrix among several plant and soil variables for M-C-Sp (CS2) cropping system.

	Yield	MEY	SP	PN	PP	P.K	S.OC	S.N	S.P
Yield	1.000								
MEY	0.998	1.000							
SP	0.998	1.000	1.000						
PN	0.956	0.968	0.967	1.000					
PP	-0.684	-0.667	-0.667	-0.499	1.000				
P.K	0.589	0.614	0.614	0.686	0.093	1.000			
S.OC	0.835	0.813	0.813	0.808	-0.548	0.279	1.000		
S.N	0.552	0.562	0.562	0.536	-0.037	0.912	0.183	1.000	
S.P	0.524	0.525	0.525	0.553	-0.617	-0.188	0.677	-0.395	1.000

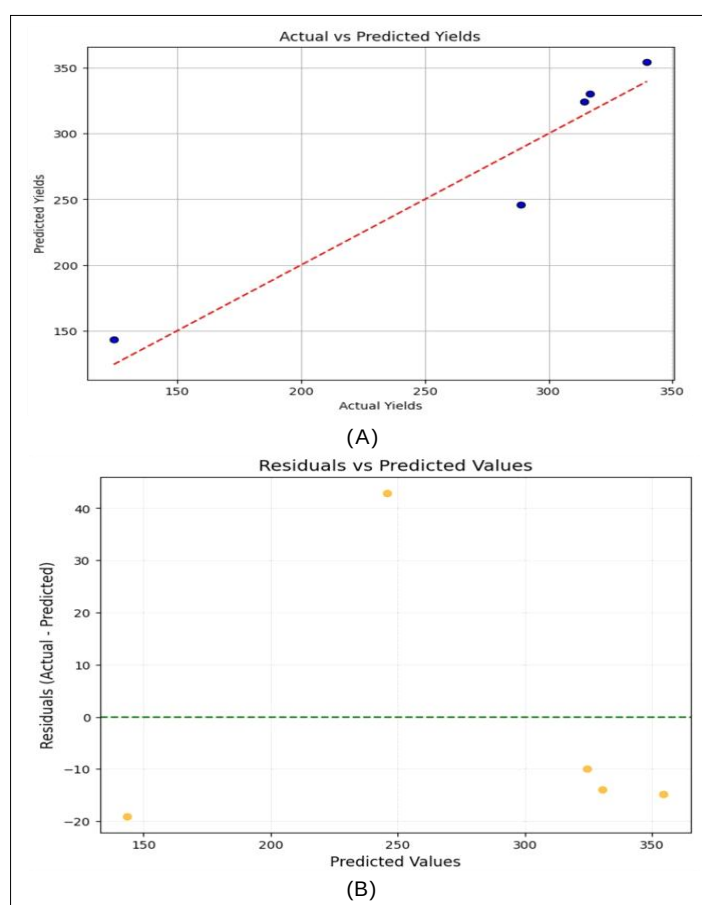


Fig 6: (A) Actual vs. Predicted (B) Residual vs. Predicted yield plots of CS1 maize cropping system.

requiring tailored nutrient management (Roy *et al.*, 2006; Yousaf *et al.*, 2016). Yield, MEY and SP showed near-perfect correlations ($r \approx 1.000$), confirming their alignment as performance indicators (Bahadur *et al.*, 2024).

Post-multicollinearity removal (Hair *et al.*, 2014), regression models were developed for each system using Python (Table 9) to predict yield, with independent predictors showing minimum residuals (Kutner *et al.*, 2005). Model

performance was assessed via R^2 , RMSE and MAE. CS3 outperformed others ($R^2 = 0.975$, RMSE = 15.34, MAE = 12.45), followed by CS1, CS2 and CS4. A composite score, integrating these metrics, confirmed CS3 as the optimal system (score = 0.52) (Crookston *et al.*, 2021).

Plots of actual vs. predicted yield and residuals vs. predicted yield (Fig 6-9) validated CS3's high explanatory power and prediction accuracy (Chatterjee and Hadi, 2015).

Table 7: Correlation matrix among several plant and soil variables for M-P-O (CS3) cropping system.

	Yield	MEY	SP	PN	PP	PK	S.OC	S.N	S.P
Yield	1.000								
MEY	0.999	1.000							
SP	0.999	1.000	1.000						
PN	0.974	0.968	0.968	1.000					
PP	0.845	0.863	0.863	0.779	1.000				
PK	0.921	0.940	0.940	0.887	0.882	1.000			
S.OC	0.896	0.918	0.918	0.832	0.906	0.990	1.000		
S.N	0.748	0.765	0.765	0.610	0.634	0.795	0.839	1.000	
S.P	0.857	0.866	0.865	0.899	0.655	0.916	0.854	0.651	1.000

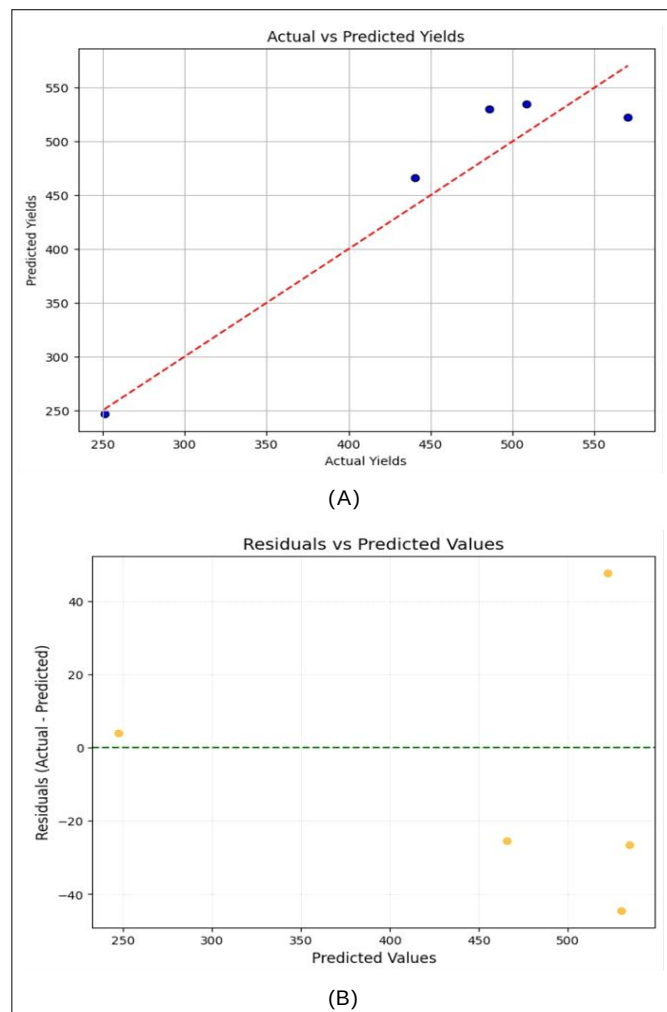


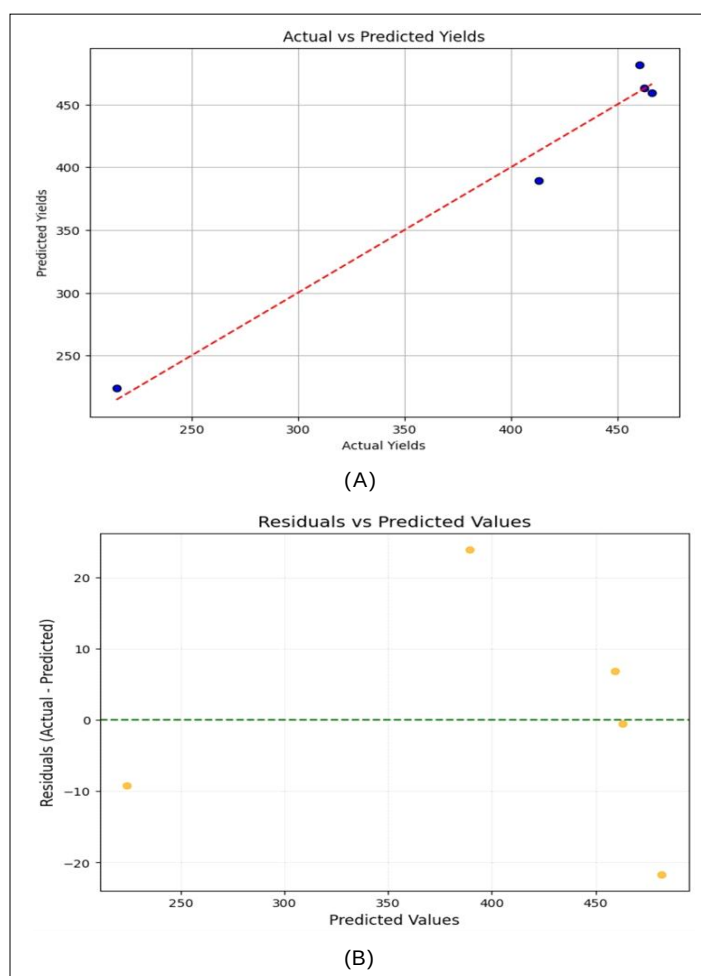
Fig 7: (A) Actual vs. Predicted (B) Residual vs. Predicted yield plots of CS2 maize cropping system.

Table 8: Correlation matrix among several plant and soil variables for M-Pe-E (CS4) cropping system.

	Yield	MEY	SP	P.N	P.P	P.K	S.OC	S.N	S.P
Yield	1.000								
MEY	0.976	1.000							
SP	0.976	1.000	1.000						
P.N	0.842	0.919	0.919	1.000					
P.P	0.850	0.758	0.758	0.646	1.000				
P.K	0.922	0.968	0.968	0.984	0.728	1.000			
S.OC	0.617	0.503	0.503	0.365	0.914	0.442	1.000		
S.N	0.365	0.426	0.426	0.578	0.073	0.559	-0.325	1.000	
S.P	0.157	0.280	0.280	0.167	-0.336	0.166	-0.449	0.114	1.000

Table 9: Python based regression and composite score analysis for maize-based cropping systems.

Cropping system	Regression equation	R ²	RMSE	MAE	Composite score
M-P-Sm (CS1)	Yield = -417.704 + (603.337) × P.K	0.910	23.31	20.14	0.48
M-C-Sp (CS2)	Yield = -1027.529 + (246.050) × P.N	0.905	33.51	29.60	0.47
M-P-O (CS3)	Yield = -332.643 + (38.794) × P.N +(535.950) × S.OC	0.975	15.34	12.45	0.52
M-Pe-E (CS4)	Yield = -341.726 + (242.812) × P.K	0.805	33.76	20.91	0.42

**Fig 8:** (A) Actual vs. Predicted (B) Residual vs. Predicted yield plots of CS3 maize cropping system.

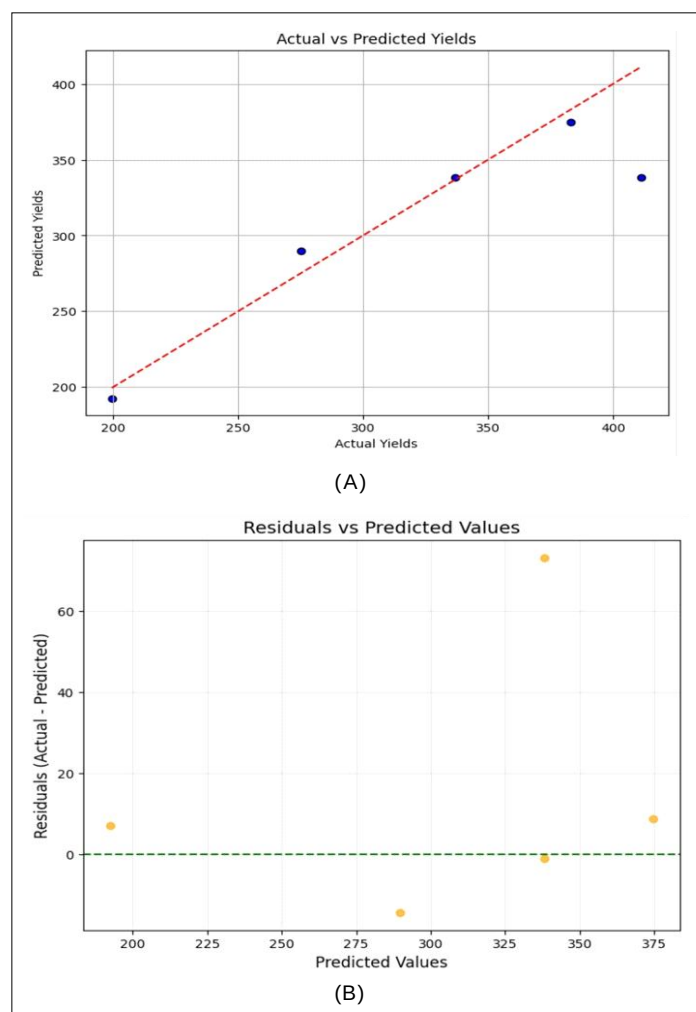


Fig 9: (A) Actual vs. Predicted (B) Residual vs. Predicted yield plots of CS4 maize cropping system.

This suggests CS3 as the best maize-based system for enhancing yield. These findings align with prior studies linking nutrient dynamics and yield prediction using correlation and regression tools (Chimonyo *et al.*, 2019; Macholdt *et al.*, 2020). Similar modeling and composite scoring approaches have been applied by Di Paola *et al.* (2023) and Murthy *et al.* (2022) in other cropping systems.

CONCLUSION

In a present study, the maize-potato-onion (M-P-O) system proved most productive, with Hey Won fertilizers-enriched with humic acid-outperforming standard recommended fertilizer doses (RDF) by enhancing nutrient uptake, yield and soil health. Yield improvements were notable across maize, potato, spring potato, summer moong and pea crops, with minimal adverse effects on soil properties.

Correlation and regression analyses identified plant N, P, K and soil organic carbon as key drivers of yield. The M-P-O system showed superior regression model performance (high R^2 , low RMSE and MAE), confirming its efficiency in maximizing productivity. Polynomial modeling

further highlighted the advantage of crop combinations with complementary growth patterns. This study emphasizes the importance of data-driven strategies, such as regression modeling, for optimizing fertilizer management and improving cropping system sustainability. These findings provide valuable tools for farmers and researchers to enhance productivity while safeguarding soil health.

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Conflict of interest

All authors declared that there is no conflict of interest.

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