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
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 Zhejiang 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 northwestern 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.
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 \textit{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 need to be determined by one time conducting a series of field experiments before starting LCC-based N management (Bijay-Singh, 2008; Varinderpal-Singh \textit{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 \textit{et al.} (2002), Varinderpal-Singh \textit{et al.} (2007), Yadvinder-Singh \textit{et al.} (2007), and Thind \textit{et al.} (2010) found that shade 4 on the LCC or simply LCC4 was the threshold leaf greenness for realising optimum yield. In South Indian states where rice is grown both in dry and wet seasons, Porpavai \textit{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 \textit{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 \textit{et al.} (2006) identified LCC3 as the threshold leaf greenness for direct wet-seeded rice, Ali \textit{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 found to be the critical greenness level for managing fertilizer N (Jyanthi \textit{et al.}, 2007; Yogendra \textit{et al.}, 2017, Lone \textit{et al.}, 2016; Premalatha, 2017; Shukla \textit{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 \textit{et al.}, 2004; Ravi \textit{et al.}, 2007). Under system of rice intensification (SRI), Bhat \textit{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 \textit{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 \textit{et al.}, 2007). Jyanthi \textit{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 \textit{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

<table>
<thead>
<tr>
<th>Region, year, critical LCC shade, number of farms</th>
<th>N used, kg N ha⁻¹</th>
<th>Grain yield, t ha⁻¹</th>
<th>AE&lt;sub&gt;gr&lt;/sub&gt; kg grain kg N⁻¹</th>
<th>PFP&lt;sub&gt;N&lt;/sub&gt; kg grain kg N⁻¹</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FFP/REC</td>
<td>LCC</td>
<td>FFP/REC</td>
<td>LCC</td>
<td>FFP/REC</td>
</tr>
<tr>
<td>Same grain yield with reduced fertilizer N application following real time approach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>India, Haryana, LCC4, 165</td>
<td>149</td>
<td>124</td>
<td>6.36a</td>
<td>6.37a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 107</td>
<td>153</td>
<td>113</td>
<td>6.0a</td>
<td>6.0a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 48</td>
<td>115</td>
<td>91</td>
<td>6.5a</td>
<td>6.5a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 53</td>
<td>134</td>
<td>100</td>
<td>8.1a</td>
<td>8.2a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 142</td>
<td>145</td>
<td>107</td>
<td>7.0a</td>
<td>7.1a</td>
<td>-</td>
</tr>
<tr>
<td>India, Jammu &amp; Kashmir, LCC4, 1</td>
<td>120</td>
<td>90</td>
<td>7.15a</td>
<td>7.01a</td>
<td>-</td>
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<tr>
<td>India, West Bengal, LCC4, 1</td>
<td>100</td>
<td>63</td>
<td>4.47a</td>
<td>4.55a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 4</td>
<td>11</td>
<td>80</td>
<td>5.42a</td>
<td>5.77a</td>
<td>-</td>
</tr>
<tr>
<td>India, Punjab, LCC4, 2</td>
<td>120</td>
<td>100</td>
<td>7.10ª</td>
<td>7.04ª</td>
<td>-</td>
</tr>
<tr>
<td>Bangladesh, Gazipur, LCC4, TPR, 9</td>
<td>72</td>
<td>46</td>
<td>4.46a</td>
<td>4.56a</td>
<td>-</td>
</tr>
<tr>
<td>India, Karnataka, LCC5, 1</td>
<td>150</td>
<td>120</td>
<td>4.24a</td>
<td>4.30a</td>
<td>-</td>
</tr>
<tr>
<td>India, Karnataka, LCC3, aerobic rice, 1</td>
<td>100</td>
<td>75</td>
<td>3.81a</td>
<td>4.05a</td>
<td>-</td>
</tr>
<tr>
<td>India, TN, LCC5, hybrid rice, 2</td>
<td>200</td>
<td>170</td>
<td>7.55a</td>
<td>7.37a</td>
<td>-</td>
</tr>
<tr>
<td>India, Haryana, LCC4, 3</td>
<td>150</td>
<td>140</td>
<td>6.0a</td>
<td>5.98</td>
<td>-</td>
</tr>
<tr>
<td>India, Jammu &amp; Kashmir, LCC4, 1</td>
<td>120</td>
<td>100</td>
<td>7.15a</td>
<td>7.09a</td>
<td>21.3a</td>
</tr>
<tr>
<td>India, Karnataka, LCC4, 4</td>
<td>120</td>
<td>60</td>
<td>6.49a</td>
<td>6.52a</td>
<td>-</td>
</tr>
</tbody>
</table>

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 | 5.5a | 6.1b | 29.3a | 28.5b | 45.8a | 49.1b | 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 | 40.5a | 57.7b | 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 | 3.16a | 4.00b | - | - | 26 | 40 | Sen et al. (2011) |
| 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 | - | - | 48 | 66 | Ahamed et al. (2016) |
| India, Gujarat, LCC4, 3, rice | 100 | 100 | 4.44a | 4.97b | 17.0a | 19.2b | 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) |
| India, Allahabad, LCC3, 1, rice | 120 | 120 | 3.98a | 4.17a | - | - | 66 | 70 |

¶ 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.
‡ AEN, agronomic efficiency of applied N; RE<sub>N</sub>, apparent recovery efficiency of applied N; PFP<sub>N</sub>, partial factor productivity of applied N.
§ For yield and N use efficiency indices of AEN and PFP<sub>N</sub> 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. Yadavinder-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 (Suressh 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 | AE₅ | Fertilizer applied, kg N ha⁻¹ | Rice yield, t ha⁻¹ | AE₅ | Fertilizer applied, kg N ha⁻¹ | Rice yield, t ha⁻¹ | AE₅ |
| 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 Yadavinder-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 prefixed 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
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,

<table>
<thead>
<tr>
<th>Region, year, critical LCC shade, number of farms</th>
<th>N used, kg N ha(^{-1})</th>
<th>Grain yield, t ha(^{-1})</th>
<th>(AE_{n1}), kg grain kg N(^{-1})</th>
<th>(PFP_{n1}), kg grain kg N(^{-1})</th>
<th>Reference</th>
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<td>Real-time approach to adjust time and dose of fertilizer</td>
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<td>India, New Delhi, LCC4, 1</td>
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<td>4.92b</td>
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<td>120</td>
<td>4.95a</td>
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<td>120</td>
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<td>4.45b</td>
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<td>100</td>
<td>4.53a</td>
<td>4.69b</td>
<td>19.7a</td>
</tr>
<tr>
<td>Using LCC for fixed time of application and adjustable dose of fertilizer N</td>
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<td>India, Punjab, LCC4, 96</td>
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<td>India, Gurdaspur, LCC4, 3</td>
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<td>100</td>
<td>4.81a</td>
<td>4.96b</td>
<td>23.1a</td>
</tr>
</tbody>
</table>

† \(AE_{n1}\), agronomic efficiency of applied N; \(RE_{n1}\), apparent recovery efficiency of applied N; \(PFP_{n1}\), 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 \(AE_{n1}\) and \(PFP_{n1}\) at different sites, values with different letters are significantly different at the 0.05 probability level.
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 Uttar Pradesh, 13 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, Yadavinder-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 Möring et al. (2021), 60 farmers in a village in district Ludhiana in the Indian Punjab were
motivated and trained to manage fertilizer N following LCC-based real time SSNM approach. These farmers applied, on average, 75 kg N ha\textsuperscript{-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\textsuperscript{-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\textit{ 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 3\textsuperscript{rd} year. On an overall basis, LCC adoption by farmers

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**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**

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

\(\text{† AE}_{\text{NN}},\) agronomic efficiency of applied N; \(\text{RE}_{\text{NN}},\) apparent recovery efficiency of applied N; \(\text{PFP}_{\text{NN}},\) partial factor productivity of applied N.

\(\ddagger\) 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 \(\text{AE}_{\text{NN}}\) and \(\text{PFP}_{\text{NN}}\) at different sites, values with different letters are significantly different at the 0.05 probability level.
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\(^{-1}\) (Möring 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 higher 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 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\(_2\)O 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\(_2\)O emissions in both rice and wheat. Application of 120 kg N ha\(^{-1}\) using LCC4 as threshold leaf greenness in rice reduced N\(_2\)O 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\(_2\)O 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 recently 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 recently 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 N use efficiency than the blanket fertilizer management in rice, wheat, and maize leads to higher N use efficiency. In 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.

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