Agric Res J **59** (4) : 583-601, *August* 2022
DOI No. 10.5958/2395-146X.2022.00087.4 ***Review Paper***

LEAF COLOUR CHART: AN INCREDIBLE TOOL FOR FIELD-SPECIFIC MANAGEMENT OF FERTILIZER NITROGEN IN CEREALS IN SOUTH ASIA

Bijay-Singh*

Formerly ICAR National Professor, Department of Soil Science,
Punjab Agricultural University, Ludhiana - 141 004, Punjab

ABSTRACT

Leaf colour chart (LCC) as a tool for field-specific management of fertilizer nitrogen (N) in rice was introduced on a commercial scale in the last decade of 20th century. During last two decades, its use has also been extended to wheat and maize. Many studies have been carried out on LCC-based N management in South Asian countries where farmers apply substantial amount of fertilizer N to cereal crops, but do not strictly follow even the regional blanket fertilizer N recommendations. LCC-based fertilizer N management in cereals leads to improvement in N use efficiency over that observed with blanket recommendation. It is an attempt to review the development of LCCs in South Asia, the modes in which LCC can be used - adjustable time and N dose in real time, fixed time adjustable N dose, and fixed N dose adjustable time, and the results of studies on field-specific LCC-based fertilizer N management carried out on rice, wheat, and maize in different parts of South Asia. By applying fertilizer N as guided by LCC, improvement in N use efficiency is observed either through reduced total amount of applied N, increased yield, or both. Performance of LCC-based site-specific N management at on-farm locations has also been reviewed. Studies providing direct evidence of reduced losses of N to environment due to LCC guided fertilizer N management rather than regional blanket recommendations suggest that LCC is going to be an incredible tool to enhance food security and minimize N related environmental degradation in South Asia.

Keywords: Fertilizer nitrogen, Leaf colour chart, Leaf greenness, Maize, Nitrogen use efficiency, Rice, Site-specific nitrogen management, South Asia

India, Pakistan, Bangladesh, Nepal, and Sri Lanka are the major countries growing cereal crops in South Asia, the region located in the Indo-Gangetic Plains and peninsular India. In 2020, cereal crops were grown in these South Asia countries on an area of 132.94 million ha leading to cereal grain production of 453.91 million tonnes (https://www.fao.org/faostat/en/#data/QCL). The application of nitrogen (N) fertilizers played a key role in achieving high production levels of cereal grains in South Asia. In 2020, 22.66 % of the total fertilizer N consumed globally was used in the five major South Asian countries and most of it was used in cereal crop production (https://www.fao.org/faostat/en/#data/RFN). Fertilizer N use per unit area of the cropland in Bangladesh, India, Nepal, Pakistan, and Sri Lanka in 2020 was 146.4, 121.0, 56.9, 111.4, and 100.2 kg N ha^{-1}, respectively; the global average was 72.9 kg N ha^{-1} (https://www.fao.org/faostat/en/#data/EF). Fertilizer N is generally managed following general recommendations for different crops. But several farmers prefer to apply even more than the general recommendations because they want to remain assured against the limitation of N supply to crops. But in recent years, it is becoming a challenging task to apply fertilizer N as per the need of the crop. While supplying less N leads to the reduced yield of the crops, applying N more than the requirement of the crop does not necessarily increase yield because N can escape the soil-plant system via leaching as nitrate, volatilization as ammonia, and in gaseous form as nitrous oxide resulting in degradation of the environment.

In the late 1960s, the introduction of high-yielding N-responsive cultivars of cereals along with expanded use of fertilizers, irrigation and supportive public policies for agriculture marked the advent of the Green Revolution era in South Asia. As N fertilizers showed the most dramatic effect on crops in terms of both the high yield levels and increasing the greenness of leaves, farmers once convinced with these effects, started applying gradually increasing amounts of fertilizer N to cereal crops. Although during those times emphasis was on producing more food by applying increasing amounts of N fertilizers, it was also realized that excessive use of fertilizer N may lead to nitrate pollution of groundwater (Bijay-Singh and Craswell, 2021). However, the trend of using increasing amounts of fertilizer N in cereals continued and now reports are appearing that long-term application of fertilizer N in amounts more than the need of the crop may also adversely affect health of the soil (Bijay-Singh, 2018). It is now increasingly being realized that to produce cereals fertilizer N will have to

*Corresponding author : bijaysingh20@hotmail.com
Date of receipt: 05.08.2022, Date of acceptance: 31.08.2022

be managed in a way that in each field amount of N is applied as per the need of the crop (Varinderpal-Singh *et al.*, 2010; Bijay-Singh *et al.*, 2020).

Soon after N fertilizers were being applied in substantial amounts to N-responsive high-yielding varieties of cereals, fertilizer N recommendations for rice, wheat, and maize were formulated by averaging data on the response of crops to increasing fertilizer N levels over large geographic areas having similar climate and landforms. Although fertilizer N recommendations are also linked with soil organic carbon content, these are not discrete enough in space and time and consider neither the dynamic changes between different N pools nor the spatial variability in indigenous N supplying capacity of soils. As general recommendations are formulated in such a way that in all the fields in the region fertilizer N is not applied below the optimum level, fertilizer management following general recommendations in many fields in the region leads to the application of N at levels more than the requirement of the crop. Blanket fertilizer N recommendations for rice, wheat, and maize as grown in different parts of South Asia vary from 60 to 150 kg N ha^{-1} applied in 2 or 3 split doses. As N fertilizers are heavily subsidized in most countries in South Asia, many farmers have developed a tendency to apply large doses of N to rice, wheat, and maize to avoid the risk of yield reduction due to deficiency of N. The average fertilizer N recovery efficiency in South Asia has been reported to be 39%, 49%, and 30% for rice, wheat, and maize (Krupnik *et al.,* 2004). Based on data for 2018 as compiled by FAO, Bijay-Singh *et al.* (2022) computed NUE as the proportion of applied N utilized by crops and it was found to be 48%, 35%, and 25% in Bangladesh, India, and Pakistan, respectively.

NUE can be substantially increased by ensuring the application of fertilizer N as per the need of the crop in each field and season. Since the late 1990s, strategies have been formulated and perfected for need-based and site-specific management of fertilizer N in cereals in South Asian countries (Bijay-Singh *et al.*, 2020). As these are based on estimating the N status of the leaves of the growing crop in real time, measurements with gadgets like canopy reflectance sensors, chlorophyll meters and their inexpensive alternative leaf colour charts (LCC) constitute integral components of these strategies. Among these, LCC-based fertilizer N management strategies are becoming popular with common farmers in South Asia as these are easy to follow and because both chlorophyll meters and canopy reflectance sensors are very expensive and neither affordable for common farmers nor easy to use. As blanket fertilizer N management will have to be replaced aggressively with need-based and site-specific N management in the years come, LCC-based strategies are going to become popular with common farmers in South Asia. In the present paper, it has been attempted to review the research carried out in South Asian countries on LCC-based fertilizer N management in rice, wheat, and maize and to discuss how NUE is going to be improved by LCC-guided fertilizer N applications to cereal crops.

Leaf nitrogen status and greenness level in field crops

Leaves are principal plant organs for transforming solar radiation into chemical energy via photosynthesis and supplying remobilized N for the development of green plant biomass (Bailey and Leegood, 2016; Bianculli *et al.*, 2016). In cereal crops, more than 90% of biomass is derived from photosynthetic products (Makino, 2011). The involvement of N in the synthesis of cellular components such as amino acids, proteins, and nucleic acids, and the production of grain yield is mediated through the role of N in chlorophyll and leaf photosynthesis (Kusano *et al.*, 2011, Pradhan *et al.*, 2014). Thus, low chlorophyll content and less green colour of plant leaves, less biomass production, and consequently reduced grain yield and quality are associated with insufficient supply of N (Fageria *et al.*, 2011; Zhao *et al.*, 2005).

Chloroplasts concentrated in the parenchyma cells of the leaf mesophyll contain about 80% of N contained in plant leaves. About half of the N associated with chloroplasts exists in combination with photosynthetic proteins that harvest sunlight (Blackmer and Schepers, 1995; Peng *et al.*, 1995; Xiong *et al.*, 2015). An increase in leaf chlorophyll content in rice with N supply has been reported by Peng *et al.* (1995). As there exists a strong relationship between leaf greenness and leaf chlorophyll content Madeira *et al.* (2000), at any given time, the greenness of the topmost fully expanded leaf of a plant, as defined by its N status, acts as a sensitive indicator of N demand because it is closely related to photosynthetic rate and biomass production (Peng *et al.*, 1996; Buresh, 2007). Thus, leaf greenness has often been used by farmers as an indicator of the N needs of field crops, though in a very subjective manner (Wells and Turner, 1984; Furuya, 1987). Since farmers deal with field-to-field and year-to-year differences in fertilizer N demand and manage variability in N supply within a field, the extent of leaf greenness can serve as a non-destructive method to guide site-specific fertilizer N management in field crops. It can prove helpful in achieving optimum production levels and reduced environmental impacts by avoiding over- and under-application of fertilizer N. However, the greenness of the topmost fully expanded leaf of crop plants cannot be considered like deficiency symptoms of different essential plant nutrients appearing on leaves of different ages on the plant.

Development of leaf colour chart

The purpose of LCC is to provide the user with a range of reference colours from light green to dark green which can be used to quantify leaf greenness objectively through a visual comparison of light reflected from the surface of leaves and the LCC. Therefore, LCC consists of a plastic strip on which are embedded a series of panels with shades of colour covering a continuum of greenness in leaves developed from very low to excessive N supply to crop plants. It was in the mid-1980s that the first LCC was developed in Japan by Fuji Film Co. and was given the name 'Standard rice leaf colour scale' (Furuya, 1987). It consisted of seven panels with light green colour (no. 1) to dark green colour (no. 7) arranged on a plastic sheet. The colour of a leaf was compared with that of panels on the LCC and was expressed by numerical values of 1 to 7 with the minimum unit of 0.5.

In 1996, the International Rice Research Institute (IRRI) developed a six-colour panel LCC. It has been the most widely used LCC in guiding fertilizer N management in rice. To express the magnitude of leaf colour in terms of colour of the LCC panels, the six panels in the LCC have been given numbers 1 to 6 in the increasing order of greenness. In the following years, researchers at IRRI improved the colour of the LCC panels by best matching the spectral reflectance of rice and maize leaves with that of LCC panels and produced a four-panel IRRI-LCC with panels corresponding to shades 2, 3, 4, and 5 in the six-panel IRRI-LCC (Witt *et al.*, 2005). Researchers at Zheijiang Agriculture University (ZAU) in China developed an eight-colour panel ZAU-LCC for managing fertilizer N in Indica, Japonica, and hybrid rice cultivars. By matching the spectral reflectance of rice leaves and panels of LCC, the University of California, Davis (UCD) in the USA also developed an eight-colour panel UCD-LCC for determining leaf greenness and associated leaf N in rice (Yang *et al.*, 2003). In a study carried out by Yang *et al.* (2003), strong correlations (r = 0.93 to 0.99) were observed among scores of leaf greenness in rice plants measured by IRRI-LCC, ZAU-LCC, and UCD-LCC.

In India, during the first decade of the 21st century, four- and six-colour panel IRRI-LCCs were used to develop guidelines on the use of LCCs adjusted to local conditions. Later as LCC-based fertilizer N management protocols were standardized for different rice ecologies and crops like maize and wheat, customized LCCs were introduced in different parts of India. In north-western India, a six-colour panel PAU-LCC developed by researchers in Punjab Agricultural University (PAU), Ludhiana is gaining popularity with farmers as it can be used to estimate leaf greenness and associated N status in transplanted rice, direct seeded rice, wheat, maize, basmati rice, and Bt cotton (Swarbreck *et al.*, 2019). It has been ensured that the spectral reflectance of the panels of PAU-LCC closely matches that of leaves of different field crops. The six-panel PAU-LCC also offers improved precision in measuring the greenness of leaves as panels approximately corresponding to very light green shades 1 and 2 in the six-panel IRRI-LCC have been removed and panels corresponding to shades 3.5 and 4.5 have been introduced in it (Fig. 1). Fertilizer N management with PAU-LCC in different crops sown on different dates is readily facilitated by a multilingual smartphone application '*PAU Urea Guide'* freely available through Play Store in Android phones. The Indian Institute of Rice Research (IIRR) located in Hyderabad introduced a five-colour panel IIRR-LCC that is particularly suited to irrigated rice ecologies. The customized IIRR-LCC has been developed based on the spectral evaluation of leaves of hundreds of irrigated rice varieties. Working on similar lines, researchers in National Rice Research Institute (NRRI) at Cuttack analysed spectral reflectance of several hundred high-yielding, as well as local varieties of rice grown under different ecologies in eastern India and developed the NRRI-LCC. The five-colour panel NRRI-LCC has been developed for use by farmers for site-specific N management in rice in eastern India (Thomas, 2021).

Although the gamut of green colours in different LCCs is visually different, the basic concept in all LCCs is similar - - in that user can compare the leaf greenness with a panel on the LCC to get an estimate

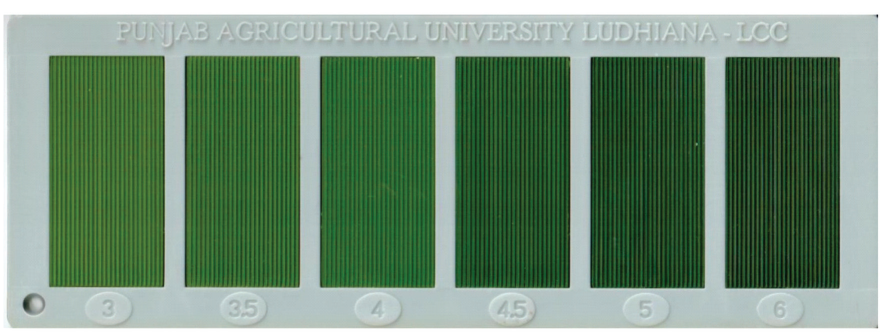

Fig. 1. Six-colour panel leaf colour chart (PAU-LCC) developed by Punjab Agricultural University, Ludhiana, India

of the N supply to the crop plant in the real-time. In all LCCs, the panels with different shades of green are numbered. Higher the number greener the colour of the panel. Nevertheless, in all the LCCs developed by IRRI and in different regions of India and currently in use in South Asia, panels with same number have similar hues of the green. These only differ slightly with respect to saturation (or brightness), which varies with different groups of cultivars of a crop. Thus, for example, panel 4 on different LCCs used in South Asia represents same hue or colour. It is also true for other panels with same number. Therefore, the colour panels with different numbers on LCCs are simply referred to as LCC4, LCC3.5, LCC3 etc. without distinguishing the LCC.

The LCC may not be as accurate as the chlorophyll meter in determining the leaf N status in field crops, but it offers a simple, inexpensive, quick, and non-destructive method for quantifying the changes in the greenness of leaves. The difference between adjacent panels, such as in IRRI-LCC, is equal to 3 to 4 units of SPAD chlorophyll meter. Thus, LCC cannot measure smaller differences in leaf greenness, but field observations indicate that it can still be used to satisfactorily determine the time of fertilizer N topdressing to cereal crops, once the threshold shades on LCC are established for different cultivar groups and crop conditions.

Using LCC for fertilizer N management in field crops

LCCs can be used for practicing site-specific management of fertilizer N in field crops in four different ways.

Real-time approach to adjust time and dose of fertilizer

In crops such as irrigated transplanted rice to which fertilizer N can be applied at any time, LCC can be used to define the time of application as well as fertilizer N dose in real-time. The time of application of fertilizer N doses is dynamically adjusted in response to N demand during the growth period of the crop (Peng *et al.*, 1996). Using LCC, the colour of the most recent fully expanded leaves of crop plants is monitored at 7 to 10-day intervals. The prescribed amount of fertilizer N, generally between 20 and 45 kg N ha^{-1}, is applied when leaf colour falls below a threshold of greenness on the LCC. The threshold LCC score is identified through a set of preliminary experiments for a varietal group in a region. Local guidelines for LCC-based real-time management of fertilizer N in different crops are now available in several regions in South Asia.

Fixed time adjustable dose approach

Using an estimated fertilizer N dose based on yield gain and targeted fertilizer N use efficiency to attain a targeted yield or blanket fertilizer N recommendation designed for a region, a pattern of splitting the total fertilizer N among pre-set application times is followed as per the critical growth stages of the crop, cropping season, crop cultivar used, and crop establishment method. Except at the planting or very early growth stages when plant height and leaf size are small, LCC is used to dynamically adjust the pre-determined N doses in the splitting pattern at critical growth stages of the crop upward or downward based on the colour of the most recent fully expanded leaf and the threshold leaf greenness on the LCC (Witt *et al.*, 2007). The LCC-based adjustment of the split N doses depends upon plant growth and the N requirement of the crop at the growth stage. In this way, the total amount of fertilizer N applied to the crop gets defined as per the field and the cropping season.

Fixed dose adjustable time approach

Total amount of fertilizer N to be applied in the cropping season is reasonably estimated before sowing/planting of the crop. The total fertilizer N is applied in split doses - - some at growths stages of the crop such as basal at sowing/planting and when the crop plants are very small. The time of application of remaining split doses of fertilizer N to be applied at later crop growth stages, is determined in real time based on threshold leaf greenness on the LCC. The threshold LCC scores may sometime differ in early and later crop growth stages.

Dynamic LCC threshold greenness approach

Leaf greenness may vary with crop cultivar and growth stage as well as due to environmental conditions such as temperature, moisture stress and sunlight. For example, if sky remains overcast continuously for several days, leaves of crops like rice tend to become less greenish due to lack of sunshine. Therefore, Bijay-Singh *et al.* (2016) gave the concept of dynamic threshold LCC greenness for each field, soil, crop cultivar and prevailing environment. It involves maintaining a small over-fertilized reference strip in the field and using its LCC reading as a standard for defining threshold leaf greenness for the crop growth stage and season. For rice, dynamic threshold greenness has been defined as 0.5 unit less than the LCC reading of the over-fertilized reference strip (Bijay-Singh *et al.*, 2016). Dynamic adjustment of the threshold leaf greenness on LCC for making fertilizer N application decisions should lead to optimum yields as well as high fertilizer N use efficiency.

Most of the agricultural soils in South Asia have low soil N supplying capacity because the organic matter content in these soils is less than 10 g kg^{-1} soil (Lal, 2004). Although blanket fertilizer N recommendations in different regions of South Asian countries have been formulated to obtain optimum yields of rice, wheat, and maize, these vary from 60 to 150 kg N ha^{-1}. Therefore, LCC-based site-specific N in cereal crops in South Asia has been simplified by moderating the elements of anticipated yield gain and targeted fertilizer N use efficiency to attain the targeted yield. It has been observed that an algorithm or criterion, such as LCC-based real time fertilizer N management, that allows the application of 60 to 150 kg N ha^{-1} in split doses of 25 to 45 kg N ha^{-1} at appropriate times to match the spatial and temporal needs of the crop amounts to site-specific nitrogen management (SSNM) in South Asia (Bijay-Singh *et al.*, 2020). Thus, in South Asia, use of LCC to improve fertilizer N management has been primarily through the real-time approach based on the threshold greenness of leaves of crops as measured by LCC. To develop complete LCC-based site-specific N management strategies for different crops, compatible doses of fertilizer N to be applied at crop growth stages (such as transplanting of rice or planting and crown root initiation of wheat) at which LCC cannot guide fertilizer N application applied need to be determined by one time conducting a series of field experiments before starting LCC-based N management (Bijay-Singh, 2008; Varinderpal-Singh *et al.* 2010, Bijay-Singh and Singh 2017a, b).

LCC-based fertilizer N management in different crops in South Asia

Rice

Real time site-specific nitrogen management using fixed threshold leaf greenness

To practise SSNM in real time in field crops, identifying the threshold greenness of the most recently exposed leaves on LCC constitutes the most important element. In North India, Bijay-Singh *et al.* (2002), Varinderpal-Singh *et al.* (2007), Yadvinder-Singh *et al.* (2007), and Thind *et al.* (2010) found that shade 4 on the LCC or simply LCC4 was the threshold leaf greenness for practising real time SSNM in irrigated rice. Application of a fertilizer N dose (generally 30 kg N ha^{-1} or less) to rice whenever colour of the most recent fully expanded leaves was less than LCC4 resulted in optimum yield levels. In South Indian states where rice is grown both in dry and wet seasons, Porpavai *et al.* (2002) determined that threshold leaf greenness for transplanted rice was equivalent to LCC5 in the wet season and LCC4 in the dry season. Islam *et al.* (2009) determined critical leaf greenness values on LCC as 3.0 and 3.5 for rice grown in Boro and T. Aman seasons in Bangladesh. In Northwest India while Bijay-Singh *et al.* (2006) identified LCC3 as the threshold leaf greenness for direct wet-seeded rice, Ali *et al.* (2015) found that high yields and high fertilizer N use efficiency for direct dry-seeded rice could be obtained with LCC4 as the threshold. For aerobic and basmati rice cultivars and rice grown under rainfed conditions, LCC3 has been identified as the critical greenness level for managing fertilizer N (Jyanthi *et al.*, 2007; Yogendra *et al.*, 2017, Lone *et al.*, 2016; Premalatha, 2017; Shukla et al, 2004). For hybrid rice, fertilizer N management based on threshold greenness equivalent to LCC5 has been found to produce optimum yield and N use efficiency (Shukla *et al.*, 2004; Ravi *et al.*, 2007). Under system of rice intensification (SRI), Bhat *et al.* (2022) found LCC5 as the threshold leaf greenness for field-specific fertilizer N management.

Table 1 lists two categories of fertilizer N management studies in rice conducted in different parts of South Asia using LCC following real time approach. When compared with farmers' fertilizer practice (FFP) or blanket recommendation for the region, in the first category of studies LCC-based N management resulted in similar rice grain yield but with reduced fertilizer N application. Gupta *et al.* (2011) and Sathiya and Ramesh (2009) have reported similar results with hybrid rice and aerobic rice, respectively. In South India, LCC4 based SSNM in direct wet-seeded rice produced yield equal to that with blanket recommendation (Budhar and Tamilselvan 2003, Nachimuthu *et al.* 2007). Jayanthi *et al.* (2007) applied 20 and 30 kg N ha^{-1} applied to rainfed rice whenever leaf colour was less than LCC3 and produced 2.84 and 2.81 t ha^{-1} rice grains with total N application of 80 and 90 kg N ha^{-1}, respectively. On the other hand, application of 100 kg N as blanket recommendation produced only 2.55 t ha^{-1}.

Since LCC-based fertilizer N management is site-specific or field-specific, less fertilizer N application than FFP or blanket fertilizer N recommendation with similar yield level does not mean that it will happen in every field. It only suggests that in the studies listed in Table 1, more fertilizer N was being applied via FFP or blanket recommendation than the need of the crop. However, one must consider that LCC-based N management is not only about amount of fertilizer. The time of application of fertilizer N dose when it is needed by the crop (when leaf greenness falls below the threshold value) can lead to higher yield of crops even with application of total amount of fertilizer N similar to that with FFP or blanket recommendation. Such studies have been listed under second category in Table 1. In these studies, by following LCC-based N management rice yield was higher than that observed with FFP or the recommended dose, but fertilizer N use was equal to or less. Based on LCC4 as the threshold, Thind *et al.* (2010) recorded significantly higher rice grain yield by applying fertilizer N less than the blanket recommendation. However, at another site, yield was same and saving in fertilizer N application only was observed when compared with

Table 1. Comparison of leaf color chart (LCC)-based site-specific fertilizer N management with farmers fertilizer practice (FFP) or blanket recommendations (REC) in rice¶ in South Asia

Region, year, critical LCC shade, number of farms	N used, kg N ha^{-1}		Grain yield, t ha^{-1}		AE_N‡, kg grain kg N^{-1}		PFP_N‡, kg grain kg N^{-1}		Reference
	FFP/ REC†	LCC	FFP/ REC	LCC	FFP/ REC	LCC	FFP/ REC	LCC	
Same grain yield with reduced fertilizer N application following real time approach									
India, Haryana, LCC4, 165	149	124	6.36a	6.37a	-	-	43	51	Balasubramanian *et al*. (2003)
India, Punjab, LCC4, 107	153	113	6.0a	6.0a	-	-	39	53	Varinderpal-Singh *et al*. (2007)
India, Punjab, LCC4, 48	115	91	6.5a	6.5a	-	-	57	71	
India, Punjab, LCC4, 53	134	100	8.1a	8.2a	-	-	61	82	
India, Punjab, LCC4, 142	145	107	7.0a	7.1a	-	-	48	66	
India, Jammu & Kashmir, LCC3, 1	120	90	7.15a	7.01a	20.5a	31.3b	60a	78b	Bhat *et al*. (2015)
India, West Bengal, LCC4, 1	100	63	4.47a	4.55a	24.3	40.3	45	73	Maiti *et al*. (2004)
India, Punjab, LCC4, 8	120	91	6.53a	6.61a	20.8	27.8	57	85	Yadvinder-Singh *et al*. (2007)
India, Punjab, LCC4, 8	120	85	7.10^a	7.04^a	15.4	20.7	60	94	
India, Punjab, LCC4, 11	126	78	6.93a	7.12a	11.3	17.8	52	83	
Bangladesh, Gazipur, LCC4, TPR, 9	72	46	4.46a	4.56a	-	-	62	102	Haque *et al*. (2003)
India, Karnataka, LCC5, 1	150	120	4.24a	4.30a	-	-	28	36	Duttarganvi *et al*. (2014)
India, Karnataka, LCC3, aerobic rice, 1	100	75	3.81a	4.05a	11.0a	17.8b	38a	54b	Yogendra *et al*. (2017)
India, Karnataka, LCC4, 1	100	75	4.81a	4.41a	10.8a	9.1a	48a	59b	Yogendra *et al*. (2013)
India, TN, LCC5, hybrid rice, 2	200	170	7.55a	7.37a	-	-	38	43	Ravi *et al*. (2007)
India, Haryana, LCC4,3	150	140	6.00	5.98	-	-	40	43	Mehta and Singh (2005)
India, Jammu & Kashmir, LCC4,1	120	100	5.42a	5.77a	-	-	45	58	Lone *et al*. (2017)
India, Punjab, LCC4, 4	120	60	6.49a	6.52a	-	-	54	109	Singh and Varinderpal-Singh (2019)
Nepal, Baitadi, LCC4,1	100	90	3.11a	3.89a	-	-	31	43	Bohara *et al*. (2021)
India, Odisha, LCC4, 15	71	59	4.85	5.07	-	-	68	86	Sarangi *et al*. (2020)
India, Punjab, LCC4, DSR, 1	150	110	7.10a	7.09a	21.3a	29.0b	47	64	Kaur (2016)
India, Bassian, LCC4, 60	165	90	7.8a	7.7a	-	-	47	86	Móring *et al*. (2021)
Increased grain yield with same or reduced fertilizer N application following real time approach									
India, UP, LCC4, hybrid rice, 1	150	135	6.9a	7.6b	20.7a	28.1b	46	56	Shukla *et al*. (2004)
India, UP, LCC4, 1	120	120	5.5a	6.1b	15.8a	21.2b	46	51	
India, UP. LCC3, basmati rice, 1	80	80	3.8a	4.3b	12.9a	17.9b	48	54	
Pakistan, Swat, LCC4, 1	115	93	5.55a	6.15b	-	-	48	66	Ahmad *et al*. (2016)
Bangladesh, South-western, LCC4, 33	149	100	3.8a	4.1b	10a	16b	25	41	Alam *et al*. (2006)
India, Jammu & Kashmir, LCC5,1	120	100	4.81a	6.03b	17.0a	32.7b	40	60	Singh *et al*. (2009)
India, Karnataka, LCC3, aerobic rice,1	100	90	4.47a	5.27b	10.1a	20.2b	45a	59b	Yogendra *et al*. (2017)
India, UP, LCC4,1	150	132	5.10a	6.07b	-	-	34	46	Ali *et al*. (2017)
India, Karnataka, LCC3, rainfed rice, 1	100	80	2.55a	2.84b	-	-	26	36	Jayanthi *et al*. (2007)
India, UP, LCC4,6	120	100	3.16a	4.00b	-	-	26	40	Sen *et al*. (2011)
India, Varanasi, LCC4, DSR, 2	120	103	3.33a	3.76b	-	-	28	37	Hemalatha and Singh (2020)
Bangladesh, Mymensingh, LCC3, 2	138	120	6.27a	7.10b	-	-	45a	53b	Jahan *et al*. (2018)
India, New Delhi, LCC4, 1	120	120	5.30a	5.95b	-	-	44	50	Bhatia *et al*. (2012)
India, J&K, LCC3, Basmati rice, 1	120	100	5.42a	5.77b	20.5a	28.2b	45.2a	57.7b	Lone *et al*. (2016)
Bangladesh, South-western, LCC4, 6	150	130	4.69a	5.21b	14a	19b	32a	40b	Alam *et al*. (2005)
Using LCC for fixed dose and adjustable time of application of fertilizer N									
India, Telangana, LCC4, 1, rice	120	120	5.50a	5.89b	29.3a	28.5b	45.8a	49.1b	Bhavana *et al*. (2020a, b)
India, Gujarat, LCC4, 3, rice	100	100	4.44a	4.97b	17.0	19.2	50.7	52.9	Gudadhe and Thanki (2021)
India, Cuttack, LCC3, 1, rice	80	80	4.26a	4.59b	-	-	53	57	Pattanaik *et al*. (2019)
	60	60	3.98a	4.17a	-	-	66	70	
India, Allahabad, LCC3, 1, rice	120	120	5.35a	5.93b	-	-	44.6a	49.4b	Kumar *et al*. (2018)

¶ Unless mentioned, all studies are on irrigated transplanted rice

† FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted on research farms, REC denotes fixed-schedule blanket fertilizer N recommendations.

‡AE_N, agronomic efficiency of applied N; RE_N, apparent recovery efficiency of applied N; PFP_N, partial factor productivity of applied N.

§ For yield and N use efficiency indices of AE_N, and PFP_N at different sites, values with different letters are significantly different at the 0.05 probability level.

blanket recommendation. In both the categories of comparisons of real time N management as listed in Table 1, higher agronomic efficiency and partial factor productivity values obtained with LCC-based SSNM than FFP or blanked N recommendations confirm that LCC helps to apply fertilizer N as per need of the crop.

In some farms, if farmers tend to apply less fertilizer N to rice, LCC-based N management will lead to application of more fertilizer N along with higher yield levels than those obtained by FFP. For example, Shukla *et al.* (2004) recorded 6.9 t ha^{-1} grain yield of rice hybrid PHB-71 by applying the recommended dose of 150 kg N ha^{-1}. But by following real time N management based on threshold LCC scores of 4 and 5, rice yield increased to 7.6 and 8.1 t ha^{-1} with fertilizer N application levels of 135 and 165 kg N ha^{-1}, respectively. Suresh *et al.* (2015) observed that by real time fertilizer N management based on LCC4.5 as the threshold greenness, 5.88 t ha^{-1} grain yield was produced through application of 180 kg N ha^{-1}. However, recommended dose of 120 kg N ha^{-1} produced significantly lower yield of 5.13 t ha^{-1}. In Nepal, Marahatta (2017) average fertilizer N dose of 53 kg N ha^{-1} following FFP resulted in rice grain yield of 4.62 t ha^{-1}, but LCC4 based SSNM produced 6.67 t ha^{-1} through application of 100 kg N ha^{-1}.

Managing fertilizer N in rice using LCC following real time approach takes into account N supply to crop from all the sources including from soil (indigenous N), organic manures, irrigation water or aerial deposition. Ravi *et al.* (2007) found that in green manured rice plots application of 150 kg N ha^{-1} following LCC5 guided N management produced significantly higher 8.14 t ha^{-1} rice grain yield than 7.55 t ha^{-1} produced with blanket fertilizer N recommendation of 200 kg N ha^{-1}. In plots receiving no green manure, LCC5 guided application of 170 kg N ha^{-1} produced only 7.37 t ha^{-1}, which was at par with the yield produced by blanket fertilizer recommendation of 200 kg N ha^{-1}. In an experiment conducted with rainfed lowland rice, by following SSNM with LCC4 as the threshold leaf greenness Manjappa (2016) observed grain yield of 5.71 and 6.04 t ha^{-1} by applying 63 and 47 kg N ha^{-1} in unamended and farmyard manure amended plots, respectively. On the other hand, rice yields of 5.62 and 6.00 t ha^{-1} were recorded by applying the general fertilizer N recommendation of 75 kg N ha^{-1} in unamended and farmyard manure amended plots.

Farmers in South Asia generally apply a basal dose of fertilizer N to rice as a security against yield loss due to N deficiency. Yadvinder-Singh *et al.* (2007) conducted 27 on-station and on-farm experiments to determine whether a basal dose of fertilizer N needs to be applied along with LCC-based real time fertilizer N management in rice. Results summarized in Table 2 revealed no advantage of applying a basal dose of N to rice at transplanting before initiating application of LCC guided fertilizer N doses at about two weeks after transplanting. While the mean yields of LCC-based SSNM plots were similar to that recorded with blanket fertilizer recommendation, the mean agronomic efficiency values were higher irrespective of applying a basal dose of fertilizer N. Mehta and Singh (2005) and Jayanthi *et al.* (2007) also observed that when managing fertilizer N following real time approach using LCC by applying or not applying a basal dose of fertilizer at transplanting rice did not affect the grain yield at maturity of the crop. Bijay-Singh *et al.* (2002) reported that in regions where yield of rice in no-N control is more than 3 t ha^{-1}, no yield benefit should be expected by applying a basal fertilizer N dose before following the real time LCC-based N management in transplanted rice.

In real time LCC-based SSNM, total amount of N to be applied as well as number of split doses and their time of application to rice crop are not fixed. These are determined by supply of N from all sources other than fertilizer and N uptake pattern of the crop as governed by cultivar and climatic factors. Therefore, as shown in Table 1, real time LCC-based fertilizer N management leads to similar or higher yield levels than those observed with general recommendations for the region. However, more often LCC guides less fertilizer N application than general recommendation, because the later is formulated in such way that in all the fields in the region yields are not limited by N supplied through the fertilizer. The blanket recommendations do not take into account field to field variability in N supply from soil or other sources. Thus, in some fields if farmers are applying fertilizer N less than the need of the crop, real time LCC approach will guide application of higher amount of N leading to significant yield improvement (Suresh *et al.*, 2015; Marahatta, 2017). In 50 on-farm experiments on real time LCC-based SSNM in rice, on an average 25% less fertilizer N was used than FFP but with no reduction in the yield (Varinderpal-Singh *et al.*, 2007). In 44% of the experiments, the first dose of fertilizer N as guided by the threshold leaf greenness was applied within 20 days of rice transplanting. In 54% experiments, the LCC guided first dose was applied during 21-40 days after transplanting. In 48% and 41% experiments, the second dose was applied during 21 to 40 and 41 to 55 days after rice transplanting, respectively. The threshold leaf greenness guided application of third dose of fertilizer N in 25 out of 50 experiments and in 14 experiments it was applied 55 days after transplanting. The pattern of time of application and total amount of application of fertilizer N in the sample of 50 experiments suggests that if N supply to the crop is inadequate even 55 days after transplanting, real time N management

Table 2. Role of applying a basal fertilizer nitrogen dose at transplanting of rice before practising leaf colour chart (LCC)-based real time site-specific N management (SSNM)† at 11 sites in the Punjab, India during 2002

Fertilizer N management	2000 (n = 8)			2001 (n = 8)			2002 (n = 11) ††		
	Fertilizer applied, kg N ha^{-1}	Rice yield, t ha^{-1}	AE_N §	Fertilizer applied, kg N ha^{-1}	Rice yield, t ha^{-1}	AE_N	Fertilizer applied, kg N ha^{-1}	Rice yield, t ha^{-1}	AE_N
LCC-based real time N management with no basal N dose	86 (75 – 90) ‡	6.59	27.4a§§	79 (75 – 120)	6.89	19.8a	71 (60 –90)	6.76	19.2a
LCC-based real time N management with 20 kg N ha^{-1} basal dose	95¶ (80 – 110)	6.63	28.1a	91¶ (80 – 110)	7.20	21.6a	91¶ (80 – 110)	7.01	16.4a
Blanket recommendation / Farmer's fertilizer practice	120	6.53	20.8b	120	7.10	15.4b	128 (115 – 142)	6.69	11.3b

† SSNM based application of fertilizer N whenever leaf colour was less than the threshold greenness of LCC4 starting from two weeks after transplanting of rice
‡ Range of total N applied
†† On-farm experiments
§Agronomic efficiency, kg grain per kg fertilizer N
¶ Includes a basal application of 20 kg N ha^{-1} along with LCC guided N applications
§§Values in column in a with same letter do not differ significantly at 0.05 probability level
(Adapted from Yadvinder-Singh *et al.*, 2007)

with LCC guides application of a fertilizer N dose and it has positive impact on the yield of the crop. Also, LCC-based SSNM avoids over-application of fertilizer N, which leads to minimal N-related degradation of the environment (Varinderpal-Singh *et al.*, 2010; Bijay-Singh *et al.*, 2020).

LCC-based site-specific N management in rice following fixed fertilizer nitrogen dose adjustable time of application approach

The third category of comparisons listed in Table 1 are between fixed amount of fertilizer N applied at pre-fixed crop growth stages (or blanket recommendation) and when the same amount of N is applied in split doses at crop growth stages guided by LCC as per the threshold leaf greenness. Grain yield and N use efficiency measures were significantly higher with application of fertilizer N during the cropping season as per threshold greenness on the LCC than the blanket recommendation for the region. Besides the data from four studies included in Table 1, recently Mohanty *et al.* (2021) conducted a detailed study with puddled transplanted rice (PTR) and aerobic direct seeded rice (ADR) in which general recommendation was to apply 100 kg N ha^{-1} - - 50% N at 14 days after sowing in ADR and at transplanting in PTR, and 25% each at maximum tillering and panicle initiation stages of the crop as top dressings. Following the LCC-based SSNM, 33% of the total fertilizer N was applied at 14 days after sowing in ADR and at transplanting in PTR and the remaining two top dressings of 33% each were applied when leaf greenness was less than LCC3. The LCC-based fixed dose adjustable time SSNM resulted in yield increase by 21.2–22.9 % and 14.6–15.9 % and N recovery efficiency by 16.3–18.0 and 11.4–14.6 % in ADR and PTR, respectively.

Site-specific N management in rice with LCC following fixed-time adjustable fertilizer nitrogen dose approach

The LCC-based fixed time adjustable dose SSNM in rice is useful when farmers do not prefer to visit fields every 7 to 10 days as in real time management in which both time and dose are decided using threshold leaf greenness. Leaf colour is monitored at critical growth stages such as active tillering, panicle initiation or close to initiation of flowering and fertilizer N dose is adjusted based on leaf colour, which reflects the relative need of N of the crop. In China, some variants of fertilizer N management following this approach based on different critical LCC values and amount of fertilizer to be applied at critical growth stages of rice have been found to perform better than the blanket recommendation (Peng *et al.*, 2006, 2010; Wang *et al.*, 2007; Witt *et al.*, 2007).

Among a few reports from South Asia, Bijay-Singh *et al.* (2012) conducted a series of experiments and found that through application of adequate amounts of fertilizer N at critical growth stages of puddled transplanted rice, high yield levels could be achieved only when a basal dose of 30 kg N ha^{-1} was applied. At maximum tillering and panicle initiation stages of rice application of 45, 30 or 0 kg N ha^{-1} depending upon leaf greenness to be less than LCC4, between LCC4 and LCC5 or more than LCC5, and 30 kg N ha^{-1} at just before initiation of flowering if leaf greenness was less than LCC4 ensured production of optimum yield of rice but with less total fertilizer N than the general recommendation for the region. In years with favourable climate, fertilizer N management in some cultivars following the fixed time adjustable N dose strategy resulted in yields higher than those recorded with blanket recommendation along with agronomic efficiency higher than 25 kg grain per kg fertilizer N (Bijay-Singh *et al.*, 2012). In dry direct seeded rice, Ali *et al.* (2015) found that after applying 20 kg N ha^{-1} at 14 days after sowing (DAS) and 30 kg N ha^{-1} at 28 DAS, application of 30, 40 or 50 kg N ha^{-1} at 49 and 70 DAS depending upon leaf greenness to be more than LCC4, between LCC4 and LCC3.5, or less than LCC3.5 constituted better strategy than the blanket recommendation to achieve optimum yield levels and high fertilizer N use efficiency. Using significant regressions between N concentration in fully expanded youngest leaves of hybrid rice and LCC score, Mahajan *et al.* (2014) determined critical LCC scores of 4.4, 4.4, and 4.5 for applying a dose of fertilizer N at tillering, panicle initiation, and flowering stages of the crop, respectively.

Site-specific nitrogen management in rice with LCC-based on dynamic threshold leaf greenness

In real time approach the time of application of fertilizer N doses to rice is determined by the threshold leaf greenness defined in terms of an LCC score. Bijay-Singh *et al.* (2016) gave the concept of dynamic threshold greenness for each field, variety, crop growth stage, and season as 0.5 units less than the LCC score of N-rich strip maintained in the field. Working with 6 different rice varieties during three consecutive seasons, Bijay-Singh *et al.* (2016) found that real time fertilizer N management following the dynamic threshold greenness concept for LCC produced grain yields of rice cultivars at par with those produced by managing fertilizer N as per blanket recommendation for the region. Since total fertilizer N application in the real time fertilizer management based on dynamic threshold LCC values was always less than the blanket recommendation, it resulted in higher fertilizer N use efficiency. Thus, LCC-based dynamic threshold leaf greenness real time fertilizer management strategy in rice can effectively take care of variations due to cultivars and seasons.

Wheat

In wheat cultivation, management of N fertilizers is generally linked with critical crop growth stages which coincide with irrigation events. But some farmers do not rigidly follow this practice. Therefore, some researchers have tested the usefulness of LCC in real time SSNM in terms of deciding time as well as amount of fertilizer N application. In Table 3 are listed outcome of such studies. Among the seven comparisons between LCC-based N management and the general recommendation, in two studies SSNM resulted in reduced fertilizer N use but with yield of wheat at par with general recommendation. In the remaining 5 comparisons listed in Table 3, while amount of fertilizer N used under LCC-based SSNM was equal to that with general recommendation, grain yield of wheat significantly increased by LCC guided fertilizer N management. Although Shukla *et al.* (2004) tested LCC3, LCC4, and LCC5 as the threshold greenness for applying fertilizer N doses for real time fertilizer N management in early sown, timely sown, and late sown wheat, they found LCC4 as the most appropriate threshold. In eastern India where temperatures during wheat season are higher than in north-western India, Maiti and Das (2006) found threshold greenness of LCC5 better than LCC4 for real time management of fertilizer N. Gobinder Singh (2006) suggested that using threshold leaf greenness values specific to different growth stages of wheat resulted in better N use efficiency than LCC-based SSNM with same threshold greenness throughout the crop growth period. It was also observed that fertilizer N application to wheat after maximum tillering stage did not improve N use efficiency. In two studies on SSNM in wheat listed in Table 3, total amount of fertilizer N to be applied was fixed but time of application of split fertilizer N doses was governed by threshold leaf greenness with the help of LCC. In both these studies, significant increase in wheat grain yield was observed. In the study conducted by Kumar *et al.* (2020), even the total fertilizer N application was also reduced.

In South Asia, large area under wheat is in the Indo-Gangetic plain where general recommendation for fertilizer N management is to apply 120 or 150 kg N ha^{-1} in two equal split doses at sowing or planting and at crown root initiation stage (about 3 weeks after sowing) when first irrigation is also applied to the crop. Some farmers tend to apply more fertilizer N at maximum tillering stage of the crop around 50 to 55 days after sowing, which generally coincides with second irrigation event. While farmers always prefer to stick to the critical growth stages of wheat for application of fertilizer N, there hardly existed any rational criteria to decide the amount of fertilizer at different growth stages even as it can vary with soil N supply in different fields, prevailing climate, and crop management practices. With LCC becoming available, systematic studies have been conducted to develop crop demand-driven N management in wheat with focus on critical growth stages where adjustments in mid-season N fertilization based on leaf greenness can be made, and on guidelines on leaf greenness to define the fertilizer N doses at different growth stages of the crop.

Varinderpal-Singh *et al.* (2012) conducted a series

Table 3. **Comparison of leaf color chart (LCC)-based site-specific fertilizer N management with farmers fertilizer practice (FFP) or blanket recommendations (REC) in wheat in South Asia**

Region, year, critical LCC shade, number of farms	N used, kg N ha^{-1}		Grain yield, t ha^{-1}		AE_N†, kg grain kg N^{-1}		PFP_N†, kg grain kg N^{-1}		Reference
	FFP/ REC‡	LCC	FFP/ REC	LCC	FFP/ REC	LCC	FFP/ REC	LCC	
Real-time approach to adjust time and dose of fertilizer									
India, New Delhi, LCC4, 1	120	120	4.9a	5.6b	-	-	41	47	Bhatia *et al.* (2012)
India, Pantnagar, LCC5, 1	150	105	4.3a	4.1a	-	-	29	39	Reena *et al.* (2017)
India, Junagarh, LCC4, 1	120	120	3.86a	4.92b	-	-	32	41	Gajera *et al.* (2014)
Nepal, Chitwan, LCC4, 1	100	65	4.05a	3.87a	27.4a	37.4b	39a	63b	Khanal *et al.* (2022)
India, Modipuram, LCC4, 1, early sown	120	120	5.05a	5.65b	-	-	42	47	Shukla *et al.* (2004)
India, Modipuram, LCC4, 1, timely sown	120	120	4.95a	5.65b	-	-	41	47	
India, Modipuram, LCC4, 1, late sown	120	120	4.0a	4.45b	-	-	33	37	
Using LCC for fixed dose and adjustable time of application of fertilizer N									
India, Anand, LCC4, 1	120	120	3.07a	4.11b	-	-	26	34	Patel *et al.* (2018)
India, New Delhi, LCC4, 1	120	100	4.53a	4.69b	19.7a	25.2b	37.8a	46.8b	Kumar *et al.* (2020)
Using LCC for fixed time of application and adjustable dose of fertilizer N									
India, Punjab, LCC4, 96	123	94	4.7a	4.7a	-	-	38	50	Varinderpal-Singh *et al.* (2014)
India, Ludhiana, LCC4, 3	120	100	4.54a	4.48a	21.0a	24.8b	38	45	Varinderpal-Singh *et al.* (2017)
India, Gurdaspur, LCC4, 3	120	100	4.66a	4.81a	22.5a	28.6b	39	48	
India, Ludhiana, LCC4, 3	120	100	4.50a	4.42a	18.4a	21.2b	38	44	Varinderpal-Singh *et al.* (2012)
India, Gurdaspur, LCC4, 3	120	100	4.81a	4.96b	23.1a	29.2b	40	50	

† AE_N, agronomic efficiency of applied N; RE_N, apparent recovery efficiency of applied N; PFP_N, partial factor productivity of applied N.
‡ FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted only on research farms and not in actual farmers' fields, REC denotes fixed-schedule blanket fertilizer N recommendations.
§ For grain yield and N use efficiency indices of AE_N, and PFP_N at different sites, values with different letters are significantly different at the 0.05 probability level.

of field experiments with irrigated wheat and concluded that when practising LCC-based SSNM, the appropriate basal dose at sowing was only 25 kg N ha^{-1} rather than as high as 60 kg N ha^{-1} in the general recommendation. Because due to small size of plants and leaves of wheat at crown root initiation stage (about 3 weeks after sowing) it is not practically possible to use LCC for quantifying greenness of most recent fully expanded leaves of plants, the strategy developed by Varinderpal-Singh *et al.* (2012) advocated that application of 45 kg N ha^{-1} produced the best results if LCC-based SSNM is to be followed. It was at the maximum tillering stage of wheat which generally coincides with second irrigation event that LCC was used to guide the quantity of fertilizer N to be applied. Experiments conducted over several wheat seasons revealed that application of 30 or 45 kg N ha^{-1} depending upon leaf greenness to be more than LCC4 or less than LCC4 at maximum tillering stage or 50 to 55 days after sowing of the crop was the best strategy to supply N as per need of the crop. By following this field-specific fertilizer N management strategy at diverse locations in three wheat varieties, either similar or higher wheat grain yield levels were observed but it always resulted in lower total fertilizer application and higher N use efficiency than the blanket recommendation for fertilizer N (Table 3). Varinderpal-Singh *et al.* (2017) tested the fixed time adjustable dose SSNM approach in cultivars of *Triticum aestivum* L. and two cultivars of *Triticum turgidum* L. ssp. Durum at three locations (Ludhiana, Gurdaspur and Bathinda) and confirmed that it could sustain wheat grain yield at levels observed with blanket recommendation but with 20 to 50 kg N ha^{-1} less fertilizer, which resulted in improvement in fertilizer N use efficiency.

Maize

Varinderpal-Singh *et al.* (2011) were the first to develop LCC-based real time SSNM strategy in maize. They conducted a systematic study involving a series of field experiments in north-western India to establish the threshold leaf greenness of most recent fully exposed collar as LCC5 to guide SSNM in maize. It was observed that maintaining the leaf greenness equivalent to LCC5 by applying a dose of fertilizer whenever leaf colour was less than LCC5 during six-leaf stage (V6) to just before R1 stage resulted in lower total fertilizer N application by 25 to 50% and higher N use efficiency than the blanket recommendation. Grain yield production in four maize cultivars (composite, and long and short duration hybrids) was similar to that observed with general fertilizer recommendation of 120 kg N ha^{-1}. After the landmark study of Varinderpal-Singh *et al.* (2011), several studies have been conducted in different parts of India and in Sri Lanka (Table 4), which convincingly proved the usefulness of LCC-based real time SSNM in terms of obtaining similar yield levels as with blanket recommendation but with reduced fertilizer application. In another category of studies as listed in Table 4, by following LCC-based SSNM maize grain yield increased significantly over that observed with general recommendation, but fertilizer N use was either reduced or same as with the general recommendation. In most of the studies including by Umesh *et al.* (2020), threshold collar greenness level was LCC5 but in some studies listed in Table 4, good results were also obtained with threshold greenness of LCC4 and LCC 4.5. It should possibly be due to varietal differences. Recently Mohapatro *et al.* (2021) studied the response of maize to application of 25 kg N ha^{-1} as basal dose and 45 kg N ha^{-1} if leaf greenness was less than LCC 5 at 21 and 45 days after sowing and found that yield with LCC-based SSNM was at par with 120 or 150 kg N ha^{-1} applied as blanket recommendation.

On-farm evaluation of LCC-based site-specific nitrogen management in cereals

During 2000 to 2002, 40 on-farm trials were conducted in five states in the Indo-Gangetic plain in India to evaluate real time SSNM with LCC4 as threshold leaf greenness in rice. While grain yields of rice with LCC-based management and blanket recommendation/FFP for fertilizer N were not different, total amount of applied was reduced due to SSNM by 27 to 56 kg N ha^{-1} in Punjab, 19 to 39 kg N ha^{-1}in Haryana, 30 kg N ha^{-1} in Uttarakhand, 30 to 40 kg N ha^{-1} in Bihar, and 20 kg N ha^{-1} in West Bengal (Bijay-Singh *et al.*, 2003). Buresh *et al.* (2005) reported benefits of managing fertilizer N following LCC4 as threshold greenness in terms of improved N use efficiency and profit in farmers' fields in northern and southern parts of India differing widely with respect to soil, climate, and crop management practices. For four rice seasons during 2000 to 2003, Yadvinder-Singh *et al.* (2007) conducted on-farm trials on rice at 100 locations in Amritsar, Patiala, Gurdaspur, Jalandhar, Ferozepur, and Ropar districts in the Indian Punjab. Average yield of rice with real time SSNM based on threshold leaf greenness equivalent to LCC4 was at par with the blanket recommendation of applying 120 kg N ha^{-1} in three equal split doses, but with 26% less fertilizer N application across locations and seasons. Varinderpal-Singh *et al.* (2007) reported results of 350 on-farm comparisons between FFP and LCC-based real time SSNM made during 2002 to 2005. While rice yields produced by LCC-based N management were at par with those with FFP, total fertilizer N applied was 9.4 to 54.2 kg N ha^{-1} or on an average 25% less than the practice followed by farmers. Varinderpal-Singh *et al.* (2014) compiled the data from 461 on-farm trials on rice and found that fertilizer N use based on LCC-based SSNM ranged from 60 to 150 kg N ha^{-1} whereas farmers applied from 80 to 225 kg N ha^{-1} to produce average grain yield that was not different than that produced by need based SSNM using LCC. On-farm evaluation of LCC-based SSNM at 165 sites in Karnal districts (Haryana, India) revealed that similar yield levels as produced by FFP were obtained by applying on average 25 kg N ha^{-1} less fertilizer (Balasubramanian *et al.* 2003). Alam *et al.* (2005) evaluated LCC as a tool for improving the time and rate of N fertilizer use in farmers' fields in southwestern Bangladesh. LCC-based SSNM resulted in average increase in rice grain yield across villages and seasons by 0.1 to 0.7 t ha^{-1} over FFP. Although fertilizer N use was more with LCC-based management than under FFP, net return was higher with LCC based fertilizer N management. In Odissa state of India, Sarangi *et al.* (2020) evaluated the use of LCC in fertilizer N management at 15 on-farm sites and observed significant reduction in fertilizer N application but with rice yields similar to those obtained by following FFP.

As reported by Móring *et al.* (2021), 60 farmers in a village in district Ludhiana in the Indian Punjab were

Table 4. Comparison of leaf color chart (LCC)-based site-specific fertilizer N management following real time approach with farmers fertilizer practice (FFP) or blanket recommendations REC) in maize in South Asia

Region, year, critical LCC shade, number of farms	N used, kg N ha^{-1}		Grain yield, t ha^{-1}		AE_N†, kg grain kg N^{-1}		PFP_N†, kg grain kg N^{-1}		Reference
	FFP/ REC‡	LCC	FFP/ REC	LCC	FFP/ REC	LCC	FFP/ REC	LCC	
Same grain yield with reduced N fertilizer application following real time approach									
India, Ludhiana, LCC5, 1, hybrid maize	120	90	4.19a	4.27a	14.9a	20.7b	35	47	Varinderpal-Singh *et al.* (2011)
India, Ludhiana, LCC5,1, composite maize	120	90	3.98a	4.03a	15.3a	21.0b	33	45	
India, Raichur, LCC5, 1	150	120	15.7¶a	15.2a			105	127	Swamy *et al.* (2016)
India, Ludhiana, LCC5, 1	120	90	5.93a	6.03a	20.1a	27.9b	49	67	Varinderpal-Singh *et al.* (2020)
India, Raichur, LCC5, 1	150	120	13.7¶a	13.2a	63.2a	67.8	91	110	Umesh *et al.* (2018)
India, Amritsar, LCC5, 1	125	120	4.04a	4.31a			32	36	Singh and Singh (2019)
India, Hyderabad, LCC4, 1	200	135	7.36a	7.40a	15.1a	22.6b	36.8a	54.8b	Jyothsna *et al.* (2021)
India, Odisha, LCC5, 1	120	115	7.24a	7.83a	33.2	39.8	60	68	Swamy *et al.* (2022)
India, Punjab, LCC5, 23	128	108	5.4a	5.5a	-	-	42	51	Varinderpal-Singh *et al.* (2014)
Increase in grain yield with same or reduced N fertilizer application following real time approach									
India, Junagarh, LCC4, 1	100	100	2.60a	3.15b			26	32	Mathukia *et al.* (2014)
India, Pantnagar, LCC4, 1	120	120	3.97a	4.25b	9.1a	11.5b	33.1a	35.4b	Singh *et al.* (2016)
India, Birbhum, LCC4, 1	150	125	3.52a	4.47b			23	36	Bhuiya *et al.* (2020)
Sri Lanka, Mahailluppallama, LCC 4.5, Yala season	120	120	6.18a	6.83b	31.3a	36.8b	52	57	Renuka and Senavirathna (2016)
Sri Lanka, Mahailluppallama, LCC 4.5, Maha season	120	120	5.37a	7.48b	16.1a	33.8b	45	62	
India, Anand, LCC4, 1	120	90	4.07a	4.53b			34	50	Kumar *et al.* (2019)
India, Punjab, LCC5, 2, spring maize	120	120	7.80a	8.44b	25.8a	31.2b	65	70	Singh *et al.* (2020)

† AE_N, agronomic efficiency of applied N; RE_N, apparent recovery efficiency of applied N; PFP_N, partial factor productivity of applied N.
‡ FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted only on research farms and not in actual farmers' fields, REC denotes fixed-schedule blanket fertilizer N recommendations.
¶ Fresh cob yield of sweet corn
§ For grain yield and N use efficiency indices of AE_N, and PFP_N at different sites, values with different letters are significantly different at the 0.05 probability level.

motivated and trained to manage fertilizer N following LCC-based real time SSNM approach. These farmers applied, on average, 75 kg N ha^{-1} less fertilizer than those who did not opt for LCC guided N application. The harvested yield by the two categories of farmers was 7.8 and 7.7 t ha^{-1}. In 2002-03 in West Bengal state of eastern India, farmers were motivated to adopt LCC for managing fertilizer N in field-specific manner - - 40 farmers in pre-kharif, 123 in the kharif season, and 57 farmers in the following boro and kharif seasons (Islam *et al.*, 2007). In an impact study conducted in 2005-06 revealed that farmers adopted LCC for managing fertilizer on 57 to 63% of their land under rice. After using LCC in the first year on about 50% of the area under rice, farmers rapidly increased it to 97% in the 3rd year. On an overall basis, LCC adoption by farmers saved fertilizer by 19.4% and increased rice yields by 50, 60 and 90 kg ha^{-1} in the pre-kharif, kharif and boro seasons, respectively (Islam *et al.*, 2007).

The SSNM strategy in wheat as standardized by Varinderpal-Singh *et al.* (2012) was tested in 96 on-farm trials conducted in the Indian Punjab. The LCC guided fertilizer N dose was applied only at maximum tillering stage after application of prescriptive doses of 25 kg N ha^{-1} at planting and 45 kg N ha^{-1} at crown root initiation stages for timely sown wheat. For wheat sown after mid-December (late sown wheat), the prescriptive dose at crown root initiation stage was 30 kg N ha^{-1}. At maximum tillering stage 30 or 45 kg N ha^{-1} for timely sown wheat and 30 or 15 kg N ha^{-1} for late sown wheat were applied depending upon leaf greenness to be more than or less than LCC4. The data from 96 on-farm trials as compiled by Varinderpal-Singh *et al.* (2014) showed that while average wheat grain yield was at par, total fertilizer N application was 90 to 150 kg N ha^{-1} (average 123 kg N ha^{-1}) with FFP and 70 to 100 kg N ha^{-1} (average 94 kg N ha^{-1}) with LCC-based SSNM. In a village near Ludhiana in the Indian Punjab, 90 farmers who opted to manage fertilizer N in wheat as per LCC guidelines produced average wheat yield of 5.1 t ha^{-1} (Móring *et al.* (2021). Although average wheat yield with FFP was almost equal (5.0 t ha^{-1}), the LCC-based N management resulted in the application of 55 kg N ha^{-1} less fertilizer and therefore, 51% improvement in the partial factor productivity of N.

Varinderpal-Singh *et al.* (2014) reported the results of 23 on-farm studies on maize conducted in the north-western India to evaluate LCC-based fertilizer N management vis-à-vis FFP. In the SSNM strategy, after applying a basal dose of 30 kg N ha^{-1}, fertilizer N doses of 30 kg N ha^{-1} were applied during six-leaf stage to initiation of silking whenever colour of the most recent fully expanded collar was less than LCC5. On an average, maize grain yields were at par whether fertilizer N was managed using LCC (5.5 t ha^{-1}) or FFP (5.4 t ha^{-1}). However, LCC guided fertilizer application was 20 kg N ha^{-1} less than that with FFP. At one location LCC-based N management resulted in application of more fertilizer N than the blanket recommendation for the region but leading to significantly higher grain yield. It proves that field-specific LCC-based fertilizer N management leads to high productivity as well high N use efficiency.

LCC-based fertilizer nitrogen management reduces losses of nitrogen to the environment

As LCC-based SSNM in cereals a is site-specific or field-specific strategy, in several fields crop yields are increased but total amount of fertilizer N remains the same as in blanket fertilizer recommendation. However, in a large number of fields, yield levels are maintained but less total amount of fertilizer N is applied (Tables 1, 3, and 4). In such situations, loss of fertilizer N via nitrate leaching, ammonia volatilization and emission of N_2O is also reduced leading to reduced environmental degradation. A few studies conducted in South Asia provide evidence direct evidence linking LCC guided fertilizer N management with reduced losses of N from soil-plant system.

In a field study conducted by Mohanty *et al.* (2018), 3.4 – 16.1 kg NO_3-N ha^{-1} was leached below 45 cm depth from aerobic rice during the whole cropping season. When urea was applied as guided by LCC to synchronize N supply and demand, along with high yield and N use efficiency nitrate leaching was reduced by 39.8%. In field studies on baby corn (*Zea mays* L.), Varinderpal-Singh *et al.* (2021) showed that using LCC to guide need-based fertilizer N topdressings not only produced an average 17% higher cob yield, but also reduced average nitrate-N leachate load by 69% over fixed-time blanket fertilizer N use practice. In a study carried out by Bhatia *et al.* (2012), LCC-based real time SSNM was compared with conventional fixed time N splitting schedule for both rice and wheat. Yield of both rice and wheat increased with LCC-based fertilizer N management, but total amount of N applied was not less than the general recommendation for the region. However, by applying LCC guided doses of fertilizer N at times when crops needed N the most resulted in reduced N_2O emissions in both rice and wheat. Application of 120 kg N ha^{-1} using LCC4 as threshold leaf greenness in rice reduced N_2O emission by 16% and methane emission by 11% over that measured under conventional split application of urea. In wheat, a reduction of 18% in the emission of N_2O was observed by applying urea following LCC-based SSNM. Bhatia *et al.* (2012) estimated that LCC guided urea application reduced global warming potential of a rice–wheat system by 10.5%. Pathak (2010) tested several technologies including LCC as a tool for fertilizer N management in rice production in the Indian state of Haryana and estimated the loss of N from the soil-plant system through leaching, volatilization, and denitrification under FFP as 67.5 kg N ha^{-1}. Managing fertilizer N as guided by LCC on a field-specific basis resulted in reduced fertilizer N application from 145 to 120 kg N ha^{-1} and reduction in loss of N to 50 kg N ha^{-1}.

Conclusions

Development of fertilizer N management practices that lead to high N use efficiency in cereal crops is central to achieve food security and minimize N related environmental degradation. It is even more true for five major countries in South Asia which use more than 22% of the fertilizer N consumed globally. Ensuring a balance between supply from the soil and demand of N by the crop plants constitutes a key element in formulating field-specific fertilizer N management strategies for production of cereals. Nitrogen status of actively growing plant leaves, best expressed through the extent of greenness of the most recent fully expanded leaf of the plant, has been exploited to assess the balance between demand and supply of N and to estimate the need of fertilizer N when the crop is growing in the field. Chlorophyll meters are useful in estimating need-based N management, but these are very expensive and not affordable for most of South Asian farmers. In recent decades, LCC, an inexpensive alternative to chlorophyll meters, has emerged as an incredible tool for field-specific fertilizer N management in cereal crops in South Asia. By comparing the greenness of the most recent fully expanded leaf of crop plant with different shades of green colour on LCC, it can be used in different ways to define time of application and amount of fertilizer N to be applied to the crop when it is growing in the field. In rice and maize, LCC has preferably been used in a real time mode in which leaf colour is monitored using LCC every 7-10 days and a dose of fertilizer N is top dressed whenever leaf colour is less than the threshold greenness. This way both time of application and amount of fertilizer N are decided. Some researchers have also used LCC in rice following fixed time adjustable dose and fixed dose adjustable time modes. Since in wheat fertilizer N application is generally linked with irrigation events at critical growths stages, LCC is most conveniently used in the fixed time adjustable dose mode. In majority of studies conducted in last two decades, LCC-based field-specific fertilizer N management in rice, wheat, and maize leads to higher fertilizer N use efficiency than the blanket fertilizer recommendation for the region. Superiority of LCC guided fertilizer N management has also been proven in on-farm trials. A few studies also provide direct evidence that LCC-based N management leads to reduction in losses of N from the soil-plant system via nitrate leaching or emission of nitrous oxide. As use of simple and inexpensive gadget like LCC for managing fertilizer N can be placed in very high benefit:cost ratio category (Ladha *et al.*, 2005), it can greatly assist South Asian farmers with small to medium size fields in applying N as per soil N supplying capacity and need of cereal crops.

LITERATURE CITED

Ahmad N, Zada A, Junaid M, Ali A 2016. Bridging the yield gap in rice production by using leaf color chart for nitrogen management. *J Bot Art*: 2728391, 6 pp. http://dx.doi.org/10.1155/2016/2728391

Alam M M, Ladha J K, Foyjunnessa, Rahman Z, Khan S R, Rashid H, Khan A H, Buresh R J 2006. Nutrient management for increased productivity of rice–wheat cropping system in Bangladesh. *Field Crops Res* **96**: 374-86. http://dx.doi.org/10.1016/j.fcr.2005.08.010

Alam M M, Ladha J K, Khan S R, Foyjunnessa M, Rashid H, Khan A H and Buresh R J 2005. Leaf colour chart for managing nitrogen fertilizer in lowland rice in Bangladesh. *Agron J* **97**: 949-59. http://dx.doi.org/10.2134/agronj2004.0206

Ali A M, Thind H S, Sharma S, Singh Y 2015. Site-specific nitrogen management in dry direct-seeded rice using chlorophyll meter and leaf colour chart. *Pedosphere* **25**: 72-81. http://dx.doi.org/10.1016/S1002-0160(14)60077-1

Ali A S, Elamathi S, Singh S, Debbarma V and Ghosh G 2017. Leaf colour chart for proficient nitrogen management in transplanted rice (*Oryza sativa* L.) in eastern Uttar Pradesh, India. *Int J Curr Microbiol Appl Sci* **6**: 5367-72. https://doi.org/10.20546/ijcmas.2017.611.513

Bailey K J and Leegood R C 2016. Nitrogen recycling from the xylem in rice leaves: dependence upon metabolism and associated changes in xylem hydraulics. *J Exp Bot* **67**: 2901-11. http://dx.doi.org/10.1093/jxb/erw132

Balasubramanian V, Ladha J K, Gupta R K, Naresh R K, Mehla R S, Bijay-Singh and Yadvinder-Singh 2003. Technology options for rice in the rice-wheat system in South Asia. In Ladha J K, Hill J E, Duxbury J M, Gupta R K, Buresh R J (Eds*), Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts.* Special Publication 65, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison. pp. 115-47. https://doi.org/10.2134/asaspecpub65.c6

Bhat T A, Kanth R H, Jan B, Nazir A *et al.* 2022. Real-time nitrogen application of rice varieties based on leaf colour chart under system of rice intensification in temperate climate. *Agron* **12**: 2229. https://doi.org/ 10.3390/agronomy12092229

Bhat T A, Kotru R, Ahmad L, Ganai M A and Mahdi S S 2015. Response of rice genotypes (*Oryza sativa* L.) to leaf colour chart based nitrogen management under temperate environment. *Int J Ecol Environ Sci* **41**: 95-100.

Bhatia, A, Pathak H, Jain N, Singh P K and Tomer R 2012. Greenhouse gas mitigation in rice–wheat system with leaf color chart-based urea application. *Environ Monit Assess* **184**: 3095-3107. https://doi.org/10.1007/s10661-011-2174-8

Bhavana B, Laxminarayana P, Latha A M and Anjaiah T 2020a. Judicious nitrogen management using leaf colour chart for enhancing growth and yield of short duration transplanted rice (*Oryza sativa* L). *Int J Curr Microbiol Appl Sci* **9**: 2850-56. https://doi.org/10.20546/ijcmas.2020.906.345

Bhavana B, Laxminarayana P, Latha A M and Anjaiah T 2020b. Need based nitrogen management using leaf colour chart for short duration transplanted rice: Effect on nitrogen use efficiency. *J Pharmacognosy Phytochem* **9**: 1704-09.

Bhuiya G S, Shankar T, Banerjee M and Malik G C 2020. Growth, productivity, nutrient uptake and economics of hybrid maize (*Zea mays* L.) as influenced by precision nutrient management. *Int J Agric Environ Biotech* **13**: 213-18. http://dx.doi.org/10.30954/0974-1712.02.2020.15

Bianculli M L, Aguirrezábal L A N, Irujo G A P and Echarte M M 2016. Contribution of incident solar radiation on leaves and pods to soybean seed weight and composition. *Eur J Agron* **77**: 1-9. http://dx.doi.org/10.1016/j.eja.2016.03.002

Bijay-Singh 2008. Crop demand-driven site-specific nitrogen applications in rice (*Oryza sativa*) and wheat (*Triticum aestivum*): Some recent advances. *Indian J Agron* **53**: 157-66.

Bijay-Singh 2018. Are nitrogen fertilizers deleterious to soil health? *Agron* **8:** 48. https://doi.org/10.3390/agronomy8040048

Bijay-Singh 2022. Nitrogen use efficiency in crop production in India: Trends, issues, and challenges. Agri Res **11**: published on-line. https://doi.org/10.1007/s40003-022-00626-7

Bijay-Singh and Craswell E 2021. Fertilizers and nitrate pollution of surface and ground water: An increasingly pervasive global problem. *SN Appl Sci* **3**: 1-24. https://doi.org/10.1007/s42452-021-04521-8

Bijay-Singh, Gupta R K, Yadvinder-Singh, Gupta S K, Singh J, Bains J S and Vashishta M 2006. Need-based nitrogen management using leaf color chart in wet direct seeded rice in North Western India. *J New Seeds* **8**: 35-47. https://doi.org/10.1300/J153v08n01_03

Bijay-Singh, Singh V K 2017a. Advances in nutrient management in rice cultivation. In: Sasaki T (Ed), Achieving Sustainable Cultivation of Rice, vol 2, pp. Burleigh Dodds Science Publishing Limited, Cambridge, pp. 25-68. http://dx.doi.org/10.19103/AS.2016.0003.16

Bijay-Singh and Singh V K 2017b. Fertilizer management in rice. In Chauhan B S, Khawar J, Mahajan G (Eds), Rice Production Worldwide. Springer International Publishing, Cham, Switzerland, pp. 217-253. http://dx.doi.org/10.1007/978-3-319-47516-5_10

Bijay-Singh, Varinderpal-Singh, Ali A M 2020. Site-specific fertilizer nitrogen management in cereals in South Asia. *Sustain Agric Rev* **39**: 137-78. https://doi.org/10.1007/978-3-030-38881-2_6.

Bijay-Singh, Varinderpal-Singh, Yadvinder-Singh, Thind H S, Kumar A, Gupta R K, Kaul A, Vashistha M 2012. Fixed-time adjustable dose site-specific fertilizer nitrogen management in transplanted irrigated rice (*Oryza sativa* L.) in South Asia. *Field Crops Res* **126**: 63-69. https://doi.org/10.1016/j.fcr.2011.09.007

Bijay-Singh, Varinderpal-Singh, Yadvinder-Singh, Kumar A, Jagmohan-Singh, Vashistha M, Thind H S and Gupta R K 2016. Fertilizer nitrogen management in irrigated transplanted rice using dynamic threshold greenness of leaves. *Agric Res* **5**:174-81. https://doi.org/10.1007/s40003-016-0213-y

Bijay-Singh, Yadvinder-Singh and Bains J S 2003. Real-time nitrogen management using chlorophyll meter and leaf colour chart (LCC) in rice and wheat. In Yadvinder-Singh, Bijay-Singh, Jagmohan-Singh, editors. Nutrient management for sustainable rice-wheat cropping system. New Delhi: NATP, Indian Council of Agricultural Research, Ludhiana: Punjab Agricultural University. pp. 115-24.

Bijay-Singh, Yadvinder-Singh, Ladha J K, Bronson K F, Balasubramanian V, Jagdeep-Singh and Khind C S 2002. Chlorophyll meter and leaf color chart-based nitrogen management for rice and wheat in northwestern India. *Agron J* **94**: 821-29. http://dx.doi.org/10.2134/agronj2002.8210

Blackmer T M and Schepers J S 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. *J Prod Agric* **8**: 56-60. https://doi.org/10.2134/jpa1995.0056

Bohara S L, Lamsal K., Yogi D N and Chaudhary G R 2021. Real time nitrogen management in rice using leaf colour chart under rainfed condition of western hills of Nepal. *Int J Environ Agric Res* **7(7)**: 39-46.

Budhar M N and Tamilselvan N 2003. Leaf colour chart based N management in wet seeded rice. *Int Rice Res Newslett* **28**: 63-64.

Buresh R J 2007. Fertile progress. *Rice Today* **6(3)**:32-33.

Buresh RJ, Witt C, Ramanathan S, Mishra B, Chandrasekaran B, Rajendran R 2005. Site-specific nutrient management: Managing N, P, and K for rice. *Fert News* **50**: 25-28, 31-37.

Duttarganvi, S., Channabasavanna A S, Rao S and Halepyati A S 2014. Effect of LCC and SPAD based nitrogen management on growth and yield of lowland rice (*Oryza sativa* L.). *The Bioscan* **9**: 663-665.

Fageria N K, Baligar V C and Jones C A 2011. *Growth and Mineral Nutrition of Field Crops.* 3rd edition. Boca Raton: CRC Press.

Furuya S 1987. Growth diagnosis of rice plants by means of leaf color. *Japan Agric Res Q* **20**: 147-53.

Gajera K, Mathukia R K and Jat R A 2014. Real time nitrogen management improves yield and economic returns in wheat in vertisols of Gujarat. *Indian J Fert* **10(2)**: 56-60.

Gobinder Singh 2006. *Nitrogen management in wheat using chlorophyll meter and leaf colour chart.* MSc Thesis, Punjab Agricultural University, Ludhiana, India.

Gudadhe N N and Thanki J D 2021. Real time nitrogen management in rice genotypes through leaf colour chart at critical growth stages. *Indian J Fert* **17**: 1040-46.

Gupta R K, Varinderpal-Singh, Yadvinder-Singh, Bijay-Singh, Thind H S, Kumar A and Vashistha M 2011. Need-based fertilizer nitrogen management using leaf colour chart in hybrid rice (*Oryza sativa*). *Indian J Agric Sci* **81**: 1153-57.

Haque M A, Husain M M, Jharna D E, Uddin M N and Iqbal Hussain A S M 2003. A comparative study of leaf color chart based and farmer's practice of nitrogen fertilizer application on rice under on-farm conditions of

Bangladesh. *Pakistan J Biol Sci* **6**: 1685-88.

Hemalatha K and Singh Y 2020. Leaf colour chart based nitrogen and weed management in rice. *J Crop Weed* **16**: 179-86. https://doi.org/10.22271/09746315.2020.v16.i3.1385

Islam M S, Bhuiya M S, Rahman S and Hussain M M 2009. Evaluation of SPAD and LCC based nitrogen management in rice (*Oryza sativa* L.). *Bangladesh J Agril Res* **34**: 661-72. http://dx.doi.org/10.3329/bjar.v34i4.5841

Islam Z, Bagchi B and Hossain M 2007. Adoption of leaf color chart for nitrogen use efficiency in rice: Impact assessment of a farmer-participatory experiment in West Bengal, India. *Field Crops Res* **103**: 70-75. https://doi.org/10.1016/j.fcr.2007.04.012

Jahan N A, Yeasmin S, Anwar M P, Islam M A, Rahman H and Islam A K M M 2018. Efficacy and economics of different need based nitrogen management approaches in winter rice. Am J Plant Sci **9**: 2601-11. https://doi.org/10.4236/ajps.2018.913189

Jayanthi T, Gali S K, Angadi V V and Chimmad V P 2007. Effect of leaf colour chart based nitrogen management on growth and yield parameters of rainfed rice. *Karnataka J Agric Sci* **20**: 272-75.

Jyothsna K, Padmaja J, Sreelatha D, Kumar R M and Madhavi A 2021. Study on nutrient management of hybrid maize (*Zea mays* L) through decision support tools. *J Pharmacognosy Phytochem* **10**: 760-64.

Kaur N 2016. *Leaf colour chart for need based fertilizer nitrogen management in direct seeded rice.* M Sc thesis. Punjab Agricultural University, Ludhiana, India.

Khanal P, Sah S K, Acharya M, Marahatta S and Neupane M P 2022. Precision nitrogen management in wheat at Rampur, Chitwan, Nepal. *J Agric Environ* **23***:*143-55.

Krupnik T J, Six J, Ladha J K, Paine M J and Van Kessel C 2004. An assessment of fertilizer nitrogen recovery efficiency by grain crops. In Mosier A R, Syers K J and Freney J R (Eds) *Agriculture and the Nitrogen cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*, SCOPE 65, Island Press, Washington DC. pp. 193-207.

Kumar D, Patel R A and Ramani V P 2019. Assessment of precision nitrogen management strategies in terms of growth, yield and monetary efficiency of maize grown in western India. *J Plant Nutr* **42**: 2844-60. https://doi.org/10.1080/01904167.2019.1659346

Kumar O, Jain N, Singh K, Ramawat N, Bhatia A and Sharma D K 2020. Effect of different mitigation options on growth, productivity and economics of wheat (*Triticum aestivum. Indian J Agric Sci* **90**: 1964-68.

Kumar P P, Abraham T, Pattanaik S S C, Kumar R, Kumar U and Kumar A 2018. Effect of customised leaf colour chart (CLCC) based real time N management on agronomic attributes and protein content of rice (*Oryza sativa* L.). *Oryza* **55**: 165-73. http://dx.doi.org/10.5958/2249-5266.2018.00019.X

Kusano M, Fukushima A, Redestig H and Saito K 2011. Metabolomic approaches toward understanding nitrogen metabolism in plants. *J Exp Bot* **62:** 1439-53. http://dx.doi.org/10.1093/jxb/erq417

Ladha J K, Pathak H, Krupnik T J, Six J and Van Kessel C 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospect and prospects. *Adv Agron* **87**: 85-156. http://dx.doi.org/10.1016/S0065-2113(05)87003-8

Lal R 2004. The potential of carbon sequestration in soils of South Asia. In: Conserving Soil and Water for Society: Sharing Solutions, ISCO 2004 - 13th International Soil Conservation Organisation Conference, Brisbane, July 2004, Paper No. 134.

Lone A H, Najar G R, Sofi J A, Ganie M A and Mir S A 2016. Calibrating leaf colour chart for optimal fertilizer nitrogen management in basmati rice under temperate conditions of Kashmir. *App Biol Res* **18**: 293-98. http://dx.doi.org/10.5958/0974-4517.2016.00045.8

Lone A H, Ganie M A, Najar J R and Mehmood M A 2017. Nitrogen management in rice through leaf colour chart under Kashmir conditions. *Int J Eng Res Tech* **6(6)**: 50-54.

Madeira A C, Mendonca A, Ferriera M E, and de Taborda M L 2000. Relationship between spectroradiometric and chlorophyll measurements in green beans. *Commun Soil Sci Plant Anal* **31**: 631-643. http://dx.doi.org/10.1080/00103620009370465

Mahajan G R, Pandey R N, Dinesh Kumar, Datta S C, Sahoo R N and Prasad R 2014. Development of critical values for the leaf color chart, SPAD and Fieldscout CM 1000 for fixed time adjustable nitrogen management in aromatic hybrid rice (*Oryza sativa* L.). *Commun Soil Sci Plant Anal* **45**: 1877-93. https://doi.org/10.1080/00103624.2014.909832

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. *Arch Agron Soil Sci* **52**: 105-12. https://doi.org/10.1080/03650340500460875

Maiti D, Das D K, Karak T and Banerjee M 2004. Management of nitrogen through the use of leaf color chart (LCC) and soil plant analysis development (SPAD) or chlorophyll meter in rice under irrigated ecosystem. *Sci World J* **4**: 838-46. https://doi.org/10.1100/tsw.2004.137

Makino A 2011. Photosynthesis, grain yield, and nitrogen utilization in rice and wheat. *Plant Physiol* **155**: 125-29. http://dx.doi.org/10.1104/pp.110.165076

Manjappa K 2016. Leaf colour chart- A simple tool for integrated nitrogen management in rainfed lowland rice. In *Proc Int Conf 'Natural Resource Management: Ecological Perspectives'* of the Indian Ecological Society, SKUAST, Jammu, India. pp. 624-25.

Marahatta S 2017. Increasing productivity of an intensive rice based system through site specific nutrient management in western terai of Nepal. *J Agric Environ* **18**: 140-50.

Mathukia R K, Rathod P and Dadhania N M 2014. Climate change adaptation: Real time nitrogen management in maize (*Zea mays* L.) using leaf colour chart. *Curr World Environ* **9**: 1028-33. http://dx.doi.org/10.12944/CWE.9.3.58

Mehta A K and Singh R 2005. Transfer of resource conserving technologies through Krishi Vigyan Kendras. In I P Abrol, R K Gupta and R K Malik (Eds) *Conservation Agriculture - Status and Prospects.* Centre for Advancement of Sustainable Agriculture, New Delhi. pp. 128-34.

Mohanty S, Nayak A K, Bhaduri D, Swain C K, Kumar A, Tripathi R, Shahid M, Behera K K and Pathak H 2021. Real-time application of neem-coated urea for enhancing N-use efficiency and minimizing the yield gap between aerobic direct-seeded and puddled transplanted rice. *Field Crops Res* **264**: 108072. https://doi.org/10.1016/j.fcr.2021.108072

Mohanty S, Swain C K, Tripathi R, Sethi S K, Bhattacharyya P, Kumar A, Raja R, Shahid M, Panda B B, Lal B and Gautam P 2018. Nitrate leaching, nitrous oxide emission and N use efficiency of aerobic rice under different N application strategy. *Arch Agron Soil Sci* **64**: 465-79. https://doi.org/10.1080/03650340.2017.1359414

Mohapatro S, Shankar T, Maitra S, Pal A, Nanda S P, Ram M S and Panda S K 2021. Growth and productivity of maize *(Zea mays* L.) as influenced by nitrogen management options. *Int J Agric Enviro Biotech* **14**: 207-14. http://dx.doi.org/10.30954/0974-1712.02.2021.14

Móring A, Hooda S, Raghuram N, Adhya T K, Ahmad A, *et al.* 2021. Nitrogen challenges and opportunities for agricultural and environmental science in India. *Front Sustain Food Syst* **5**: 505347. http://doi.org/10.3389/fsufs.2021.505347

Nachimuthu G, Velu V, Malarvizhi P, Ramasamy S and Gurusamy L 2007. Standardisation of leaf colour chart based nitrogen management in direct wet seeded rice (*Oryza sativa* L.). *J Agron* **6**: 338-43. http://dx.doi.org/10.3923/ja.2007.338.343

Patel P D, Patel M V, Ombase K C, Mevada K D, Patel A P and Lakum Y C 2018. Real time nitrogen management through organic and inorganic sources in wheat. *J Pure App Microbiol* **12**: 1001-10. http://dx.doi.org/10.22207/JPAM.12.2.64

Pathak H 2010. Mitigating greenhouse gas and nitrogen loss with improved fertilizer management in rice: quantification and economic assessment. *Nutr Cycl Agroecosyst* **87**: 443-54. https://doi.org/10.1007/s10705-010-9350-z

Pattanaik I, Mishra V N and Nayak A K 2019. Effect of customized leaf colour chart and different doses of neem coated urea on the nitrogen use efficiency and yield of rice. *Int J Chem Stud* **7**: 311-12.

Peng S, Buresh R J, Huang J, Yang J, Zou Y, Zhong X, Wang G and Zhang F 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Res* **96**: 37-47. http://dx.doi.org/10.1016/j.fcr.2005.05.004

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 site-specific N management. A review. *Agron Sustain Dev* **30**: 649-56. http://dx.doi.org/10.1051/agro/2010002

Peng S, Cassman K G and Kropff M J 1995. Relationship between leaf photosynthesis and nitrogen content of field-grown rice in the tropics. *Crop Sci* **35**: 1627-30. https://doi.org/10.2135/cropsci1995.0011183X003500060018

Peng S, Garcia F V, Laza R C, Sanico A L, Visperas R M, Cassman K G 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. *Field Crops Res* **47**: 243-52. http://dx.doi.org/10.1016/0378-4290(96)00018-4

Porpavai S, Murlikrishnasamy S, Nadanassabapady, Jayapaul, Balasubramanian V 2002. Standardising critical leaf colour chart values for transplanted rice in Cauvery New Delta. *Agric Sci Digest* **22**: 207-08.

Pradhan S, Patra P, Mitra S, Dey K K, Jain S, Sarkar S, *et al.* 2014. Manganese nanoparticles: impact on non-nodulated plant as a potent enhancer in nitrogen metabolism and toxicity study both in vivo and in vitro. *J Agr Food Chem* **62**: 8777–85. https://doi.org/10.1021/jf502716c

Premalatha B R 2017. Use of leaf colour chart for nitrogen management as a tool in bridging the yield gap in rainfed rice (*Oryza sativa* L.) production. *Adv Res J Crop Improv* **8:** 36-44. https://doi.org/10.15740/HAS/ARJCI/8.1/36-44

Ravi S, Ramesh S and Chandrasekaran B 2007. Exploitation of hybrid vigour in rice hybrid (*Oryza sativa* L.) through green manure and leaf colour chart (LCC) based N application. *Asian Plant Sci* **6**: 282-87.

Reena, Dhyani V C, Chaturvedi S, Gouda H S 2017. Growth, yield and nitrogen use efficiency in wheat as influenced by leaf colour chart and chlorophyll meter based nitrogen management. *Int J Curr Microbiol App Sci* **6**: 1696-1704. https://doi.org/10.20546/ijcmas.2017.612.191

Renuka K A and Senavirathna W M I 2016. Need based nitrogen management of maize (*Zea mays* L.) grown in the dry zone of Sri Lanka using a six panel leaf colour chart. *Annals Sri Lanka Dept Agric* **18**: 64-67.

Sarangi D R, Chourasia M, Sahoo T R., Prasad S M, Sethy S, Das S K and Mohanta R K 2020. Use of customized leaf colour chart for input saving and disease occurrence in rice var. *Swarna* (MTU-7029). e-planet **18 (1)**: 13-17

Sathiya K and Ramesh T 2009. Effect of split application of nitrogen on growth and yield of aerobic rice. *Asian J Expl Sci* **23**: 303-06.

Sen A, Srivastava V K, Singh M K, Singh R K, Kumar S 2011. Leaf colour chart vis-a-vis nitrogen management in different rice genotypes. *Am J Plant Sci* **2**: 223-36. https://doi.org/10.4236/ajps.2011.22024

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, Padre A T and Yadav R L 2004. Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. *Agron J* **96**: 1606-21. https://doi.org/10.2134/agronj2004.1606

Singh A and Varinderpal-Singh 2019 Evaluation of leaf colour chart based fertilizer nitrogen management technology using PAU-LCC in transplanted rice (*Oryza sativa* L.). *Int J Chem Stud* **7**: 344-49

Singh B and Singh A 2019. Response of Kharif maize (*Zea mays* L.) to planting methods and nitrogen management approach by leaf color chart. *J Krishi Vigyan* **7**: 206-10. https://doi.org/10.5958/2349-4433.2019.00034.5

Singh D K, Singh J K, Singh L 2009. Real time nitrogen management for higher N-use efficiency in transplanted rice (*Oryza sativa*) under temperate Kashmir conditions. *Indian J Agric Sci* **79**: 772-75.

Singh J, Singh V and Kaur S 2020. Precision nitrogen management improves grain yield, nitrogen use efficiency and reduces nitrous oxide emission from soil in spring maize. *J Plant Nutr* **43**: 2311-21. https://doi.org/10.1080/01904167.2020.1771588

Singh V, Bhatnagar A and Singh A P 2016. Evaluation of leaf-colour chart for need-based nitrogen management in maize (*Zea mays*) grown under irrigated condition of Mollisols. *Indian J Agron* **61**: 47-52.

Suresh M, Balaguravaiah D, Jayasree G and Kumar B N 2015. Integrated approaches through leaf colour chart and SPAD based N management on yield, N concentration in leaf and nutrients uptake in Rice (*Oryza sativa* L.). *Res J Agric Sci* **6**: 680-83.

Swamy G V V S N, Shankar T, Maitra S, Adhikary R, Praharaj S and Sairam M 2022. Influence of nitrogen management on productivity, nutrient uptake and efficiency of summer maize (*Zea mays*). *Res Crops* **23**: 313-20. https://doi.org/10.31830/2348-7542.2022.043

Swamy M, Umesh M R, Ananda N, Shanwad U K, Amaregouda A and Manjunath N 2016. Precision nitrogen management for rabi sweet corn (*Zea mays saccharata* L.) through decision support tools. *J Farm Sci* **29(1)**: 14-18.

Swarbreck S M, Wang M, Wang Y, Kindred D, Sylvester-Bradley R, Shi W, Varinderpal-Singh, Bentley A R and Griffiths H 2019. A roadmap for lowering crop nitrogen requirement. *Trends Plant Sci* **24**: 892-904. https://doi.org/10.1016/j.tplants.2019.06.006

Thind H S, Bijay-Singh, Pannu R P S, Yadvinder-Singh, Varinderpal-Singh, Gupta R K, Vashistha M, Jagmohan-Singh and Kumar A 2010. Relative performance of neem (*Azadirachta indica*) coated urea *vis-a-vis* ordinary urea applied to rice on the basis of soil test or following need based nitrogen management using leaf colour chart. *Nutr Cycl Agroecosyst* **87**:1-8. http://dx.doi.org/10.1007/s10705-009-9307-2

Thomas B 2021. Nitrogen Parameters: Worldwide leaf color chart producer. *Just Agric* **1(5)**: 32-35.

Umesh M R, Basavanneppa M A, Shivakumar, Mallesh, Chittapur B M, Ajayakumar M Y, Desai B K and Ananda N 2020. Optimization of nitrogenous fertilizers using leaf-colour chart for irrigated hybrid maize (*Zea mays*) grown in Vertisol of sub-tropical India. *Indian J Agron* **65**:77-82.

Umesh M R, Mallikarjun Swamy T S, Ananda N, Shanwad U K, Chittapur B M, Desai B K, Sangu Angadi 2018. Nitrogen application based on decision support tools to enhance productivity, nutrient-use efficiency and quality of sweet corn (*Zea mays*). *Indian J Agron* **63**: 331-36.

Varinderpal-Singh, Bijay-Singh, Thind H S,Yadvinder Singh, Gupta R K, Satinderpal-Singh, Mehrban-Singh, Satwinder-Kaur, Manmohanjit-Singh, Brar J S, Angrez-Singh, Jagmohan-Singh, Kumar A, Sukhwinder Singh, Amanpreet-Kaur and Balasubramanian V 2014. Evaluation of leaf colour chart for need-based nitrogen management in rice, maize and wheat in north-western India. *J Res (Punjab Agric Univ)* **51**: 239-45.

Varinderpal-Singh, Bijay-Singh, Yadvinder-Singh, Thind H S, Buttar G S, Satwinderjit-Kaur, Meharban-Singh, Sukhvir-Kaur and Bhowmik A 2017. Site-specific fertilizer nitrogen management for timely sown irrigated wheat (*Triticum aestivum* L. and *Triticum turgidum* L. spp. durum) genotypes. *Nutr Cycl Agroecosys* **109**: 1-16. http://dx.doi.org/10.1007/s10705-017-9860-z

Varinderpal-Singh, Bijay-Singh, Yadvinder-Singh, Thind H S, Gobinder-Singh, Satwinderjit-Kaur, 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 Res* **130**: 109-19. http://dx.doi.org/10.1016/j.fcr.2012.02.005

Varinderpal-Singh, Bijay-Singh, Yadvinder-Singh, 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. *Nutr Cycl Agroecosyst* **88**: 361-80. http://dx.doi.org/10.1007/s10705-010-9363-7

Varinderpal-Singh, Kaur N, Kunal, Blestar-Singh, Kumar J, Thapar A and Ober E S 2021. Nitrate leaching from applied fertilizer is reduced by precision nitrogen management in baby corn cropping systems. *Nutr Cycl Agroecosyst* **120**: 379-91. https://doi.org/10.1007/s10705-021-10156-3

Varinderpal-Singh, Kunal, Sharma S, Gosal S K, Choudhary R, Singh R, Adholeya A and Bijay-Singh 2020. Optical sensing and arbuscular mycorrhizal fungi for improving fertilizer nitrogen and phosphorus use efficiencies in maize. *J Soil Sci Plant Nutr* **20**: 2087-98. https://doi.org/10.1007/s42729-020-00277-z

Varinderpal-Singh, Yadvinder-Singh, Bijay-Singh, Baldev-Singh, Gupta R K, Jagmohan-Singh, Ladha J K, Balasubramanian V 2007. Performance of site-specific nitrogen management for irrigated transplanted rice in northwestern India. *Arch Agron Soil Sci* **53**: 567-79. http://dx.doi.org/10.1080/03650340701568971

Varinderpal-Singh, Yadvinder-Singh, Bijay-Singh, 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 Res*

120: 276-82. http://dx.doi.org/10.1016/j.fcr.2010.10.014

Wang G, Zhang Q C, Witt C and Buresh R J 2007. Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang province, China. *Agric Syst* **94**: 801-06. http://dx.doi.org/10.1016/j.agsy.2006.11.006

Wells B R, Turner F T 1984. Nitrogen use in flooded rice soils. In Hauck R D (Ed) *Nitrogen in crop production*. American Society of Agronomy Crop Science Society of America Soil Science Society of America Madison, Wisconsin USA. pp. 349-62. https://doi.org/10.2134/1990.nitrogenincropproduction.c23

Witt C, Buresh R J, Peng S, Balasubramanian V and Dobermann A 2007. Nutrient management. In Fairhurst T H, Witt C, Buresh R, Dobermann A (Eds), *Rice: A Practical guide to nutrient management.* International Rice Research Institute, Los Baños, Philippines and International Plant Nutrition Institute and International Potash Institute, Singapore

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**: 36-39.

Xiong D L, Chen J, Yu T T, Gao W L, Ling X X, Li Y, *et al.* 2015. SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. *Sci Rep* **5**: 1-12. http://dx.doi.org/10.1038/srep13389

Yadvinder-Singh, Bijay-Singh, Ladha J K, Bains J S, Gupta R K, Jagmohan-Singh, Balasubramanian V 2007. On-farm evaluation of leaf color chart for need-based nitrogen management in irrigated transplanted rice in northwestern India. *Nutr Cycl Agroecosyst* **78**: 167-76. http://dx.doi.org/10.1007/s10705-006-9082-2

Yogendra N D, Kumara B H, Chandrashekar N, Prakash N B, Anantha M S and Shashidhar H E 2017. Real-time nitrogen management in aerobic rice by adopting leaf color chart (LCC) as influenced by silicon. *J Plant Nutr* **40**: 1277-86. http://dx.doi.org/10.1080/01904167.2016.1263333

Yogendra N D, Prakash N B, Malagi M T, Kumara B H, Kumar R M and Chandrashekar N 2013. Effect of calcium silicate on yield and nitrogen use efficiency (NUE) of wetland rice. *Plant Arch* **13**: 89-91.

Yang W-H, Peng S, Huang J, Sanico A L, Buresh R J, Witt C 2003. Using leaf color charts to estimate leaf nitrogen status of rice. *Agron J* **95:** 212-17. https://doi.org/10.2134/agronj2003.2120

Zhao D L, Reddy K R, Kakani, V G and Reddy V R 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. *Eur J Agron* **22**: 391-403. http://dx.doi.org/10.1016/j.eja.2004.06.005