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Weather-based precision fertilizer scheduling for climate-smart agriculture

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Abstract
Unstable weather conditions are becoming an important constraint to crop production. Variations in rainfall and temperature, drought periods and intense rainfall can alter soil water status, nutrient availability and crop nutrient absorption. Therefore, fertilizer application based only on predetermined dates may not match the actual requirements of crops. Weather-responsive nutrient management can improve fertilizer timing by considering weather conditions, soil moisture and crop development.
This study evaluated an adaptive fertilizer scheduling approach in maize (Zea mays L.) using four management strategies: conventional practice (T1), soil-test-based management (T2), weather-guided scheduling (T3), and combined weather-, soil- and crop-stage-based management (T4). Crop growth, grain production, nutrient absorption and nutrient-use efficiency were assessed. Among the treatments, T4 recorded the highest plant height (207 cm), biomass (196 g plant^{-1}), grain yield (7.48 t ha^{-1}), N uptake (158 kg ha^{-1}), P uptake (31.5 kg ha^{-1}) and K uptake (126 kg ha^{-1}). Nitrogen-use efficiency also increased to 59.4% under T4 compared with 42.5% in T1. The lowest estimated nutrient loss was observed with the integrated scheduling approach. Overall, the results indicate that combining weather information, soil conditions and crop growth stages can support more efficient and climate-responsive fertilizer management. The numerical results are illustrative and require confirmation through field experimentation.

Keywords: Climate-smart farming, fertilizer scheduling, precision nutrient management, weather information, soil moisture, nutrient-use efficiency, maize, sustainable agriculture

Introduction
Crop growth and productivity are closely influenced by rainfall, temperature, soil water and sunlight. Increasing weather fluctuations can disturb nutrient availability, plant nutrient absorption and fertilizer performance. Therefore, changing environmental conditions need to be considered when planning fertilizer application.
Fertilizers support crop production, but their effectiveness depends on the dose, application time and field conditions. Heavy rainfall after fertilizer application can cause nutrient losses through runoff and leaching, whereas very dry soil may restrict nutrient movement towards plant roots. Fixed fertilizer schedules may therefore be less effective when weather conditions change rapidly. Precision agriculture provides tools such as soil testing, sensors, weather monitoring and remote sensing to improve fertilizer decisions. Combining these technologies with weather forecasts can help identify suitable periods for nutrient application based on soil moisture and crop demand.
Weather-responsive fertilizer management can support climate-smart agriculture by improving nutrient-use efficiency, reducing unnecessary nutrient losses and promoting more sustainable crop production.

Research Gap
Nutrient application in many farming systems is still planned mainly from standard recommendations and laboratory-based soil fertility assessments. These practices provide a general basis for fertilizer management, but they may not capture rapid changes in field conditions during the growing season. Variations in rainfall, soil water availability and crop nutrient demand can change the suitability of a fertilizer application period. Hence, there is scope for a dynamic management strategy that links soil nutrient status with crop development and current or expected weather conditions. Such a system may allow fertilizer inputs to be better matched with crop requirements while limiting nutrient losses during unfavorable weather events.

Objectives
The study was undertaken to:
1. Develop a dynamic nutrient-application strategy using weather information.
2. Examine how different fertilizer-timing approaches influence crop performance.
3. Quantify crop nutrient acquisition under the selected management practices.
4. Determine differences in the efficiency of fertilizer utilization among treatments.
5. Examine the possibility of minimizing nutrient wastage through improved application timing.
6. Formulate a practical framework for weather-responsive nutrient management under climate variability.

Materials and Methods
1. Experimental Design
A field-based study was planned to examine different approaches for managing fertilizer application in maize (Zea mays L.). Four nutrient-management strategies were evaluated under a randomized complete block design (RCBD), with each treatment repeated three times to provide replication.
The management practices included:

- **T1:** Fertilizer application according to the standard schedule.
- **T2:** Nutrient application guided by soil-test results.
- **T3:** Fertilizer timing modified according to prevailing weather conditions.
- **T4:** Nutrient management based on a combined assessment of weather, soil condition and crop growth stage.

The experimental arrangement was intended to assess the progression from a conventional calendar-based fertilizer practice to increasingly adaptive, information-driven nutrient management systems.

2. Experimental Treatments

Table 1: Fertilizer treatments used in the study

Treatment	Description
T1	Conventional fertilizer schedule
T2	Soil-test-based fertilizer management
T3	Weather-adjusted fertilizer scheduling
T4	Integrated weather, soil and crop-stage scheduling

3. Soil Characteristics

Table 2: Initial physiochemical characteristics of experimental soil

Parameter	Value
Soil texture	Sandy loam
pH (1:2.5 soil:water)	6.8
Electrical conductivity (dS m^{-1})	0.42
Organic carbon (%)	0.58
Available nitrogen (kg ha^{-1})	245
Available phosphorus (kg ha^{-1})	18.6
Available potassium (kg ha^{-1})	312
Cation exchange capacity (cmol(+) kg^{-1})	12.4

4. Weather Data Collection

Weather and field conditions were monitored during the crop period. Data on maximum and minimum temperature, rainfall, relative humidity, wind speed, solar radiation, and soil moisture were considered. Short-term rainfall forecasts were also used to guide fertilizer decisions. Weather data were assumed to be obtained from an automated weather station. Forecasts helped identify suitable application periods and avoid fertilizer application before heavy rainfall

5. Weather-Based Fertilizer Scheduling

Fertilizer timing was adjusted according to crop stage, soil moisture, and prevailing weather conditions. Application was carried out when adequate soil moisture and crop nutrient demand were present and when favorable weather was expected. Fertilization was avoided during very dry conditions or when heavy rainfall was likely immediately after application.

6. Fertilizer Application

Nitrogen, phosphorus, and potassium were applied through suitable fertilizer sources. The required nutrient dose was divided among major crop growth stages to match fertilizer availability with crop demand.

Growth stage	Days after sowing (DAS)	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})
Basal (at sowing)	0	20	40	20
Vegetative stage	15–20	40	0	30
Knee-high stage	35–40	40	0	30
Tasseling stage	55–60	20	0	20
Grain filling stage	75–80	20	0	20
Total	—	140	40	120

7. Crop Growth Measurements

Crop performance was monitored through selected morphological and biomass traits. Plant height, leaf production, leaf area, fresh weight, and dry weight were recorded at suitable stages during crop development. These observations were used to describe changes in vegetative growth among the fertilizer treatments.

8. Yield Measurements

Yield attributes were assessed following crop maturity. Ear size, ears produced per plant, mass of 100 grains, and total grain production were recorded for each treatment. The final yield was converted and reported as tonnes per hectare (t ha^{-1}).

9. Nutrient Uptake

Samples representing the harvested crop were used for nutrient estimation. Nitrogen, phosphorus, and potassium concentrations were determined from the plant material. Nutrient removal by the crop was subsequently estimated by combining the measured nutrient concentration with the corresponding dry-matter production.

10. Nutrient-Use Efficiency

The efficiency of fertilizer utilization was estimated by comparing the additional nutrient accumulated by fertilized plants with the amount of nutrient supplied through fertilizer. For nitrogen, the following expression was used:

NUE (%) = [(N uptake in fertilized treatment − N uptake in control) / N applied] × 100

A similar calculation framework was used for determining phosphorus-use efficiency and potassium-use efficiency.

11. Statistical Analysis

The experimental layout was considered suitable for treatment comparison through analysis of variance (ANOVA). A suitable mean-separation procedure at the 5% probability level could be applied when statistical testing of actual observations is performed. Since the numerical values presented in this manuscript are illustrative, they are not interpreted as statistically significant experimental results.

Result

1. Weather Conditions during the crop season

Table 4: Illustrative weather conditions dueing crop growth

Crop stage	Mean temperature (°C)	Rainfall (mm)	Relative humidity (%)
Germination / Early vegetative	24.5	32.4	76.8
Vegetative growth	26.8	58.7	72.3
Flowering	28.6	42.1	68.5
Pod development	27.9	67.3	70.2
Grain filling	26.7	49.6	73.4
Maturity	25.3	36.8	75.6

2. Fertilizer Scheduling ans estimated nutrient loss

Table 5: Fertlizer scheduling and estimated nutrient loss

Treatment	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Estimated nutrient loss (%)
T1 (Conventional schedule)	120	60	60	18.5
T2 (Soil-test-based schedule)	120	60	60	12.7
T3 (Weather-adjusted schedule)	120	60	60	9.3
T4 (Integrated schedule)	120	60	60	6.8

3. Effect on Crop Growth

Table 6: Effect of fertilizer scheduling on maize growth

Treatment	Plant height (cm)	Leaves plant^{-1}	Leaf area (cm^2 plant^{-1})	Dry biomass (g plant^{-1})
T1 (Conventional schedule)	152.3	9.8	412.5	45.6
T2 (Soil-test-based schedule)	158.7	11.2	465.3	52.8
T3 (Weather-adjusted schedule)	162.4	12.7	512.6	59.3
T4 (Integrated schedule)	168.9	14.1	563.7	66.7

4. Effect on Yield and Yield components

Table 7: Effect of fertlizer scheduling on yield and yield components

Crop stage	Mean temperature (°C)	Rainfall (mm)	Relative humidity (%)
Germination / Early vegetative	24.5	32.4	76.8
Vegetative growth	26.8	58.7	72.3
Flowering	28.6	42.1	68.5
Pod development	27.9	67.3	70.2
Grain filling	26.7	49.6	73.4
Maturity	25.3	36.8	75.6

5. Nutrient Uptake

Table 8: Nutrient uptake at harvest

Treatment	N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	K uptake (kg ha^{-1})
T1 (Conventional schedule)	98.4	18.7	122.6
T2 (Soil-test-based schedule)	112.7	21.5	146.3
T3 (Weather-adjusted schedule)	128.9	26.8	172.4
T4 (Integrated schedule)	136.2	30.7	188.5

6. Nutrient-Use Efficiency

Table 9: Nutrient-Use efficiency under different treatments

Treatment	N-use efficiency (%)	P-use efficiency (%)	K-use efficiency (%)
T1 (Conventional schedule)	42.6	36.8	48.3
T2 (Soil-test-based schedule)	56.7	49.5	65.2
T3 (Weather-adjusted schedule)	62.4	56.8	73.6
T4 (Integrated schedule)	68.9	63.2	81.7

Discussion

The simulated findings indicate that fertilizer timing can be improved by incorporating weather information into nutrient management. Unlike fixed schedules, weather-responsive application allows fertilizer timing to be adjusted according to field conditions. Rainfall can influence nutrient retention and movement. Applying fertilizer just before heavy rain may increase nutrient losses through runoff or leaching. Therefore, short-term rainfall forecasts can help identify safer application periods. Nutrient availability is also affected by soil properties, drainage, moisture status, fertilizer type, application method, and crop development. Hence, weather data should be considered together with soil and crop information.

Crop nutrient requirements vary with growth stage. Matching fertilizer supply with periods of greater nutrient demand may improve nutrient uptake and reduce unnecessary losses.

The simulated improvement in nutrient-use efficiency under integrated management supports the concept of synchronizing fertilizer supply with crop needs and environmental conditions. However, these values are illustrative and require confirmation through actual field experiments.

Proposed Weather-Based Precision Fertilizer Scheduling Model

The proposed approach combines weather forecasts, soil moisture, crop stage, and nutrient requirements before deciding fertilizer timing. Field conditions are subsequently monitored so that later applications can be modified when necessary.

Weather forecast → Soil moisture → Crop stage → Nutrient requirement → Fertilizer decision → Application → Monitoring → Adjustment

Table 10: Proposed fertilizer decision rules

Field condition	Fertilizer decision
Rainfall is expected within 1–2 days	Postpone application to avoid nutrient loss.
Soil moisture is low (< 60% field capacity)	Apply only a reduced dose or wait until adequate moisture is available.
Soil moisture is optimal (60–80% field capacity)	Apply the recommended dose as per crop stage.
Soil moisture is high (> 80% field capacity)	Delay application to prevent leaching and runoff.
Crop is at early vegetative stage	Apply a basal dose with balanced nutrients.
Crop is at reproductive stage	Increase nutrient supply, especially P and K.
Soil nutrient level is low	Apply full recommended dose.
Soil nutrient level is medium to high	Apply a reduced dose based on soil test results.

Economic Analysis

Table 11: Illustrative economic analysis

Parameter	T1 Conventional	T4 Precision
Fertilizer cost (₹ ha^{-1})	6,000	4,500
Monitoring cost (₹ ha^{-1})	500	1,000
Total input cost (₹ ha^{-1})	6,500	5,500
Grain yield (t ha^{-1})	5.8	7.2
Gross return (₹ ha^{-1})	29,000	36,000
Net return (₹ ha^{-1})	22,500	30,500
Benefit–cost ratio	4.46	5.55

Conclusion

Using weather information as part of fertilizer management can make nutrient application more responsive to changing field conditions. Information on expected weather, soil-water availability, crop development, and nutrient demand can be considered together to select suitable periods for fertilizer application and minimize unnecessary nutrient losses.

The illustrative results showed that the integrated scheduling approach was associated with better crop development, grain production, nutrient accumulation, and nutrient-use efficiency, while the estimated nutrient loss was comparatively lower than under the conventional schedule.

This management concept fits within climate-smart agriculture by shifting fertilizer application from a predetermined timetable toward a condition-based approach.

However, the values presented in this manuscript are simulated and should not be considered experimental measurements. Further field studies covering multiple locations and growing seasons are necessary to establish the reliability, practical benefits, and economic and environmental performance of the proposed system.

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