


RESEARCH ARTICLE

# Fixed-time corrective dose fertilizer nitrogen management in wheat using atLeaf meter and leaf colour chart

Ali M. Ali<sup>1\*</sup>, Sherif M. Ibrahim<sup>1</sup>, Wahby M. Hassany<sup>2</sup>, Ashraf N. El-Sadek<sup>2</sup> and Bijay-Singh<sup>3</sup>

<sup>1</sup>Department of Soil Fertility and Microbiology, Desert Research Center, Cairo 11753, Egypt, <sup>2</sup>Department of Plant Production, Desert Research Center, Cairo 11753, Egypt and <sup>3</sup>Department of Soil Science, Punjab Agricultural University, Ludhiana 141004, India

\*Corresponding author. Email: [alimohamed1982@gmail.com](mailto:alimohamed1982@gmail.com)

(Received 18 November 2020; revised 30 June 2021; accepted 15 July 2021; first published online 21 September 2021)

## Abstract

Fertilizer nitrogen (N) management in any region following standard general recommendations discount the fact that crop response to N varies between sites and seasons. To devise field-specific N management in wheat at jointing stage (Feekes 6 growth stage) using atLeaf meter and leaf colour chart (LCC), eight field experiments were conducted in three wheat seasons during 2017–2020 in the West Delta of Egypt. In the first two seasons, four experiments consisted of treatments with a range of fertilizer N application levels from 0 to 320 kg N ha<sup>-1</sup>. Monitoring atLeaf and LCC measurements at Feekes 6 growth stage in plots with different yield potentials allowed formulation of different criteria to apply field-specific and crop need-based fertilizer N doses. In the four experiments conducted in the third season in 2019/20, different field-specific N management strategies formulated in 2017/18 and 2018/19 wheat seasons were evaluated. In the atLeaf-based fertilizer N management experiment, prescriptive application of 40 kg N ha<sup>-1</sup> at 10 days after seeding (DAS) and 60 kg N ha<sup>-1</sup> at 30 DAS followed by application of an adjustable dose at Feekes 6 stage computed by multiplying the difference of atLeaf measurements of the test plot and the N-sufficient plot with 42.25 (as derived from the functional model developed in this study), resulted in grain yield similar or higher to that obtained by following the standard treatment. The LCC-based strategy to apply field-specific fertilizer N at Feekes 6 stage consisted of applying 150, 100 or 0 kg N ha<sup>-1</sup> based on LCC shade equal to or less than 4, between 4 and 5 or equal to or more than 5, respectively. Both atLeaf- and LCC-based fertilizer N management strategies not only recorded the highest grain yield levels but also resulted in higher use efficiency with 57–60 kg N ha<sup>-1</sup> in average less fertilizer use than the standard treatment.

**Keywords:** Field-specific nitrogen management; atLeaf meter; Leaf colour chart; Wheat

## Introduction

Fertilizer nitrogen (N) recommendations in Egypt and elsewhere for wheat (*Triticum aestivum* L.) generally constitute fixed rates for large areas having similar climates and landforms. Although these general or standard recommendations have served the purpose in producing high yield levels, these cannot achieve high use N efficiency because of spatial and temporal variability in soil N supply. N supply from the soil differs from field to field (spatial variability) and year after year (temporal variability). Optimum rates of N are dependent on yearly environmental conditions that are random and cannot be predicted in advance (Raun *et al.*, 2019). Further, the standard general fertilizer N recommendations in a region are always associated with risks of low profits and environmental degradation (Fageria and Baligar, 2005;

Ladha *et al.*, 2005; Bijay-Singh, 2018). Ali *et al.* (2017) reported that fertilizer N recovery efficiency in wheat in some parts of Egypt was in the range of 35.6–51.1% by following the standard recommendation. Worldwide N recovery efficiency in cereal is reported to be around 35% (Omara *et al.*, 2019).

Increasing synchronization between N needed by the crop and fertilizer N supply is crucial for improving N use efficiency. Applying N when demand by the crop is high will not only increase yield but also N use efficiency (Cassman *et al.*, 2003; Diacono *et al.*, 2013; Peng *et al.*, 2010). Optimization of fertilizer N in several crops was successfully achieved by management approaches following chlorophyll meters and leaf colour charts (LCC) (Ali *et al.*, 2015; Bijay-Hussain *et al.*, 2003; Bijay-Singh *et al.*, 2020; Singh *et al.*, 2002; Varinderpal-Singh *et al.*, 2010). The underlying principle in using these tools is that chlorophyll and N contents of leaves are closely linked with N supply to the crop plants because N is involved in the formation of chloroplasts and is considered a structural element of chlorophyll (Benincasa *et al.*, 2017; Bojovic and Markovic, 2009; Schepers *et al.*, 1992). These tools can be used in making in-season fertilizer N decisions as these can rapidly and non-destructively quantify leaf N status by measuring spectral properties of leaves. However, protocols for using these gadgets for field-specific N management in wheat will have to be evolved in a given region as per the agronomic practices being followed in the region. No such study has been reported from Egypt where wheat is grown in coarse textured calcareous soils and with standard fertilizer N recommendations as high as 250 kg N ha<sup>-1</sup>.

The Soil Plant Analysis Development (SPAD) meter and atLeaf meter are the commonly used chlorophyll meters, which provide a quick estimation of relative chlorophyll content in leaves. The absolute threshold value and sufficiency index approaches are the widely used criteria to guide fertilizer N application in wheat using chlorophyll meters (Islam *et al.*, 2014; Bijay-Singh *et al.*, 2002; 2013; 2018; Bijay-Singh and Ali, 2020). Although most of the investigations conducted so far have used SPAD meter, it has been found that the performance of the recently introduced atLeaf meter is comparable to SPAD meter (Basyouni *et al.*, 2015; Dunn *et al.*, 2018; Zhu *et al.*, 2012). In a study conducted by Ali *et al.* (2020) on wheat, atLeaf meter could capture the variation in N uptake to the tune of 55.3%.

LCC operates differently than the chlorophyll meters as it allows comparing visually the different scores on the chart with leaf greenness. The LCC has been used as an indicator of N status in leaves and then to guide field-specific fertilizer N applications in wheat, maize and rice (Alam *et al.*, 2006; Ali *et al.*, 2015; Bijay-Singh *et al.*, 2002; Varinderpal-Singh *et al.*, 2011, 2012; Bijay-Singh *et al.*, 2020; Witt *et al.*, 2005). In wheat, Shukla *et al.* (2004) used threshold LCC score 4 as a guide to apply fertilizer N. Compared with the standard recommendation, this management strategy performed better and resulted in high yield and use efficiency. However, Maiti and Das (2006) found that the LCC score 5 performed better than score 4 in wheat. Varinderpal-Singh *et al.* (2012) developed an LCC plan for N management in wheat in the Indian Punjab and it consisted of applying 30 or 45 kg N ha<sup>-1</sup> at maximum tillering stage based on LCC to be more than or equal to score 4 or less than score 4, respectively.

In a study carried out in ten countries on wheat, IAEA (2000) advocated that most of fertilizer N should be applied by jointing growth stage (Feekes 6) to obtain high grain yield. Several studies have also concluded that in wheat it is the appropriate stage to apply adjustable dose of fertilizer N (Ali, 2020; Raun *et al.*, 2001; Bijay-Singh *et al.*, 2011, 2013; Varinderpal-Singh *et al.*, 2017). The present study was designed to formulate strategies for fertilizer N application in wheat using atLeaf meter and LCC at Feekes 6 growth stage. Specific objectives were to (i) develop a functional model based on atLeaf meter measurements to predict optimum fertilizer N dose, (ii) establish threshold LCC scores to guide N optimum fertilizer N applications and (iii) compare the improved fertilizer N management strategies with the general fertilizer recommendations.

**Table 1.** Some physical and chemical properties of the surface soil of the experimental sites in the three wheat seasons during 2017–2020

Experiment no. and season	Texture <sup>a</sup>	pH <sup>b</sup>	EC <sup>c</sup> dS m <sup>-1</sup>	CaCO <sub>3</sub> <sup>d</sup> , %	Organic matter <sup>e</sup> , %	Available N <sup>f</sup> , mg kg <sup>-1</sup>	Available P <sup>g</sup> , mg kg <sup>-1</sup>	Available K <sup>h</sup> , mg kg <sup>-1</sup>
1, 2017/18	Sandy loam	8.66	5.6	19.5	0.86	61.4	9.5	224
2, 2017/18	Loamy sand	8.37	4.7	23.4	1.51	87.8	10.8	187
3, 2018/19	Sandy loam	8.54	6.2	24.6	0.96	59.3	8.4	231
4, 2018/19	Loamy sand	8.42	5.4	22.8	1.59	87.4	11.2	214
5, 2019/20	Sandy loam	8.48	7.5	21.5	1.22	61.4	9.5	261
6, 2019/20	Loamy sand	8.13	4.1	19.2	1.77	85.7	13.7	176
7, 2019/20	Sandy loam	8.58	8.2	26.4	0.92	52.8	8.4	232
8, 2019/20	Loamy sand	8.23	5.6	18.6	1.37	75.1	11.3	161

a) Using the pipette method (Page *et al.*, 1982); b) Measured in soil paste; c) Electrical conductivity measured in soil paste extract; d) Using calcimeter (Nelson, 1983); e) Walkely and Black (1934); f) Bremner (1965); g) Olsen *et al.* (1954); h) Pratt (1965).

## Materials and Methods

### Experimental sites

Eight field experiments on wheat were carried out during three winter seasons (2017/18 to 2019/20) in the West of Delta, Egypt. Experiments 1, 3, 5 and 7 were conducted at the Mariout Research Station Farm of the Desert Research Center (31° 0' 12.2" N, 29° 47' 3.0" E), located about 200 km away from Cairo. Experiments 2, 4, 6 and 8 were conducted at an on-farm location (30° 48' 11.7" N, 29° 44' 59.8" E), about 22 km away from the Mariout Research Station. Average rainfall in this area is 180 mm year<sup>-1</sup> and it is received mainly in winter. In winter, mean temperature ranged between 10 and 20 °C. Wheat cultivation in the study area is carried out using surface irrigation. From all the experimental sites, soil samples from 0 to 0.15 m depth were collected before seeding of wheat and analyzed for different characteristics (Table 1).

### Treatments and experimental design

To create plots with a range in yield potential and soil N supply, field experiments were conducted at two locations and in two wheat seasons (Experiments 1 and 2 in 2017/18 and Experiments 3 and 4 in 2018/19), with treatments consisting of an increasing rate of fertilizer N from 0 to 320 kg ha<sup>-1</sup> applied as ammonium nitrate in doses completed at least 10 days preceding Feekes 6 growth stage. These experiments were used to generate data to establish strategies for field-specific fertilizer N application using atLeaf meter and LCC.

In the 2019/20 wheat season, four experiments were carried out at two locations to validate the established model in this study based on atLeaf meter and threshold scores based on LCC. In the two atLeaf meter experiments (Experiment 5 and 6), besides a no-N control and 250 kg N ha<sup>-1</sup> applied in three split doses (the standard recommendation), four treatments consisted of applying (i) 100 kg N ha<sup>-1</sup> (40 kg N ha<sup>-1</sup> at 10 DAS and 60 kg N ha<sup>-1</sup> at 30 DAS), (ii) 80 kg N ha<sup>-1</sup> either at 10 DAS or (iii) at 30 DAS and (iv) no prescriptive fertilizer N followed by applying an adjustable dose at Feekes 6 stage using atLeaf meter (Table 2). Also, an N-sufficient plot was maintained by applying 350 kg N ha<sup>-1</sup> in both the experiments to ensure that N in this plot is not limited.

In LCC experiments (Experiments 7 and 8), the two adjustable sets consisted of application of 120, 80 or 0 kg N ha<sup>-1</sup> and 150, 100 or 0 kg N ha<sup>-1</sup> at Feekes 6 stage corresponding to leaf greenness equal to or less than LCC score 4, between 4 and 5 and equal to or more than 5, respectively. Before applying each of the two LCC-guided treatments at Feekes 6 stage, different doses were applied at early stages to create variability and to define the optimum prescriptive N management (Table 3). Besides these treatments, control and the standard recommendation were also included. The treatments in the experiments were organized in a randomized complete block design replicated three times.

**Table 2.** Wheat grain yields, total N uptake and N use efficiency as influenced by field-specific fertilizer nitrogen management treatments based on atLeaf meter

Treatment	10 DAS <sup>a</sup> kg N ha <sup>-1</sup>	30 DAS kg N ha <sup>-1</sup>	atLeaf reading jointing <sup>b</sup>	Adjustable dose <sup>c</sup> kg N ha <sup>-1</sup>	Total amount of N fertilizer kg N ha <sup>-1</sup>	Grain yield kg ha <sup>-1</sup>	Total N uptake kg ha <sup>-1</sup>	RE <sub>N</sub> <sup>d</sup> %	AE <sub>N</sub> <sup>e</sup> kg grain kg <sup>-1</sup> N
Experiment 5									
T1 (zero-N)	0	0	–	0	0	3157 c	90.0 c	–	–
T2 (standard recommendation)	83.3	83.3	–	83.3 (fixed)	250	8276 a	227.6 a	55.0 b	20.5 c
T3	40	60	53.9	106	206	8205 a	225.6 a	66.0 a	24.5 a
T4	80	0	51.7	199	279	8372 a	230.2 a	50.4 c	18.7 d
T5	0	80	52.6	161	241	8193 a	225.3 a	56.3 b	20.9 b
T6	0	0	48.9	317	317	7176 b	197.3 b	33.9 d	12.7 e
Experiment 6									
T1 (zero-N)	0	0	–	0	0	3789 d	120.6 e	–	–
T2 (standard recommendation)	83.3	83.3	–	83.3 (fixed)	250	9468 b	260.4 ab	55.9 c	22.7 d
T3	40	60	53.2	80	180	9369 b	246.4 c	69.8 a	31.0 a
T4	80	0	52.3	118	198	9468 b	255.6 b	68.1 ab	28.7 b
T5	0	80	51.8	139	219	9831 a	265.4 a	66.0 b	27.5 c
T6	0	0	48.8	266	266	7874 c	216.5 d	36.1 d	15.4 e

<sup>a</sup>DAS = days after seeding.

<sup>b</sup>atLeaf values in N-sufficient plot were 56.4 and 55.1 in Experiments 5 and 6, respectively.

<sup>c</sup>Adjustable dose is based on the developed model of atLeaf sensor in treatments 3–6.

<sup>d</sup>RE<sub>N</sub> = recovery efficiency of N.

<sup>e</sup>AE<sub>N</sub> = agronomic efficiency of N.

Critical differences between means were detected by Duncan's multiple range test (DMRT) at  $p < 0.05$ .

**Table 3.** Wheat grain yields, total N uptake and N use efficiency as influenced by field-specific fertilizer nitrogen management treatments based on leaf colour chart

Treatment	10 DAS <sup>a</sup> (kg N ha <sup>-1</sup> )	30 DAS (kg N ha <sup>-1</sup> )	LCC score at jointing	Adjustable dose (kg N ha <sup>-1</sup> ) <sup>b</sup>	Total amount of N fertilizer (kg N ha <sup>-1</sup> )	Grain yield kg ha <sup>-1</sup>	Total N uptake kg ha <sup>-1</sup>	RE <sub>N</sub> <sup>c</sup> %	AE <sub>N</sub> <sup>d</sup> kg grain kg <sup>-1</sup> N
Experiment 7									
T1 (zero-N)	0	0	–	0	0	2746 g	81.0 h	–	–
T2 (standard recommendation)	83.3	83.3	–	83.3	250	7541 c	199.8 c	47.5 f	19.2 i
T3	40	60	4.5	80	180	7495 c	198.6 cd	65.3 d	26.4 f
T4	40	60	4.5	100	200	8169 a	216.5 a	67.7 c	27.1 e
T5	80	0	4.0	80	160	7444 c	194.8 d	71.1 a	29.4 b
T6	80	0	4.0	100	180	7734 b	205.0 b	68.9 bc	27.7 c
T7	0	80	4.0	80	160	6767 e	179.3 f	61.5 e	25.1 g
T8	0	80	4.0	100	180	7154 d	189.6 e	60.3 e	24.5 h
T9	0	0	3.0	120	120	6379 f	165.7 g	70.6 ab	30.3 a
T10	0	0	3.0	150	150	6864 e	181.9 f	67.3 cd	27.5 d
Experiment 8									
T1 (zero-N)	0	0	–	0	0	3389 h	102.5 g	–	–
T2 (standard recommendation)	83.3	83.3	–	83.3	250	8422 a	223.2 a	48.3 e	20.1 h
T3	40	60	5.0	0	100	6777 e	170.6 e	68.1 ab	33.9 b
T4	40	60	5.0	0	100	6877 e	172.2 e	69.7 a	34.9 a
T5	80	0	4.5	80	160	7176 d	187.8 d	53.3 d	23.7 f
T6	80	0	4.5	100	180	7575 c	200.7 c	54.6 d	23.3 g
T7	0	80	4.5	80	160	7874 b	208.7 b	66.3 bc	28.0 d
T8	0	80	4.5	100	180	8322 a	220.5 a	65.6 c	27.4 e
T9	0	0	4.0	80	80	6080 g	158.0 f	69.3 a	33.6 b
T10	0	0	4.0	100	100	6478 f	171.7 e	69.2 ab	30.9 c

<sup>a</sup>DAS = days after seeding.<sup>b</sup>Treatments # 3, 5, 7 and 9 are based on application of 120, 80 or 0 kg N ha<sup>-1</sup> at leaf greenness equal to or less than LCC score 4, between 4 and 5, and equal to or more than 5. Treatments # 4, 6, 8 and 10 are based on application of 150, 100 or 0 kg N ha<sup>-1</sup> at leaf greenness equal to or less than LCC score 4, between 4 and 5, and equal to or more than 5<sup>c</sup>RE<sub>N</sub> = recovery efficiency of N.<sup>d</sup>AE<sub>N</sub> = agronomic efficiency of N.Critical differences between means were detected by Duncan's multiple range test (DMRT) at  $p < 0.05$ .

Experimental fields were ploughed, levelled and divided into 15 m<sup>2</sup> plots. Wheat variety Giza 171 was sown by hand in early November in all the experiments. Phosphorus (50 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> as single superphosphate) and potassium (50 kg K<sub>2</sub>O ha<sup>-1</sup> as potassium sulphate) fertilizers were applied. When required, weeds and diseases were controlled following the standard recommendations in the region. The standard recommendations in this region for wheat were obtained from the advisory manual of the Egyptian Ministry of Agriculture and Land Reclamation (<http://www.vercon.sci.eg/extpub/NeperWheat.htm>).

### Measurements of atLeaf meter and LCC

The atLeaf chlorophyll meter (FT Green LLC<sup>®</sup>, Wilmington, DE, USA) used in this study estimates light transmittance through the measured leaf at two different wavelengths (660 and 940 nm) and generates an index expressing the status of chlorophyll content. The topmost fully expanded leaf was used to collect the atLeaf readings by inserting the middle portion of the leaf in the slit of the meter. The six scores LCC manufactured as per specifications of IRRI (1996) was used in this study. The first fully expanded leaf was matched with the scores on the LCC. Measurements with atLeaf meter and LCC were recorded from 10 to 20 plants in each plot and mean values were calculated. The measurements were collected at 50–55 DAS (Feekes 6 growth stage). Abnormally looking or disease-affected plants were avoided for measurements with atLeaf meter and LCC.

### Plant sampling and analysis

Wheat crop was picked manually from an area of 6 m<sup>2</sup> in the center of different plots. The collected biomass was separated into grain and straw and weighed. Samples were collected, dried in an oven at about 70 °C to a stable weight and ground for further analysis. Total N content was determined using the micro-Kjeldahl method (Kalra, 1997) after digesting the samples in H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O<sub>2</sub> mixture.

### Data analysis

Calculations and fitting curves in this study were performed using EXCEL (Microsoft Office 2016). Analysis of variance (ANOVA) was carried out on the data generated from the validation experiments to interpret the results. Duncan's test at probability level <0.05 was used for detecting the critical differences between means (Gomez and Gomez, 1984). Nitrogen use efficiency expressed as apparent recovery (RE<sub>N</sub>) and agronomic (AE<sub>N</sub>) efficiencies were computed as per the following equations (Cassman *et al.*, 1998):

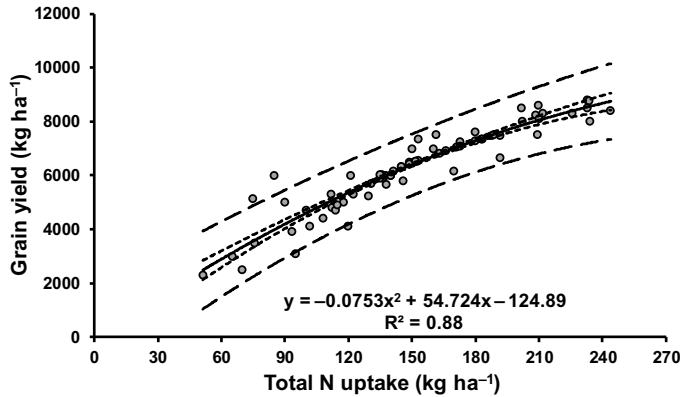
$$RE_N(\%) = \frac{\text{Total N uptake in fertilized plot} - \text{Total N uptake in control N plot}}{\text{Quantity N fertilizer applied}}$$

$$AE_N (\text{kg grain kg}^{-1} \text{ N}) = \frac{\text{Grain yield in N fertilized plot} - \text{Grain yield in control N plot}}{\text{Quantity N fertilizer applied}}$$

## Results

### Establishment of fertilizer N management strategies using atLeaf meter and LCC

Application of different fertilizer N rates in Experiments 1–4 generated a high degree of variability in atLeaf meter and LCC measurements collected at Feekes 6 stage and grain yield and total N uptake at maturity. Grain yield responded to N uptake following a second-degree regression model (Figure 1). The curve flattened at 9818 kg ha<sup>-1</sup> (computed through derivation analysis)



**Figure 1.** Grain yield and total N uptake by wheat fitted to a second-degree regression model. The confidence and prediction intervals at 95% level are the dashed lines near and far the regression solid line, respectively.

with total N uptake of 363 kg N ha<sup>-1</sup>. Economic yield, defined as 90% of maximum, was found to be 8836 kg ha<sup>-1</sup> and it was achievable at total N uptake of 250 kg N ha<sup>-1</sup>.

The difference in atLeaf measurements collected at Feekes 6 stage from the N-sufficient plot and the test plot was plotted against the difference in optimum total N uptake (uptake at 250 kg fertilizer N ha<sup>-1</sup> considered as optimum) and the N uptake in test plot at maturity. As shown in Figure 2, a linear relation forced through the origin ( $y = bx$ ) was obtained with  $R^2$  value of 0.69. In this model, the intercept was purposely dropped under the assumption that there is no need to apply fertilizer N when atLeaf value in test plot is equal to that in N-sufficient plot. The difference in atLeaf measurements can then predict N uptake to be compensated to achieve target N uptake for optimum grain yield. However, some of the applied fertilizer N will be lost, then an efficiency factor of 0.6 was used as suggested by Morris *et al.* (2006). Thus, the functional model to predict fertilizer N applications at Feekes 6 stage of wheat, as inferred from Figure 2, can be written as:

$$N \text{ Fertilizer dose (kg ha}^{-1}\text{)} = \frac{(\text{atLeaf value in the N sufficient plot} - \text{atLeaf value in test plot}) \times 25.352}{0.6}$$

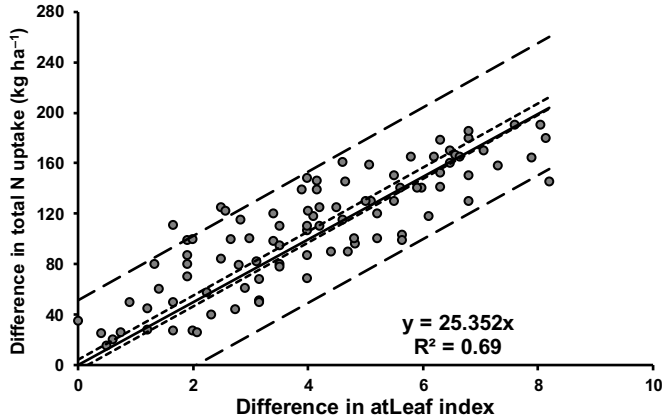
It can also be summarized by dropping the divider as:

$$N \text{ Fertilizer dose (kg ha}^{-1}\text{)} = (\text{atLeaf value in the N sufficient plot} - \text{atLeaf value in test plot}) \times 42.25$$

The LCC scores recorded at Feekes 6 stage were pooled for all locations and seasons. The median value of LCC scores was 4.5, the interquartile range was 4.2–4.8 and 1.5 times the interquartile range was 4–5. It therefore suggests that wheat may respond to fertilizer N when applied at leaf greenness equivalent to LCC scores between 4 and 5. However, when the leaf greenness approaches to LCC score 4, high amount should be required to achieve optimum yield levels, as well as fertilizer N application may be omitted at leaf greenness equivalent to LCC score 5.

### **Fine-tuning of fertilizer N application using atLeaf meter**

Different fertilizer N management scenarios (as shown in Table 2) greatly influenced the atLeaf meter reading and thus the adjustable atLeaf meter-guided N dose at Feekes 6 stage. The doses of fertilizer N as determined from the atLeaf meter reading following the model developed in this study ranged from 106 to 317 kg N ha<sup>-1</sup> in Experiment 5 and 80 to 266 kg N ha<sup>-1</sup> in Experiment 6. In the Experiment 5, the mean grain yields in different treatments based on atLeaf meter-guided N doses ranged between 7176 and 8372 kg ha<sup>-1</sup>, whereas in Experiment 6, this range was 7874 and



**Figure 2.** Relationship between the difference in atLeaf index (atLeaf meter reading in the N-sufficient plot minus atLeaf meter reading in test plots) at jointing stage of wheat and the difference in total N uptake between optimum (N uptake taken as 250 kg N ha<sup>-1</sup>) and that in the test plots fitted to linear regression model forced through the origin. The dashed lines near and far the regression solid line show confidence and prediction intervals at 95% level, respectively.

9831 kg ha<sup>-1</sup>. In both the experiments, when no prescriptive fertilizer N dose was applied (T6), as expected the atLeaf meter-guided fertilizer N dose was the highest (Table 2). Among the four field-specific N management treatments, the application of total as well as atLeaf meter adjustable dose was the least in T3 in which 40 and 60 kg N ha<sup>-1</sup> were applied at 10 and 30 DAS, respectively, before applying the adjustable dose. However, the grain yield in this treatment was statistically similar to that recorded with applying 250 kg N ha<sup>-1</sup> in three splits; the total fertilizer N applied in T3 was only 206 and 180 kg N ha<sup>-1</sup> in Experiments 5 and 6, respectively. When 80 kg N ha<sup>-1</sup> was applied as the prescriptive dose either at 10 DAS (T4) or at 30 DAS (T5), the yields were either at par (Experiment 5) or higher (in Experiment 6) than the yield obtained by following the standard recommendation but at the cost of applying higher amount than in T3.

As both the fertilizer N use efficiency measures – agronomic and recovery efficiencies are determined by yield, N uptake and the quantity of fertilizer N, the statistically highest values of both the measures were observed for the T3 (Table 2). It was true in both Experiments 5 and 6 conducted at two different sites. By following field-specific N management strategy using atLeaf meter, increase of 11% RE<sub>N</sub> and 4 kg grain kg<sup>-1</sup> N AE<sub>N</sub> in Experiment 5 and 13.9% RE<sub>N</sub> and 8.3 kg grain kg<sup>-1</sup> N AE<sub>N</sub> in Experiment 6 were observed over the values recorded for the standard fertilizer recommendation treatment.

### **Fine-tuning of fertilizer N application using LCC**

The results of the performance of the LCC threshold scores proposed in this study for fertilizer N management are shown in Table 3. In Experiment 7, the highest grain yield level was recorded when 40 and 60 kg N ha<sup>-1</sup> were applied at 10 and 30 DAS, respectively, as prescriptive doses followed by applying an LCC-guided dose following the criteria of applying 150, 100 or 0 kg N ha<sup>-1</sup> based on LCC scores to be equal to or less than 4, between 4 and 5 or equal to or more than 5 (T4). Even when fertilizer N doses for the same LCC thresholds were 120, 80 and 0 (T3), the grain yield was statistically similar to that obtained by following the standard recommended dose of 250 kg N ha<sup>-1</sup>. In T3 and T4, 180 and 200 kg N ha<sup>-1</sup> were applied, respectively. Interestingly, in Experiments 5 and 6 also, the best treatments based on atLeaf meter-guided field-specific N management used almost similar amounts of total N (Table 2). Application of an adjustable dose at the Feekes 6 stage following the two LCC-based criteria along with application of 80 kg N ha<sup>-1</sup> at 10



DAS (T5 and T6), grain yields obtained were statistically equal to or more than that recorded in the standard recommendation treatment.

The data pertaining to total N uptake in different experiments, in general, followed the trend in grain yield. Thus, apparent N recovery and agronomic efficiency measures following field-specific N management using LCC resulted in increase of 20.2% RE<sub>N</sub> and 7.9 kg grain kg<sup>-1</sup> N AE<sub>N</sub> in Experiment 7 (T4) and 17.3% RE<sub>N</sub> and 7.3 kg grain kg<sup>-1</sup> N AE<sub>N</sub> in Experiment 8 (T8) over the values recorded for the general recommendation (T2) (Table 3).

## Discussion

Wide difference in the amount of atLeaf-guided doses convincingly proves the usefulness of the field-specific N management strategy developed in this study. Obviously, smaller atLeaf meter-guided dose of fertilizer N in Experiment 6 than in Experiment 5 was due to the difference in the soil N supplying capacity at the two field sites. The soil at the site where Experiment 6 was conducted contained 1.77% organic matter as compared to 1.22% in the soil at the site of Experiment 5 (Table 1). It further proves the efficacy of the developed model in guiding field-specific fertilizer N applications in wheat.

Applying fertilizer N whenever chlorophyll meter reading is less than a prescribed absolute value or a sufficiency index (ratio of measurements in the test plot and the N-sufficient strip) are the two mainly used approaches using chlorophyll meters (Bijay-Singh and Ali, 2020). However, in crops like wheat, in which fertilizer N is applied at certain stages, application of fixed prescriptive fertilizer N doses interferes with the field-specific N management decisions made following these two strategies thereby leading to suboptimal total fertilizer N application doses. The functional model as developed in this study provides an effective, dynamic and simple way for field-specific fertilizer N applications. For instance, following the relative sufficiency index approach with threshold value of 0.95 [(atLeaf value in test plot)/(atLeaf value in N sufficient plot)] as extensively used in previous studies, application of fertilizer N at Feekes 6 stage would have been completely skipped in T3 in both Experiments 5 and 6 (Table 2). Also, the sufficiency index approach would have guided application of a similar rate of fertilizer N in T4 and T5, despite a variation in the need of fertilizer N in these treatments.

In the LCC-based field-specific N management strategy as developed in the present study, criterion for determining fertilizer N allows application of discrete amounts of fertilizer N as per leaf greenness. For example, if the LCC score is equal to or more than shade 5, no fertilizer is to be applied. But if it is just less than shade, the LCC strategy recommends application of 80 or 100 kg N ha<sup>-1</sup>, which makes a big difference in the performance of the crop. Looking at the data listed in Table 3 for Experiment 8, it is revealed that in T3 and T4, due to application of 100 kg N ha<sup>-1</sup> up to 30 DAS, leaf greenness was just equal to LCC shade 5 and decision was made for not application of any fertilizer N at Feekes 6 stage. As a result, total fertilizer N applied in these treatments was 100 kg N ha<sup>-1</sup> and accordingly was the performance of the crop. The highest yield was recorded in the treatment based on standard fertilizer recommendation (Table 3). Thus, data from only Experiment 7 were used to draw conclusions about the validity of LCC-based strategy for field-specific N management in wheat.

On an overall basis, results of Experiments 7 and 8 indicate that wheat has a noteworthy ability to respond to fertilizer N applied at Feekes 6 stage. Also in LCC-based application, applying 150 and 100 kg N ha<sup>-1</sup> at Feekes 6 stage (T4, T6, T8 and T10) gives better results than 120 and 80 kg N ha<sup>-1</sup>. Bijay-Singh *et al.* (2002, 2013) and Varinderpal-Singh *et al.* (2012) convincingly revealed that applying moderate doses of fertilizer N for wheat at seeding and Feekes 2 followed by adjustable dose at Feekes 6 performed better than the standard recommendation. In the present study, application of 100 kg N ha<sup>-1</sup> in two doses prior to applying an adjustable dose guided by leaf greenness measured by LCC at Feekes 6 stage was found to be the appropriate strategy of management. This is supported

by the fact that N uptake in wheat proceeds very slow at early growth stages and N flux increases to a maximum around Feekes 6 growth stage (Doerge *et al.*, 1991; Shukla *et al.*, 2004; Tian *et al.*, 2018).

## Conclusions

The standard or general recommendation of fertilizer N consisting of applying a fixed rate for large areas is not optimum to achieve high N use efficiency in wheat in coarse textured calcareous soils in Egypt. Applying an adjustable field-specific dose at Feekes 6 stage using atLeaf- and LCC-based schemes can result in grain yields comparable to those obtained with standard recommendation but with less quantities of fertilizer N. The atLeaf meter-based strategy provides continuous range of adjustable fertilizer N doses so that fertilizer needs of the crop are determined more precisely than LCC-based strategy which recommends discrete fertilizer N doses. These field-specific N management strategies as developed and validated in this study should be readily acceptable with farmers as these are based on one time measurements and fertilizer N decisions can be made with simple calculations.

**Acknowledgments.** This research work was conducted as part of the project 'Nitrogen Fertilizer Optimization Technologies for Wheat in Newly Reclaimed Lands (Grant 25447)' funded by the Science and Technology Development Fund (STDF), Egypt. We acknowledge the support of the STDF.

## References

- Alam M.M., Ladha J.K., Rahman Z., Khan S.R., Khan A.H. and Buresh R.J. (2006). Nutrient management for increased productivity of rice-wheat cropping system in Bangladesh. *Field Crops Research* **96**(2–3), 374–386.
- Ali A.M. (2020). Development of an algorithm for optimizing nitrogen fertilization in wheat using GreenSeeker proximal optical sensor. *Experimental Agriculture* **56**(5), 688–698.
- Ali A.M., Ibrahim S. and Fawy H. (2017). Soil-Based Technique for Managing Nitrogen Fertilization in Wheat in some Desert Soils at West Nile Delta, Egypt. *Alexandria Science Exchange Journal* **38**, 699–706.
- Ali A.M., Ibrahim S.M. and Singh B. (2020). Wheat grain yield and nitrogen uptake prediction using atLeaf and GreenSeeker portable optical sensors at jointing growth stage. *Information Processing in Agriculture* **7**(3), 375–383.
- Ali A.M., Thind H.S., Sharma S. and Singh Y. (2015). Site-specific nitrogen management in dry direct-seeded rice using chlorophyll meter and leaf colour chart. *Pedosphere* **25**(1), 72–81.
- Basyouni R., Dunn B.L. and Goad C. (2015). Use of nondestructive sensors to assess nitrogen status in potted poinsettia (*Euphorbia pulcherrima* L.(Willd. ex Klotzsch)) production. *Scientia Horticulturae* **192**, 47–53.
- Benincasa P., Antognelli S., Brunetti L., Fabbri C.A., Natale A., Sartoretti V., Modeo G., Guiducci M., Tei F. and Vizzari M. (2017). Reliability of NDVI derived by high resolution satellite and UAV compared to in-field methods for the evaluation of early crop N status and grain yield in wheat. *Experimental Agriculture* **54**(4), 604–622.
- Bijay-Singh, Singh V., Singh Y., Thind H.S., Choudhary O.P., Gupta R.K. and Vashistha M. (2013). Supplementing fertilizer nitrogen application to irrigated wheat at maximum tillering stage using chlorophyll meter and optical sensor. *Agricultural Research* **2**(1), 81–89.
- Bijay-Singh, Singh Y., Ladha J.K., Bronson K.F., Balasubramanian V., Singh J. and Khind C.S. (2002). Chlorophyll meter-and leaf color chart-based nitrogen management for rice and wheat in Northwestern India. *Agronomy Journal* **94**(4), 821–829.
- Bijay-Singh (2018). Are nitrogen fertilizers deleterious to soil health? *Agronomy* **8**(4), 48.
- Bijay-Singh and Ali A.M. (2020). Using hand-held chlorophyll meters and canopy reflectance sensors for fertilizer nitrogen management in cereals in small farms in developing countries. *Sensors* **20**(4), 1127.
- Bijay-Singh, Sharma R.K., Jat M.L., Martin K.L., Chandna P., Choudhary O.P., Gupta R.K., Thind H.S., Uppal H.S., Khurana H.S., Uppal R.K. and Vashistha M. (2011). Assessment of the nitrogen management strategy using an optical sensor for irrigated wheat. *Agronomy for Sustainable Development* **31**(3), 589–603.
- Bijay-Singh, Singh V., Singh Y., Kumar A., Sharma S., Thind H.S., Choudhary O.P. and Vashistha M. (2018). Site-specific fertilizer nitrogen management in irrigated wheat using chlorophyll meter (SPAD meter) in the north-western India. *Journal of the Indian Society of Soil Science* **66**, 53–65.
- Bijay-Singh, Singh V. and Ali A.M. (2020). Site-specific fertilizer nitrogen management in cereals in South Asia. *Sustainable Agriculture Reviews* **39**, 137–178.
- Bojović B. and Marković A. (2009). Correlation between nitrogen and chlorophyll content in wheat (*Triticum aestivum* L.). *Kragujevac Journal of Science* **31**(5827), 69–74.

- Bremner J.T.** (1965). *Inorganic forms of nitrogen. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, Agronomy Monographs 9*. Madison (WI): American Society of Agronomy, pp. 1179–1237.
- Cassman K.G., Dobermann A., Walters D.T. and Yang H.** (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources* **28**(1), 315–358.
- Cassman K.G., Peng S., Olk D.C., Ladha J.K., Reichardt W., Dobermann A. and Singh U.** (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research* **56**(1–2), 7–39.
- Diacono M., Rubino P. and Montemurro F.** (2013). Precision nitrogen management of wheat. A review. *Agronomy for Sustainable Development* **33**(1), 219–241.
- Doerge T.A., Roth R.L. and Gardner B.R.** (1991). *Nitrogen Fertilizer Management in Arizona*. Tucson, Arizona: College of Agric, University of Arizona, p. 87.
- Dunn B.L., Singh H., Payton M. and Kincheloe S.** (2018). Effects of nitrogen, phosphorus, and potassium on SPAD-502 and atLEAF sensor readings of Salvia. *Journal of Plant Nutrition* **41**(13), 1674–1683.
- Fageria N.K. and Baligar V.C.** (2005). Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy* **88**, 97–185.
- Gomez K.A. and Gomez A.A.** (1984). *Statistical Procedures for Agricultural Research*. Hoboken, NJ: John Wiley & Sons.
- Hussain F., Zia M.S., Akhtar M.E. and Yasin M.** (2003). Nitrogen management and use efficiency with chlorophyll meter and leaf colour chart. *Pakistan Journal of Soil Science* **22**, 1–4.
- IAEA** (2000). *Optimizing nitrogen fertilizer application in irrigated wheat: Results of a co-ordinated research project organized by the joint FAP/IAEA Division of Nuclear Techniques in Food and Agriculture 1994–1998, IAEA TECDOC-1164*. Vienna, Austria: International Atomic Energy Agency, p. 245.
- IRRI** (1996). *Use of Leaf Color Chart (LCC) for N Management in Rice Crop Resource Management Network Technology Brief No. 1*. Manila, Philippines: International Rice Research Institute.
- Islam M.R., Haque K.S., Akter N. and Karim M.A.** (2014). Leaf chlorophyll dynamics in wheat based on SPAD meter reading and its relationship with grain yield. *Scientia Agriculturae* **8**(1), 13–18.
- Kalra Y.** (1997). *Handbook of Reference Methods for Plant Analysis*. Boca Raton, FL: CRC Press.
- Ladha J.K., Pathak H., Krupnik T.J., Six J. and van Kessel C.** (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy* **87**, 85–156.
- Maiti D. and Das D.K.** (2006). Management of nitrogen through the use of Leaf Colour Chart (LCC) and Soil Plant Analysis Development (SPAD) in wheat under irrigated ecosystem: (Stickstoffbemessung mittels Blattfärbungstabelle (LCC) und analyse der Boden-Pflanze Entwicklung (SPAD) in Bewässerungs-Weizen Ökosystemen). *Archives of Agronomy and Soil Science* **52**(1), 105–112.
- Morris K.B., Martin K.L., Freeman K.W., Teal R.K., Girma K., Arnall D.B., Hodgen P.J., Mosali J., Raun W.R. and Solie J.B.** (2006). Mid-season recovery from nitrogen stress in winter wheat. *Journal of Plant Nutrition* **29**(4), 727–745.
- Nelson R.E.** (1983). *Carbonate and gypsum. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. Madison (WI): Agronomy Monographs 9, American Society of Agronomy, p. 181–197.
- Olsen S.R.** (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939)*. Washington, DC: U.S. Department of Agriculture.
- Omara P., Aula L., Oyebiyi F. and Raun W.R.** (2019). World cereal nitrogen use efficiency trends: Review and current knowledge. *Agrosystems, Geosciences & Environment* **2**(1), 1–8.
- Page A.L., Miller R.H. and Keeney D.R.** (1982). *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 2nd Edn. Madison, Wisconsin, USA: American Society of Agronomy.
- Peng S., Buresh R.J., Huang J., Zhong X., Zou Y., Yang J., Wang G., Liu Y., Hu R., Tang Q. and Cui K.** (2010). Improving nitrogen fertilization in rice by sitespecific N management: A review. *Agronomy for Sustainable Development* **30**(3), 649–656.
- Pratt P.F.** (1965). *Potassium. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. Madison (WI): Agronomy Monographs 9, American Society of Agronomy, pp. 1022–1030.
- Raun W.R., Dhillion J., Aula L., Eickhoff E., Weymeyer G., Figueirde B., Lynch T., Omara P., Nambi E., Oyebiyi F. and Fornah A.** (2019). Unpredictable nature of environment on nitrogen supply and demand. *Agronomy Journal* **111**(6), 2786–2791.
- Raun W.R., Solie J.B., Johnson G.V., Stone M.L., Lukina E.V., Thomason W.E. and Schepers J.S.** (2001). In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy Journal* **93**(1), 131–138.
- Schepers J.S., Francis D.D., Vigil M. and Below F.E.** (1992). Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. *Communications in Soil Science and Plant Analysis* **23**(17–20), 2173–2187.
- Shukla A.K., Ladha J.K., Singh V.K., Dwivedi B.S., Balasubramanian V., Gupta R.K., Sharma S.K., Singh Y., Pathak H., Pandey P.S. and Padre A.T.** (2004). Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. *Agronomy Journal* **96**(6), 1606–1621.
- Tian Z.W., Liu X.X., Gu S.L., Yu J.H., Zhang L., Zhang W.W., Jiang D., Cao W.X. and Dai T.B.** (2018). Postponed and reduced basal nitrogen application improves nitrogen use efficiency and plant growth of winter wheat. *Journal of Integrative Agriculture* **17**(12), 2648–2661.

- Varinderpal-Singh, Singh B., Singh Y., Thind H.S. and Gupta R.K.** (2010). Need based nitrogen management using the chlorophyll meter and leaf colour chart in rice and wheat in South Asia: a review. *Nutrient Cycling in Agroecosystems* **88**(3), 361–380.
- Varinderpal-Singh, Singh B., Singh Y., Thind H.S., Buttar G.S., Kaur S., Kaur S. and Bhowmik A.** (2017). Site-specific fertilizer nitrogen management for timely sown irrigated wheat (*Triticum aestivum* L. and *Triticum turgidum* L. ssp. durum) genotypes. *Nutrient Cycling in Agroecosystems* **109**(1), 1–16.
- Varinderpal-Singh, Singh B., Singh Y., Thind H.S., Singh G., Kaur S., Kumar A. and Vashistha M.** (2012). Establishment of threshold leaf colour greenness for need-based fertilizer nitrogen management in irrigated wheat (*Triticum aestivum* L.) using leaf colour chart. *Field Crops Research* **130**, 109–119.
- Varinderpal-Singh, Singh Y., Singh B., Thind H.S., Kumar A. and Vashistha M.** (2011). Calibrating the leaf colour chart for need based fertilizer nitrogen management in different maize (*Zea mays* L.) genotypes. *Field Crops Research* **120**(2), 276–282.
- Walkley A. and Black I.A.** (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**(1), 29–38.
- Witt C., Pasuquin J.M.C.A., Mutters R. and Buresh R.J.** (2005). New leaf color chart for effective nitrogen management in rice. *Better Crops* **89**(1), 36–39.
- Zhu J., Tremblay N. and Liang Y.** (2012). Comparing SPAD and atLEAF values for chlorophyll assessment in crop species. *Canadian Journal of Soil Science* **92**(4), 645–648.

---

**Cite this article:** Ali AM, Ibrahim SM, Hassany WM, El-Sadek AN, and Bijay-Singh (2021). Fixed-time corrective dose fertilizer nitrogen management in wheat using atLeaf meter and leaf colour chart. *Experimental Agriculture* **57**, 232–243. <https://doi.org/10.1017/S0014479721000168>