Rice production in the northwest part of the Indo-Gangetic Plains (IGP) is critical for India’s food security as this region contributes more than 50% of the rice procured by the Indian government for buffer and distribution to the public. The state of Punjab alone contributes 35 to 45% of rice to the national pool despite its small size while occupying only 1.5% of the geographical area of the country. The epicenter of the Green Revolution of the 1960s and 1970s, Punjab’s agricultural fecundity earned the state the recognition as the food bowl of India. Rice in this region is grown using the traditional system of puddling and transplanting, which has led to overuse of water for the last three to four decades. The underground water level in Punjab has declined by an average of about 21 inches per year between 1996 and 2006, with the rate of decline increasing to about 38 inches per year in many regions in recent years. In addition to being water intensive, the puddled-transplanted rice is highly labor intensive. To sustain rice production and productivity over a longer period, alternate rice production systems are required.

Dry-seeded rice (DSR) is an alternative production system that could help in saving water and labor costs. It appears that DSR could be adopted on a large area in the IGP where the rice–wheat cropping system predominates. Nitrogen is the most important yield-limiting nutrient for rice. A study on DSR revealed that the crop responds up to about 134 lb/ac under weed-free environments; however, under a weedy environment, the crop responds only up to 107 lb/ac. In that study, N was applied in four splits, and no comparisons were made among different split applications. The study suggested that there was a need to study crop dry matter and N translocation in response to nutrient supply so that optimum N management strategies for enhancing crop production and nutrient use efficiency in DSR could be developed.

In puddled soils, ammonium is the dominant form of available N and is lost through ammonia volatilization. Some of the ammonia is nitrified in oxidized soil zones and in floodwater; this nitrate moves into reduced layers, where it denitrifies and is lost to the atmosphere as N₂. Since nitrate is barely present in flooded rice soils, very little nitrate N is leached to the groundwater. In aerobic systems, on the other hand, the dominant form of N is nitrate, and relatively little ammonia volatilization is expected after fertilizer N application. The alternate moist and dry soil conditions may stimulate nitrification–denitrification processes in DSR, resulting in a loss of N through N₂ and N₂O. The differences in soil N dynamics and pathways of N losses in DSR systems may result in different fertilizer N recoveries. With even high N applications in aerobic rice, grain filling may be limited by a low contribution of post-anthesis assimilates. In addition, in the absence of transplanting, the roots of DSR are located in the shallow surface soil, which results in a relatively low uptake of N. These observations suggest that traditional lowland rice fertilizer schedules are not optimal for DSR.

The fertilizing schemes for DSR have become the focus of new studies to ensure rice yield and to reduce environ-
mental influence on water bodies. The rate and timing of N fertilizer should be adjusted to balance the crop’s demand before and after anthesis; therefore, proper management of crop nutrition in DSR is of immense importance. Timely and split application of N allows for more efficient use of N throughout the growing season as it provides specific amounts of nutrients to the crop during peak periods of growth and may reduce leaching of nitrate N. Making accurate N fertilizer recommendations for rice is becoming more important as concern grows about the high cost of this input and nitrate pollution of surface and ground waters in agricultural areas.

It was hypothesized that the N requirement of DSR at different growth stages can be met by increasing the number of splits and doses of N. A recent study published in Agronomy Journal was conducted to evaluate the performance of DSR in relation to grain yield and dry matter of rice as well as N translocation as affected by rate and timing of N application. Specifics about the experimental site and design are provided in the original article (see reference information at the end of this article).

Field experiments were conducted at the research farm of Punjab Agricultural University, Ludhiana, India during the rainy seasons of 2009 and 2010. The climate is subtropical with a hot summer, wet monsoon season (July–September), and a cool, dry winter. Average annual rainfall is 29 inches, 85% of which falls during the monsoon season. The site was under a rice–wheat cropping system for five years before the establishment of the experiment.

Monthly average maximum and minimum temperature did not vary greatly across the year for the same month during the rice season. Average maximum temperature during the rice season (June–October) ranged from 89 to 104°F in both 2009 and 2010. Similarly, average minimum temperature during the rice season (June–October) ranged from 62 to 80°F in 2009 and from 66 to 80°F in 2010.

Crop management

Fields were prepared with two passes using a disc-harrow, followed by leveling with a wooden board. Rice seeds were sown on June 10, 2009 and June 13, 2010 using medium-duration variety PAU-201. Seeds were sown by single-row drill at a seeding rate of 27 lb/ac and at 20-cm row spacing using a hand-furrow opener. The field was surface-irrigated immediately after sowing. Nitrogen fertilizer was applied to each plot at three N levels (107, 134, and 161 lb/ac) and three timings (three equal splits at sowing time and 21 and 42 days after sowing; four equal splits at sowing and 21, 42, and 63 days after sowing; and four equal splits at 15, 30, 40, and 60 days after sowing). Recommended herbicides and insecticides were used to control weeds and insects, respectively. All plots were sprayed twice with 1% ferrous sulfate solution (27 gal/ac) at 20 and 40 days after sowing (DAS). The crop was harvested at 15 to 18% grain moisture content in all treatments each year. Dry matter translocation, translocation efficiency, and dry matter contribution to grain yield were calculated as:

\[
\text{Dry matter translocation} = \text{total aboveground dry matter at anthesis} - \text{dry matter of vegetative parts at maturity}
\]

\[
\text{Dry matter translocation efficiency} = \left(\frac{\text{dry matter translocation}}{\text{total aboveground dry matter at anthesis}}\right) \times 100
\]

\[
\text{Contribution of pre-anthesis assimilates to grain weight} = \left(\frac{\text{dry matter translocation}}{\text{grain weight at maturity}}\right) \times 100
\]

In the first year of the study, the authors observed that early senescence induced by N deficiency due to application of N in three splits altered the remobilization of stored assimilates during grain filling and that N accumulation in plants before anthesis and its translocation after anthesis could be an important source of photosynthetic products and nitrogenous compounds for grain development in DSR. Therefore, in 2010, N translocation-related parameters were also calculated on the basis of N content in the corresponding plant parts. Nitrogen harvest index
Yield and yield attributes

Increasing N rates and splits had a significant influence on grain yield, while straw yield and harvest index were not influenced, indicating that N rates and timings had more influence on grain N uptake than on straw N uptake. Positive and significant relationships were reported between grain N uptake and grain yield and between straw N uptake and straw yield. Increasing N rates had no influence on grain yield when applied in three splits. However, when applied in four splits, grain yield increased with increasing N rates from low to high levels. This might be due to greater N use efficiency and reduction in N losses (probably denitrification and leaching) with N application in four splits than in three splits due to timely availability of N to the crop. The highest grain yield was obtained when 134 lb/ac was applied with no N at sowing, and the lowest grain yield was obtained with 107 lb/ac applied in three splits. In DSR, root systems are not well developed at the beginning of plant growth or seedling growth stage, and plants could not absorb the entire N applied at sowing, so most of the N applied at sowing may be lost through denitrification or leaching. Recently, it was reported at the same location that deep drainage losses occur more with DSR than in the puddled-transplanted rice due to a higher infiltration rate in the non-puddled soil in daily irrigated puddled and non-puddled soil, respectively. Yield attributes such as panicle number per square meter, filled grains per panicle, and 1,000-grain weight showed the same trend as that of grain yield. Application of 134 lb/ac in four splits with no N at sowing resulted in 9 to 12, 19 to 24, and 5% increase in panicle number per square meter, filled grains per panicle, and 1,000-grain weight, respectively, over the application of 107 lb/ac in three splits due to greater N translocation efficiency. Increases in yield components with increasing N rates and splits are associated with improved nutrition, plant growth, and increased nutrient uptake. Where grain yield response is negative, yield reduction is primarily caused by a reduction in the proportion of the number of filled spikelets per panicle.

Several studies in lowland rice indicated that filled grains per panicle is significantly correlated with dry matter translocation from stems and leaves into grains. Spikelet sterility was higher when N fertilizer was applied in three splits rather than four splits. Application of 134 lb/ac in four splits had stimulatory effects on plant growth, leading to increased yield and yield attributes such as number of panicles, filled grains per panicles, and 1,000-grain weight. The apparent mechanism for achieving these improvements was the increase in leaf area index (LAI) and dry matter accumulation at anthesis, providing an improved resource-generating base for the crop (i.e., an improved carbohydrate resource). A significant and positive correlation was observed between LAI and grain yield in the present study. Improvements in panicle number and filled grains per panicle are important aspects to achieve more sink size. Elsewhere, it has been reported that the DSR crop, due to better exploitation of assimilates to the panicle during anthesis, resulted in highly fertile florets.

Nitrogen application at 134 lb/ac in four splits also improved assimilate partitioning in favor of yield as seen in greater dry matter translocation, dry matter translocation efficiency, and higher contribution of pre-anthesis assimilate to grain weight. Early studies conducted in Korea indicated that 40 to 50% more N fertilizer should be applied in DSR than in transplanted rice. Compared with puddled-transplanted rice, N applied at 60 DAS in DSR might have met the crop’s N demand immediately before anthesis and during grain filling. In general, final grain yield of rice is determined by dry matter (mainly carbohydrate) that accumulated in the shoots before anthesis and dry matter from photosynthetic production after anthesis. Pre-anthesis reserves of sugar and starch in plants may contribute 20 to 40% to the final crop yield, which means...
that dry matter production during grain filling potentially contributes 60 to 80% to crop yield. In the current experiment, the contribution of pre-anthesis assimilates to grain yield ranged from 12 to 50%, but the contribution of post-anthesis assimilates was reduced from 88 to 50% with 134 lb/ac N applied in four splits. These rates of pre- and post-anthesis contributions indicate that pre-anthesis productivity and dry matter translocation to grains were acceptable with this level of N applied in four splits; there remains a scope for yield improvement by increasing post-anthesis productivity.

The results of the present study suggest that an important period for N uptake in rice plants in DSR was from panicle initiation to the end of anthesis as the crop response was poor when N was applied in three splits, irrespective of N dose. Fertilization rate and timing may be the most critical factors in determining fertilizer uptake efficiency and crop yield. Improving the N utilization rate of plants may significantly reduce the total amount of added fertilizers. The regime of fertilizer N application needs to promote the contribution of dry matter production between anthesis and post-anthesis to achieve more sink size.

Increased splits with 107 and 134 lb/ac N had no influence on N uptake at anthesis. However, N uptake at anthesis was highest with 134 lb/ac N applied in four splits. Nitrogen uptake in grain and total N uptake were significantly influenced by N rates and splits while straw N uptake was not affected. At each N level, four splits had more N uptake in the grains than the three splits.

N translocation efficiency was not influenced by the number of splits at lower levels of N. However, at higher N levels, N translocation efficiency was greater with four splits as compared with that using three splits.

Conclusions

The DSR responded up to 134 lb/ac N applied in four splits resulting in increased LAI, higher relative water content of the flag leaf, and pre-anthesis dry matter accumulation of the crop. Compared with the three splits, the four-split treatment resulted in greater dry matter translocation from pre-anthesis biomass to grain yield. Application of N at sowing time could be skipped in DSR as it may not be used immediately by rice plants. Application of N fertilizer at or after anthesis may increase post-anthesis dry matter accumulation and grain filling in DSR; however, this needs to be verified by using various rice cultivars.