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RESEARCH ARTICLE

Enhancing nitrogen use efficiency of wheat through real-time SPAD-based N fertilization

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Abstract

Nitrogen (N) fertilization is critical for optimal wheat productivity, yet traditional application methods often lead to inefficiencies, economic losses and environmental pollution. Real-time monitoring of N through chlorophyll meter readings offers a promising approach. This method can optimize N use efficiency while maintaining yield potential. To investigate this approach, a field trial was established during the winter growing season of 2015-16. The study was conducted at the research station of Bihar Agricultural University, Sabour, Bihar, India. The experimental layout utilized a split-plot arrangement with fourteen treatment combinations, encompassing two soil plant analysis development (SPAD) measurement levels (42 and 44) across seven wheat genotypes (HD 2967, HD 2985, HI 1563, PBW 343, HW 1105, HD 3086 and Sabour Samriddhi), each treatment replicated thrice. Nitrogen management using SPAD threshold of 42 and 44 effectively preserved wheat cultivar growth and yield characteristics while reducing N fertilizer usage by 33 and 12 kg ha^{-1} respectively as compared to the state recommended dose of 120 kg N ha^{-1}. Linear correlations between foliar N content and SPAD measurements at the crown root initiation (CRI) and tillering stages identified optimal SPAD values of 45.3 and 42.0 respectively, for maximizing grain yield. Economic analysis revealed that HD 2967 generated the highest profit margins and return ratios, with Sabour Samriddhi ranking second, both significantly outperforming PBW 343 in financial metrics. Thus, SPAD threshold of 42 proved most effective for maintaining wheat productivity and profitability through efficient N fertilizer management.

Keywords: nitrogen use efficiency; SPAD; wheat; yield

Introduction

After rice (*Oryza sativa* L.) and maize (*Zea mays* L.), wheat (*Triticum aestivum* L.) is the third most widely cultivated and important field crop for all climates and the staple source of nutrients for around 40 % of world's population (1, 2). Nitrogen (N) is the most widely used nutrient by wheat growers. However, nitrogen use efficiency (NUE) in wheat production averages only 33 % globally, with reported values ranging from 14 to 59 % depending on management practices and environmental conditions (3, 4). Wide fluctuations in soil N levels and generalized fertilizer application based on unsuitable universal recommendations by growers lead to excess N application (5). It is evident that standardized N recommendations for extensive farming areas have adequately fulfilled grain production requirements but cannot enhance NUE beyond particular limits (6). The principal reason for substandard NUE is poor N dose segmentation together with N provision exceeding crop uptake capacity (7). The excess N may be lost through volatilization, denitrification and leaching, which also lead to low NUE (8) and environmental impacts (9-11). The global NUE in cereal crop production is 33 %, which means 67 % of applied N is not used by the intended crops and it is still a major issue in agriculture (12). Low NUE is due partly to high N applications that do not correspond to the timing and spatial variability of the crop's N requirements, such as when all N is applied at a uniform rate prior to planting under rainfed condition. Regarding sustainability considerations, adopting sensor-controlled N management systems is crucial for enhancing NUE, obtaining economically sound yields and preventing fertilizer N environmental losses. These sensing technologies are instrumental in documenting spatial and temporal field heterogeneity, enabling input modifications according to site-specific requirements for achieving better NUE and partial factor productivity (13–15). Standard Asian cultivation practices include supplying half the recommended N during sowing along with full phosphorus (P) and potassium (K) fertilizers, with the balance N provided through two equal supplemental applications at crown root initiation (CRI) and maximum tillering (MT) stages, aligned with irrigation events. Nonetheless, NUE enhancement is only attainable when application schedules coincide with developmental phases exhibiting strong N uptake affinity. Effective N management must balance the dual objectives of maximizing grain yield while maintaining sufficient plant N concentration.

In eastern Indo-Gangetic Plains, the general recommendation for N is 150 kg ha^{-1} but in most of the cases the limit was crossed up to 180 kg ha^{-1} which indicates a huge spatial variation in farmers' field (16). Growers routinely increase N rates to minimize deficiency risks, particularly when timed with irrigation applications. Scientific evidence suggests that three N applications compared with two can boost wheat grain production by approximately 10-12 % (17). The root cause of economic inefficiency and environmental degradation from N overuse originates from inadequate universal guidelines and inappropriate splitting strategies across diverse locations. Research emphasis has targeted NUE improvement through precision tools like chlorophyll or soil plant analysis development (SPAD) meters that measure leaf light absorption to inform real-time N management in wheat systems (18, 19). These SPAD devices function as portable, non-destructive instruments quantifying leaf transmittance at two specific wavelengths absorbed by individual leaves. The underlying principle of SPAD 502 chlorophyll meters involves decreasing uncertainty about plant N variability across space and time, enabling optimal N placement and timing decisions (20, 21). Significant correlations exist between SPAD measurements and leaf N concentration plus dry matter content in wheat crops (5, 21). In Northern India, by applying 30 kg N ha^{-1} at SPAD readings of 42-44 during maximum tillering; yields had been increased by 20 % over standard farmer practices (22).

A number of researchers have underlined the necessity of effective N management under a variety of soil and agroclimatic circumstances. Studies were conducted to compare the SPAD-based strategy and farmers' practice for suitable N recommendation in irrigated wheat but there is no specific information on SPAD limit for several popular cultivars of wheat in eastern India. We hypothesized that SPAD meter-based N management will significantly improve NUE and yield of wheat as compared to conventional fixed-rate N application methods by enabling more precise matching of N supply with crop demand throughout the growing season. The objectives of the study were: a) to determine the relationship between SPAD meter readings, leaf N concentration and wheat growth attributes; b) to develop SPAD threshold values for making N fertilization decisions at critical growth stages of wheat; c) To compare the effects of SPAD meter-guided N fertilization with conventional fixed-rate N application methods on performance, economic benefits and NUE of wheat.

Materials and Methods

Site description

During the winter season of 2015–16, a field experiment was conducted at the experimental farm of Bihar Agricultural University, Sabour, Bihar, India (25°15′40″ N, 87°02′42″ E; 37.0 m above mean sea level) to evaluate nitrogen fertilizer management in wheat using SPAD meter under zero-tillage line sowing. During the experimental period, the average temperature ranged from 19.0 to 29.6 °C and a total rainfall of 53.4 mm was received. The soil was sandy loam in texture, low in available N (192 kg ha^{-1}) (23) and organic carbon (0.55) (24); medium in available P (9.4 kg ha^{-1}) (25) and K (142 kg ha^{-1}) (26); neutral in reaction with a soil pH 7.3 (26) and non-saline in nature.

Experimental details and crop management

A split-plot experimental design was implemented with three replications, featuring two SPAD threshold values (42 and 44) in the main plots and seven wheat genotypes (HD 2967, HD 2985, HI 1563, PBW 343, HW 1105, HD 3086, Sabour Samriddhi) in the subplots. The Directorate of Research at Bihar Agricultural University supplied seed stocks for all wheat varieties examined in this research. Chlorophyll concentration measurements (SPAD index) were obtained using a SPAD device (SPAD-502, Minolta, Japan). Soil plant analysis development measurements were initiated 25 days after sowing (DAS) and continued at 10-day intervals until flowering (95 DAS), using fully expanded leaves. The representative SPAD value for each experimental unit was determined by averaging 15 measurements per plot. The basal fertilizer dose consisted of 40–60–40 kg N–P_2O_5–K_2O ha^{-1} and 20 kg N ha^{-1} was top-dressed based on SPAD threshold values of 42 and 44. The sources of chemical fertilizers were urea, single super phosphate and muriate of potash. The gross plot size was 3 m × 6 m. The seeds of wheat cultivars were sown at a row spacing of 20 cm with a seed rate of 100 kg ha^{-1} on 1 December 2015. The plots were kept weed-free by hand weeding at 30 DAS. A total of five irrigations were applied to supplement the rainfall during crop growth period. The wheat crop was harvested on 10 April 2016.

Growth, yield attributes and yield

Excluding the peripheral border rows, ten plants were randomly chosen and marked from each net plot area within each treatment for recording various growth and yield parameters. Plant height measurements were recorded at 105 DAS from ten randomly selected tagged plants per plot using a measuring scale, from the soil surface to the apex of the uppermost fully expanded leaf and mean values were expressed in centimeters. The leaf area index (LAI) was measured at anthesis stage (85 DAS) of the crop. The ACCUPAR LP-80 (METER Group, Inc., Pullman, WA, USA) instrument was used to measure the LAI. Ten randomly selected plants were uprooted from the sampling row from each plot at maturity (130 DAS). Plant samples were meticulously cleaned to remove soil residues prior to fresh weight determination. After sun-drying for 3–4 days, specimens were transferred to properly marked brown paper bags and subjected to oven-drying at 65 °C for 2 days until weight stabilization occurred. Dry weight values were recorded per treatment, with mean plant weight calculated as g m^{-2}. Yield parameters such as earhead count, grain number per earhead and test weight were assessed at harvest using ten randomly chosen plants from each net plot area. Grain and straw production (kg ha^{-1}) were evaluated from a central 10 m^2 sampling zone (2 m × 5 m) within each plot. Grain yield determinations were adjusted to 12 % moisture basis. Straw materials from each net plot were field-dried for 3-4 days before mass measurement, with data recorded as kg plot^1 and later transformed to kg ha^{-1}.

Nitrogen uptake, nitrogen use efficiency and soil nitrogen

Plant specimens were harvested at physiological maturity for N content analysis. These samples were then subjected to oven-drying, pulverization and preservation for later chemical examinations. Nitrogen concentration in foliar, stem and grain tissues was quantified using digestion and distillation procedures with the Kel-Plus system (27). The amount of nutrients taken up by the plant was calculated by using the following formula:

Nutrient uptake (kg ha^{-1}) =

$$\frac{\text{Nutrient content in sample} \times \text{Yield (leaf or stem or grain)}}{100}$$

The total N uptake was calculated as the sum of N uptake by leaf, stem and grain. Nitrogen use efficiencies, including partial factor productivity of applied N (PFP_N), internal N use efficiency (IE_N), N harvest index (NHI) and physiological N use efficiency (PE_N) were calculated using the following equations (28, 29):

$$PFP_N\ (\text{kg kg}^{-1}) = \frac{GY}{FN}$$

$$IE_N\ (\text{kg kg}^{-1}) = \frac{GY}{NU}$$

$$NHI\ (\%) = \frac{NU_{Grain}}{NU_{Total}} \times 100$$

$$PE_N\ (\text{kg kg}^{-1}) = \frac{AGB}{NU}$$

Where, GY = grain yield (kg ha^{-1}), FN = quantity of fertilizer N applied (kg N ha^{-1}), NU = total uptake of N (kg ha^{-1}), NU_{Grain} = grain N uptake (kg ha^{-1}), NU_{Total} = total uptake of N (kg ha^{-1}), AGB = total above ground biomass (kg ha^{-1}).

Surface (0-15 cm) soil samples were collected from each plot at 25, 35, 45, 55, 65, 75, 85, 95, 105 and 130 DAS of wheat. The soil samples were used for time-series available N estimation (23).

Economic analysis

Economic assessments were conducted using prevailing market prices for inputs and outputs. The cost of cultivation included all variable expenses (seeds, fertilizers, labour, farm operations and crop protection), excluding land rent. Labour costs were calculated based on person-days ha^{-1} (1 person-day = 8 hr) at statutory minimum wage rates as per Indian labour laws. Gross returns were calculated by multiplying grain yield with the minimum support price (MSP) declared by the Government of India (2016), in addition with the straw market value at local market rates. Net returns were computed as:

Net returns = Gross returns – Cost of cultivation

The return per rupee invested was determined by dividing the net returns by the total cost of cultivation. For the economic analysis of this study, an exchange rate of 1 USD equivalent to ₹ 67.63 for the year 2016 was considered as per the average exchange rate (30).

Statistical analysis

All experimental data were subjected to analysis of variance (ANOVA) tailored for a split-plot design (31) using SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA). Treatment means were compared using the *F*-test and significant differences among means were determined by the least significant difference (LSD) test at the 5 % probability level.

Results

Growth attributes

The plant height, LAI and dry biomass did not vary significantly between the SPAD 42 and 44 (Table 1). Sabour Samriddhi recorded the highest plant height (91.6 cm); however no statistically significant differences were observed among the varieties. It also exhibited the highest LAI (4.42), which was statistically at par with HD 2967, HD 2985 and HI 1563. The cultivar, HD 2967 recorded the highest biomass of 12264 kg ha^{-1} which was 22.0 and 18.2 % higher as compared to PBW 343 and HW 1105 respectively, but statistically at par with cultivars Sabour Samriddhi, HD 2985 and HI 1563.

Yield attributes and yield

The SPAD based N management treatments did not show significant effect on number of earheads m^{-2} between the SPAD values and among the cultivars. The number of grain earhead^{-1} and the test weight of wheat were significantly influenced by SPAD-based N management practices (Fig. 1). The variety HD 2967 produced the highest number of grains per earhead, which was statistically at par with all other varieties except PBW 343. However, the SPAD values did not vary significantly between them in grain earhead^{-1} and test weight.

Application of N based on SPAD 44 recorded the highest grain yield (4839 kg ha^{-1}) and straw yield (6800 kg ha^{-1}) but these were statistically at par with SPAD 42 (4391 and 6163 kg ha^{-1}) (Fig. 2). This comparison reveals an important trade-off between NUE and yield maximization. While SPAD 44 achieved 9 % higher yield than SPAD 42, it required 19 % more N to do so. From an economic perspective, SPAD 42 may be more advantageous, delivering comparable statistical yields with substantially lower N input costs and reduced environmental N loading. Conversely, SPAD 44 would be preferable where maximizing absolute yield is the primary objective, despite

Table 1. Effect of SPAD thresholds and varieties on maximum plant height (cm), LAI and total biomass (kg ha^{-1}) of wheat

Treatments	N rate (kg ha^{-1})	Plant height	LAI	Biomass
SPAD level (S)				
SPAD 42	87	90.4	3.76	10553
SPAD 44	108	87.5	4.01	11639
SEm (±)	-	1.7	0.12	357
LSD (*p*=0.05)	-	NS	NS	NS
Variety (V)				
HD 2967	97	89.0	3.86	12264
HD 2985	93	86.4	4.08	11298
HI 1563	103	89.2	3.91	11365
PBW 343	97	90.0	3.62	10053
HW 1105	90	88.3	3.77	10378
HD 3086	97	88.0	3.53	10565
Sabour Samriddhi	103	91.6	4.42	11750
SEm (±)	-	2.8	0.15	465
LSD (*p*=0.05)	-	NS	0.44	1357
Interaction (S × V)	-	NS	NS	NS

SEm = standard error of the mean; LSD = least significant difference; NS = non-significant

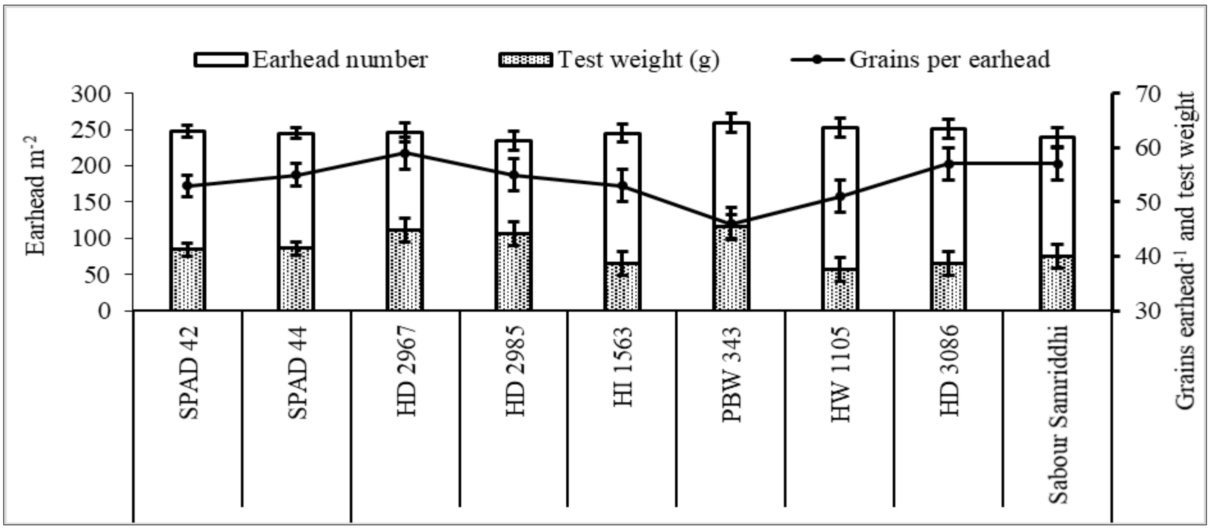

Fig. 1. Influence of various SPAD thresholds and varieties on number earhead m^{-2}, grains earhead^{-1} and test weight of wheat.

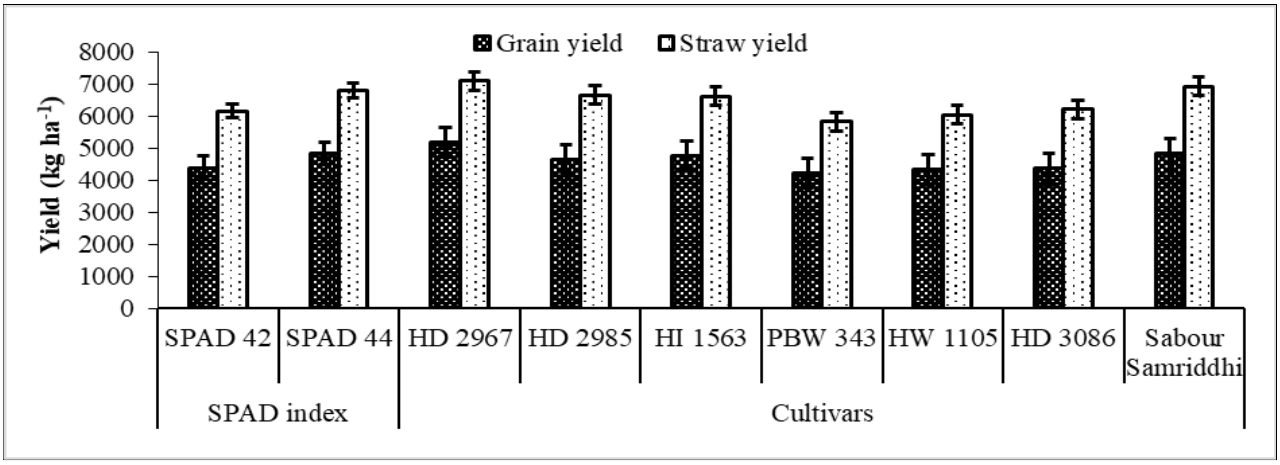

Fig. 2. Effect of various SPAD thresholds and varieties on productivity of wheat crop.

the increased fertilizer requirement. The choice between these two thresholds should therefore be guided by farmer priorities-whether optimizing input costs and sustainability (SPAD 42) or achieving maximum productivity (SPAD 44). Cultivar HD 2967 produced the maximum grain yield of 5172 kg ha^{-1} followed by Sabour Samriddhi (4817 kg ha^{-1}) among the sub–plot treatments and both these were significantly superior over the PBW 343, HW 1105 and HD 3086. Furthermore, PBW 343 attained lowest straw yield (5825 kg ha^{-1}) which was 17.8 % lower relative to cultivar HD 2967. The interaction between SPAD thresholds and wheat cultivars was found to be non-significant for all yield components.

Nitrogen uptake

The N uptake was found comparable between the SPAD levels though the SPAD 44 recorded slightly higher uptake than that of SPAD 42. Total N uptake of SPAD 44 was 10 % higher as compared to SPAD 42 (Table 2). Among different varieties, Sabour Samriddhi attained the highest N uptake in leaf (7.4 kg ha^{-1}) and stem (26.3 kg ha^{-1}). Similarly, the total N uptake was highest in Sabour Samriddhi which was significantly superior over PBW 343, HW 1105 and HD 3086; but in grain N uptake, it was significantly superior over only PWB 343 and HD 3086. However, PBW 343 recorded the lowest N uptake in leaf, stem, grain and total as well as in leaf at maturity among all varieties.

Nitrogen use efficiency

Precision N management practices under SPAD levels did not show significant effect on PFP_N, IE_N, NHI and PE_N of wheat (Table 3). The PFP_N, IE_N, NHI and PE_N decreased at increasing SPAD levels 44, due to increasing the rate of N top dressing. Among the different varieties, the highest PFP_N and IE_N was recorded in HD 2967 and in PE_N HD 3086, which was significantly superior over all other cultivars except HD 2985. The other cultivars remained at par with each other. Sabour Samriddhi recorded lower value of PFP_N, IE_N and PE_N as compared to HD 2967, though it was performed well with respect to other cultivars. Overall, HD 2967 exhibited 12.8 % and 16.9 % higher PFP_N and IE_Nvalues respectively, compared to the other cultivars, while HD 3086 recorded 15.8 % higher PE_N than the rest. The N management practices had very little effect on NHI of wheat. In general, the NHI did not vary significantly between the SPAD levels as well as among the cultivars in sub–plot. The PE_N at SPAD levels 42 and 44 were comparable during the study and the interaction effect was found to be non-significant.

Available soil nitrogen

The available soil N showed a decreasing trend up to maturity stage in all the treatments and it was not varied significantly between the SPAD thresholds as well as among the cultivars (Fig. 3). The maximum available soil N was obtained at 25 DAS in all the cases but was at lower range and as the crop growth increases the status followed downward. At 130 DAS, the highest soil N (177 kg ha^{-1}) was found with HD 2985 which was 9.2, 7.3 and 6.0 % higher in comparison with varieties HI 1563, HW 1105, HD 3086 respectively.

Economics

The highest net returns (₹ 50666 ha^{-1}) were noted in SPAD 44 as

Table 2. Impact of SPAD thresholds and varieties on N uptake (kg ha^{-1}) of wheat at maturity

Treatments	Leaf	Stem	Grain	Total
SPAD level (S)				
SPAD 42	5.7	19.5	88.6	113.7
SPAD 44	6.5	24.1	95.3	126.2
SEm (±)	0.2	1.4	0.6	1.3
LSD (*p*=0.05)	NS	NS	NS	3.7
Variety (V)				
HD 2967	6.7	23.6	91.5	121.8
HD 2985	6.4	22.9	96.2	125.5
HI 1563	6.3	21.9	97.0	125.3
PBW 343	5.3	18.5	85.5	109.3
HW 1105	5.9	18.9	90.8	115.6
HD 3086	5.4	20.3	78.7	104.5
Sabour Samriddhi	7.4	26.3	104.0	137.7
SEm (±)	0.5	1.7	6.3	5.6
LSD (*p* =0.05)	1.3	5.1	16.3	18.4
Interaction (S × V)	NS	NS	NS	NS

SEm = standard error of the mean; LSD = least significant difference; NS = non-significant

Table 3. Effect of various SPAD thresholds and varieties on NUE of wheat at maturity

Treatments	N rate (kg ha^{-1})	PFP_N (kg kg^{-1})	IE_N (kg kg^{-1})	NHI (%)	PE_N (kg kg^{-1})
SPAD levels (S)					
SPAD 42	87	50.95	39.12	78.11	93.84
SPAD 44	108	45.23	38.83	75.24	93.41
SEm (±)	-	0.98	1.16	1.12	2.98
LSD (*p*=0.05)		NS	NS	NS	NS
Variety (V)					
HD 2967	97	54.05	42.60	74.97	101.17
HD 2985	93	49.80	37.24	77.02	90.49
HI 1563	103	46.61	38.30	76.95	91.72
PBW 343	97	44.69	39.15	78.01	92.85
HW 1105	90	48.48	37.91	78.20	90.52
HD 3086	97	45.93	42.24	75.42	102.39
Sabour Samriddhi	103	47.07	35.38	76.08	86.24
SEm (±)	-	1.82	2.13	2.06	4.90
LSD (*p*=0.05)	-	5.31	6.20	NS	14.29
Interaction (S × V)	-	NS	NS	NS	NS

SEm = standard error of the mean; LSD = least significant difference, NS = non-significant

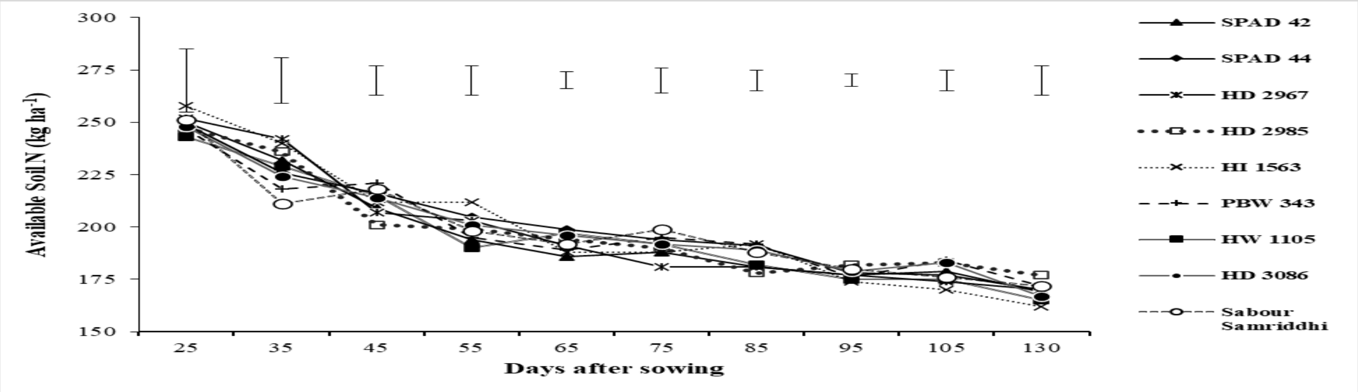

Fig. 3. Effect of various SPAD thresholds and varieties on available soil N status of wheat at different growth stages.

compared to SPAD 42 (Table 4). Furthermore, among the SPAD levels, return per rupee invested was found highest in SPAD 44 (2.58) which was 8.4 % higher over SPAD 42 (2.38). Among the varieties, the highest net returns (₹ 56404 ha^{-1}) and return per rupee invested were obtained in HD 2967, which were comparable to Sabour Samriddhi (₹ 50659 ha^{-1}). The lowest net returns (₹ 40343 ha^{-1}) was obtained by PBW 343 which was 28.5 and 20.3 % lower as compared to HD 2967 and Sabour Samriddhi respectively.

Discussion

The results obtained from the current investigation have revealed that Sabour Samriddhi recorded the maximum plant height and LAI. It was also noticed that Sabour Samriddhi received the maximum dose of N fertilizer (103 kg N ha^{-1}), resulted in luxuriant vegetative growth which led to the crop lodging and yield penalty (21, 32). The dry matter accumulation after blooming was associated with grain yield and greater the dry matter production after blooming, the higher would be the grain yield. Results demonstrate that SPAD 42 achieved grain and straw yields statistically comparable to the higher SPAD 44, while reducing N fertilizer input by 19.4 % through optimized top-dressing applications of 20 kg N ha^{-1}. The superior performance of cultivars HD 2967 and Sabour Samriddhi can be attributed to their greater dry matter accumulation during the

Table 4. Effect of various SPAD thresholds and varieties on economics of wheat

Treatments	N rate (kg ha^{-1})	Net returns (₹ ha^{-1})	Return per rupee invested
SPAD levels (S)			
SPAD 42	87	43572	2.38
SPAD 44	108	50660	2.58
SEm (±)	-	2324	0.07
LSD (*p*=0.05)		NS	NS
Variety (V)			
HD 2967	97	56404	2.77
HD 2985	93	47909	2.51
HI 1563	103	49089	2.53
PBW 343	97	40343	2.27
HW 1105	90	42581	2.35
HD 3086	97	42827	2.34
Sabour Samriddhi	103	50659	2.58
SEm (±)	-	3234	0.10
LSD (*p*=0.05)	-	9438	0.29
Interaction (S × V)	-	NS	NS

SEm = standard error of the mean; LSD= least significant difference; NS= non-significant; 1 USD equivalent to ₹ 67.63

critical grain-filling phase, which enhanced both grain weight and test weight (33, 34). This pattern suggests that these varieties possess stronger sink strength and more efficient remobilization of assimilated N, enabling them to maximize yield potential under precision N management without excess fertilizer application. Similarly, grain yield of wheat increased by approximately 25.0 % using SPAD-meter-based N management compared to fixed-time N management, despite requiring 14 % more N application (21). The strong association between N uptake and biomass production in high-yielding varieties (Sabour Samriddhi, HD 2967, HD 2985 and HI 1563) underscores the importance of sink capacity in determining NUE. These varieties likely possess superior physiological traits such as enhanced root architecture, more efficient N assimilation enzymes or better translocation mechanisms that enable them to capitalize on available N for greater biomass accumulation and subsequent grain filling (34, 35). The effectiveness of SPAD-based N management in these varieties suggests that real-time chlorophyll monitoring successfully synchronized N supply with crop demand during critical growth stages, minimizing luxury consumption while ensuring adequate nutrition. This demand-driven approach may explain why SPAD-guided treatments achieved higher total N uptake without the inefficiencies associated with blanket fertilizer applications, where asynchrony between supply and crop requirements often leads to losses through leaching, volatilization or immobilization (36). Maximum NUE was achieved at a SPAD threshold of 42 for wheat production. This may be due to the optimal balance between N supply and plant demand at this threshold, where sufficient chlorophyll content supported photosynthetic activity while avoiding excess nitrogen application that could lead to luxury consumption or losses through leaching and volatilization. Below this threshold, N deficiency limited productivity, while exceeding it resulted in excessive vegetative growth or N accumulation beyond metabolic capacity, both decreasing NUE. An enhanced PFP_N of 9.36 kg kg^{-1} was recorded in HD 2967 compared to PBW 1563, indicating greater N fertilizer conservation and improved fertilizer NUE. This improvement may be attributed to synchronized N supply with crop requirements and minimized nutrient losses, promoting effective N absorption and utilization of applied fertilizers (37, 38). The reason for higher IE_N, NHI and PE_N with SPAD 42 could be due to higher nutrient uptake as compared to SPAD 44 leading to better grain and straw yield (39).

A significant positive correlation (R^2= 0.47, p = 0.01) between leaf N content and SPAD values at 45 DAS enabled derivation of optimal SPAD thresholds for maximum grain yield (Table 5). Using averaged leaf N content of 4.07 % (CRI stage) and 3.32 % (tillering stage) across seven cultivars, the corresponding target SPAD values were calculated as 45.3 and 42.0 respectively. Notably, the tillering stage emerged as more N-critical with SPAD values falling below the threshold-indicating this growth phase as pivotal for yield forecasting through chlorophyll monitoring (17). Economic analysis revealed that SPAD 42 combined with cultivar HD 2967 yielded the highest net returns, corroborating findings on SPAD-guided N management benefits (40). These results underscore that optimizing grain yield and profitability in wheat hinges on the dual strategy of precision N timing and strategic cultivar selection (41).

Conclusion

While SPAD thresholds of 42 and 44 produced statistically comparable yields, SPAD 42 offers a more sustainable and economically viable strategy for wheat producers in eastern India, reducing N fertilizer requirements by approximately 19.4 % without compromising productivity. When integrated with high-performing cultivar HD 2967, this precision N management approach delivered superior net returns while substantially improving NUE compared to the conventional blanket recommendation of 120 kg N ha^{1}. From an extension perspective, SPAD–based N management represents a practical, scalable technology that empowers farmers to make real-time fertilizer decisions, reducing input costs and environmental nitrogen losses simultaneously. The portability and ease of use of SPAD meters make this approach particularly well-suited for smallholder farming systems prevalent in the region. We recommend that agricultural extension programs prioritize farmer training on SPAD meter use and promote the SPAD 42 threshold combined with proven cultivars like HD 2967 to enhance both farm profitability and agronomic sustainability. Future research should validate these findings across diverse agroecological zones and explore the integration of SPAD–based management with other precision agriculture tools to further optimize wheat production systems in South Asia.

Table 5. Relationships between leaf N content and SPAD value at different growth stages of wheat and SPAD value for maximum grain yield

Growth stages	Relationship (leaf N and SPAD value)	R^2 value	Desired SPAD value
CRI	Y = -0.476X + 47.16	0.04	45.3
Tillering	Y = 5.988X + 22.17	0.47**	42.0

**indicates significance at p = 0.01

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Authors' contributions

VP and MG conceptualized the study, developed the methodology, performed formal analysis and investigation. VP, MG and SS prepared the original draft. MG, AB, AK, NM and SS contributed to writing, review and editing. MG provided resources. VP and MG supervised the study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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