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Methodology for Evaluation of Lowland Rice Genotypes for Nitrogen Use Efficiency

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ABSTRACT

Rice is a staple food for more than 50% of the world's population. Based on land and water management practices, rice ecosystem is mainly divided into lowland, upland, and deep water or floating rice. However, major area and production at global level comes from lowland or flooded rice system. In rice growing regions nitrogen (N) is one of the most yield-limiting nutrients for rice production. Adaptation of cultivars or genotypes with high N use efficiency is a potential strategy in optimizing N requirements of crops, lowering the cost of production and reducing the environmental pollution. The objectives of this paper are to discuss rate and timing of N application, define N-use efficiency, discuss mechanisms involved for genotypic variation in N-use efficiency and present

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experimental evidence of genotypic variations in N-use efficiency in lowland rice. Evaluation methodology and criteria for screening N-use efficiency are also discussed. Significant variation in N use efficiency exists in lowland rice genotypes. Nitrogen use efficiency parameters (grain yield per unit of N uptake, grain yield per unit of N applied and recovery of applied N) are useful in differentiating lowland rice genotypes into efficient and non-efficient responders to applied N. Such an evaluation could assist in identification of elite genotypes that could be used in breeding program to produce cultivars with high N use efficiency and capable of producing high yields.

Key Words: Grain yield; Grain yield efficiency index; Nutrient use efficiency mechanisms; Screening for N use efficiency.

INTRODUCTION

Rice is an important crop worldwide, providing a major portion of the staple diet in many regions. A major portion of the world's rice crop is produced and consumed in Asia. China and India are the leading producers as well as consumers of rice. Other major rice-producing countries are Japan, Thailand, Vietnam, and Indonesia. *Oryza sativa* L. and *Oryza glaberrima* Steud. are two cultivated species of rice. *Oryza sativa* is widely cultivated, but *O. glaberrima* is mainly cultivated in Africa where it is rapidly being replaced by *O. sativa*. The origin of *O. sativa* is controversial but it is thought to have been domesticated in India or Indochina.[1] *Oryza glaberrima* originated in Africa. *Oryza sativa* is further divided into the japonica, indica, and javanica ecological groups. Japonica rice, adapted to cooler areas, is widely grown in temperate regions such as central and northern China, Korea, and Japan, while indica is widely grown in tropical regions. Both of these groups can be grown in subtropical regions. Javanica is the tall, large, and bold (heavy) grain bulu cultivar of Indonesia, but it has spread to Japan, Taiwan, and the Philippines.[2]

In most of the rice producing regions of the world, nitrogen (N) is one of the most yield limiting nutrients for rice production.[1,3,4] Rice requires more N than other essential nutrients except for potassium (K).[1,5,6] Fertilizer along with pesticides are the most expensive inputs in rice production. Environmental pollution due to leaching or runoff of nutrients, especially N, from rice fields has become major concern.[4,7] On-farm research conducted in different countries has demonstrated the presence of a large and potentially useful variability in soil nutrient supply and crop response to added nutrients.[4,7–11] Therefore, the objectives of this paper are to discuss the rate and timing of N application, define the N use efficiency parameters (uptake, utilization, recovery) and evaluation of existence of variation in N-use efficiency in lowland rice genotypes.

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RATE AND TIMING OF NITROGEN APPLICATION FOR LOWLAND RICE

Nitrogen is the most important nutrient for crop production, and its deficiency occurs in most rice growing regions of the world. The main reasons for N deficiency are (i) loss of N by leaching, volatilization, and denitrification; (ii) lower rates of N applied compared to rates of N removed in the harvested portion of the crop; (iii) low N use efficiency by the crops; (iv) use of high yielding and N responsive cultivars; and (v) soil degradation with successive crop cultivation. The loss of N in lowland rice culture depends on soil properties, timing of N application and water management during crop growth cycle. Losses of N are minimum in heavy textured soils with high cation exchange capacity, N applied during maximum absorption or requirements of the crop and once rice is established, the flood is maintained until physiological maturity. If water is drained during crop growth cycle, NH_4^+ is oxided to NO_3^- and NO_2^- and upon flooding N is lost through leaching and denitrification or both depending on soil properties, crop root system development and level of demand for N.

Traditionally, the optimum rate of N-fertilization has been, the rate that results in maximum economic yield. Required optimum N rate varies with soil type, yield potential of cultivar, levels of phosphorus (P) and K in the soil, water management practices, and intensity of diseases, insects, and weeds. These are technological factors. However, rate of fertilizer application is also governed by socio-economic factors. Such factors are production cost, economic situation of the farmers, efficiency of extension service, and availability of credit to the growers.

Use of adequate N rate is important not only for obtaining maximum economic return, but also to reduce environmental pollution. Excessive N application can result in accumulation of large amounts of postharvest residual soil N. Residual soil NO_3^- may be available for subsequent crops in the next season, but such N is highly susceptible to leaching during noncrop periods under high rainfall and low evaporation. The optimum rate and timing of N application in selected countries are presented in Table 1.

DEFINITION OF NUTRIENT USE EFFICIENCY AND METHODS OF CALCULATION

The nutrients use efficiency can be defined as the maximum economic yield produced per unit of nutrient applied, absorbed or utilized by the plant to produce grain and straw. However, in the literature, nutrient use efficiency has been defined in several ways. Nutrient use efficiencies are grouped or

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Table 1. Rate and timing of N application reported for lowland rice in different countries.

Country/state	Soil type	Rate used ($kg\,N\,ha^{-1}$)	Grain yield ($kg\,ha^{-1}$)	Application timing[a]	Reference
Brazil (Goiás)	Inceptisol	90–120	6,345–6,400	1/3 at S + 1/3 at AT + 1/3 at PI	Fageria and Baligar[12]
Brazil (Tocantins)	Inceptisol	90	7,093	1/2 at S + 1/2 at AT	Fageria and Prabhu[13]
USA (California)	Not given	130	7,000	All at sowing	Jongkaewwattana et al.[14]
USA (Louisiana)	Typic Albaqualf	134	7,017	All at sowing	Mengel and Wilson[15]
IRRI (Philippines)	Andaqueptic Haplaquoll	80	6,494	1/2 at S + 1/2 PI	Ladha et al.[16]
IRRI (Philippines)	Aquandic Epiaqualfs	225	5,050	1/4 at S + 1/4 at MT + 1/4 at PI + 1/4 at F	Hussain et al.[17]
India (Ludhiana—Punjab)	Typic Ustipsamments	240	6,410	1/3 at S + 1/3 at MT + 1/3 at PI	Hussain et al.[17]
Bangladesh	Typic Haplaquept	135	6,312	1/3 at BT + 1/3 at MT + 1/3 at 3 to 5 DBPI	Timsina et al.[18]
IRRI (Philippines)	Andaqueptic Haplaquoll	240	9,100	100 kg at MT + 100 kg at PI + 40 kg N at F	Peng and Cassman[19]

[a]S, sowing; AT, active tillering; PI, panicle initiation; MT, midtillering; F, flowering; BT, before transplanting; DBPI, days before panicle initiation.

classified as agronomic efficiency, physiological efficiency, agro-physiological efficiency, apparent recovery efficiency, and utilization efficiency and are calculated by using the following formulas:[1,3]

$$\text{Agronomic efficiency (AE)} = \frac{G_f - G_u}{N_a} = \text{kg kg}^{-1}$$

where G_f is the grain yield in the fertilized plot (kg), G_u is the grain yield in the unfertilized plot (kg), and N_a is the quantity of nutrient applied (kg).

$$\text{Physiological efficiency (PE)} = \frac{Y_f - Y_u}{N_f - N_u} = \text{kg kg}^{-1}$$

where Y_f is the total biological yield (grain plus straw) of the fertilized plot (kg), Y_u is the total biological yield in the unfertilized plot (kg), N_f is the nutrient accumulation in the fertilized plot (kg), and N_u is the nutrient accumulation in the unfertilized plot (kg).

$$\text{Agrophysiological efficiency (APE)} = \frac{G_f - G_u}{N_f - N_u} = \text{kg kg}^{-1}$$

where G_f is the grain yield in the fertilized plot (kg), G_u is the grain yield in the unfertilized plot (kg), N_f is the nutrient accumulation by straw and grains in the fertilized plot (kg), and N_u is the nutrient accumulation by straw and grains in the unfertilized plot (kg).

$$\text{Apparent recovery efficiency (ARE)} = \frac{N_f - N_u}{N_a} \times 100 = \%$$

where N_f is the nutrient accumulation by the total biological yield (straw plus grain) in the fertilized plot (kg), N_u is the nutrient accumulation by the total biological yield (straw plus grain) in the unfertilized plot (kg), and N_a is the quantity of nutrient applied (kg).

$$\text{Utilization efficiency (EU)} = \text{PE} \times \text{ARE} = \text{kg kg}^{-1}$$

Fageria and Baligar[3] calculated N use efficiency for lowland rice and values are presented in Table 2. All the N-use efficiencies were significantly decreased with increasing applied N rates with some exception in physiological efficiency. Eagle et al.[20] reported that in rice N use efficiency, which has both a physiological and soil N supply component, decreased with increase in soil N supply.

Table 2. Nitrogen use efficiency parameters of lowland rice under different N rates across the three years.

N added (kg ha^{-1})	Agronomic efficiency (kg kg^{-1})	Physiological efficiency (kg kg^{-1})	Agrophysiological efficiency (kg kg^{-1})	Apparent recovery efficiency (%)	Utilization efficiency (kg kg^{-1})
30	35	156	72	49	76
60	32	166	73	50	83
90	22	182	75	37	67
120	22	132	66	38	50
150	18	146	57	34	50
180	16	126	51	33	42
210	13	113	46	32	36
Average	23	146	63	39	58
R^2	0.93**	0.62*	0.87**	0.82**	0.90**

*,**Significant at the 0.05 and 0.01 probability levels, respectively.
Source: Fageria and Baligar.[3]

Across N rates, agronomic efficiency was 23 kg grain produced per kg N applied, and physiological efficiency was 146 kg biological yield (straw plus grain) per unit of N accumulated. Agrophysiological efficiency was 63 kg grain produced per kg of N accumulated in the grain and straw across N rates. Apparent recovery efficiency was 39% and utilization efficiency was 58 kg grain produced per kg of N utilized.

Agronomic efficiency in lowland rice in the tropics is reported to be in the range of 15 to 25 kg grain produced per kg of applied N.[21] Results presented in Table 2 are within this range. Higher physiological efficiency (146 kg kg^{-1}) as compared to agrophysiological efficiency (63 kg kg^{-1}) across the N rates is due to inclusion of dry matter in calculating this efficiency. Singh et al.[22] reported an agrophysiological efficiency of about 64 kg grain produced per kg of N uptake and agronomic efficiency of 37 kg grain produced per kg of N applied in 20 lowland rice genotypes. An apparent recovery efficiency of 39% across N rates is quite low. The percentage of N recovery varies with soil properties, methods, amounts, and timing of fertilizer applications and other adapted management practices. It usually ranges from 30 to 50% in the tropics.[23] Studies conducted in the southern United States on the influence of different application timings and N management strategies have on N-use efficiency showed an ARE at rice maturity of 17 to 61% of the applied N.[24,25] Singh et al.[22] reported a N recovery efficiency of 37% in 20 lowland rice genotypes. Raun and Johnson[26] reported that in the world cereals, ARE for N is about 33%. These authors also reported that an increase of N use efficiency of 20% would result in a savings in excess of 4.7 billion US$ in N fertilizers costs per year worldwide for cereal production. Results obtained by Fageria and Baligar[3] (Table 2) are within this limit. The low N recovery efficiency in lowland rice may be related to N losses from soil via nitrification–denitrification, NH_3 volatilization, or leaching.[27] The average utilization efficiency for grain production in lowland rice in the tropics is about 50 kg grain produced per kg N absorbed.[21] The utilization efficiency for lowland rice genotypes obtained under Brazilian conditions are in the range of 36 to 83 and average across the N rates was 58 (Table 2).

MECHANISMS FOR GENOTYPIC DIFFERENCES IN NUTRIENT USE EFFICIENCY

Plant genetic variability can be defined as the heritable character of a particular crop species or cultivar that shows differences in growth or production in comparison with other species, or cultivars of the same species, under favorable or unfavorable growth conditions.[28] In the last three decades it has been shown that large differences do exist among species, or cultivars of

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the same species, in absorption, translocation, and utilization of mineral nutrients.[29–36] Similarly, differences have also been observed between plant species and varieties in their tolerance to nutrient and/or element toxicities.[1,28,29]

Table 3 summarizes various soil and plant mechanisms and processes and other factors that influence the genotypic differences in plant nutrient use efficiency. However, here no attempt is being made in this review to discuss these mechanisms or processes in details. For extensive reviews related to nutrient flux at the soil–root interface and across roots and shoot and mechanisms of uptake and utilization in soil–plant system, see Fageria et al.[1] Baligar and Fageria,[35] Mengal and Kirkby,[37] Barber,[38] and Marschner.[39]

GENOTYPES EVALUATION CRITERIA AND METHODOLOGY FOR NUTRIENT USE EFFICIENCY

Since the first experiments with fertilizers were reported in the middle of the 19th century, it has been known that some crops are more sensitive than others to nutrient stresses.[40] In early work at the Rothamsted experimental station in England, root crops were found to respond more to the applied phosphate fertilizer than cereal crops grown on the same soil.[40] It has been also known for several years that genotypes/cultivars of the some species differ in their sensitivity to nutrient deficiencies and toxicities of aluminum (Al), manganese (Mn), and salinity.[41] With increasing world population, high costs of crop production and issues related to environmental pollution, the need for breeding and selecting more efficient or tolerant cultivars to sustain or improve crop production on low productive soils has gained the momentum.

Following basic principles or considerations should be taken into account for mineral stress-screening programs for identification of improved rice genotypes.[32]

1. Uniform growth medium.
2. Uniform ecological conditions.
3. Well-defined plant evaluation parameters.
4. Screening techniques: these techniques must be simple, repeatable, and inexpensive and should permit evaluation of a large number of genotypes with reasonable precision.
5. Selection of an appropriate site: soil of the experimental site should be deficient in a selected nutrient, if the objective of the study is to determine efficiency for low nutrient level. Similarly, if the objective of plant screening is for Al toxicity tolerance, the selected site

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Table 3. Soil and plant mechanisms and processes and other factors that influence genotypic differences in nutrient use efficiency.

A. Nutrient acquisition
   1. Diffusion and mass flow (buffer capacity, ionic concentration, ionic properties, tortuosity, soil moisture, bulk density, temperature).
   2. Root morphological factors (number, length, root hair density, root extension, root density).
   3. Physiological [root : shoot, root microorganisms such as mycorrhizal fungi, nutrient status, water uptake, nutrient influx and efflux, rate of nutrient transport in roots and shoots, affinity to uptake (K_m), threshold concentration ($C_{\min}$)].
   4. Biochemical (enzyme secretion as phosphate, chelating compounds, phytosiderophore), proton exudate, organic acid production such as citric, transaconitic, malic acid exudates.

B. Nutrient movement in root
   1. Transfer across endodermis and transport within root.
   2. Compartmentation/binding within roots.
   3. Rate of nutrient release to xylem.

C. Nutrient accumulation and remobilization in shoot
   1. Demand at cellular level and storage in vacuoles.
   2. Retransport from older to younger leaves and from vegetative to reproductive parts.
   3. Rate of chelates in xylem transport.

D. Nutrient utilization and growth
   1. Metabolism at reduced tissue concentration of nutrient.
   2. Lower element concentration in supporting structure, particularly the stem.
   3. Elemental substitution, e.g., Na for K function.
   4. Biochemical nitrate reductase for N-use efficiency, glutamate dehydrogenase for N metabolism, peroxidase for Fe efficiency, pyruvate kinase for K deficiency, metallothionein for metal toxicities.

E. Other factors
   1. Soil factors
      a. Soil solution (ionic equilibria, solubility precipitation, competing ions, organic ions, pH, phytotoxic ions).
      b. Physico-chemical properties of soil (organic matter, pH, aeration, structure, texture, compaction, soil moisture).
   2. Environmental effects.
      a. Intensity and quality of light (solar radiation).
      b. Temperature.
      c. Moisture supply.
   3. Plant diseases, insects, and allelopathy.

Source: Compiled from various sources by Baligar and Fageria.[35]

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should have toxic levels of Al to influence growth of the tested genotypes. According to Hamblin et al.,[42] the criteria of site selection for screening should be that the yield of the selected genotypes at the test locality consistently corresponds to their yield when grown over the range of environments for which they are intended.

6. Nutrient levels: the minimum and maximum nutrient requirements for the growth of a crop species under investigation should be known in advance.
7. When screening for a determined nutrient use efficiency, other nutrients in growth medium must be present in adequate amounts.
8. Two genotypes may respond equally well at one concentration and quite differently at a second level of elemental concentrations. A response curve for a determined nutrient levels is desirable before deciding the appropriate level or levels of nutrient that should be adopted for evaluation in the experiment.
9. If the concentration of the limiting nutrient is either too low or too high, selection pressure falls to zero, therefore, such levels should be avoided.
10. Known efficient and non-efficient cultivar should be included in the screening study.
11. Plant materials chosen for screening should be genetically uniform.
12. Plant materials under screening should be separated according to their growth cycle to facilitate growth observations as well as harvesting for comparison of obtained results.
13. Appropriate statistical analysis technique should be adapted to classify genotypes into efficient and inefficient groups.

FIELD SCREENING

Field screening is an important step in the evaluation of crop genotypes for mineral stresses and their subsequent uses in breeding programs. The first question that generally arises in field screening trials is that, what should be the plot size and how many levels of given nutrient should be adopted for screening purposes. When a large number of crop genotypes are used for screening it is not possible to use larger plots due to labor and input cost involved. Therefore, in screening trials, field plots may be smaller as large number of cultivars/lines can be tested. This raises questions about possible interference between plots, particularly when cultivars in trial show marked differences in growth characteristics. The problem is especially critical in cereals when taller cultivars are compared along with dwarf ones. Several

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studies have shown that yields of semi-dwarf wheat are substantially reduced when grown in plots along with taller conventional cultivars.[43] Workers with other crops have found interferences to be associated with cultivars differences in tillering ability[44] or root size.[45] However, under field conditions we have screened large number of upland and lowland rice cultivars for N and P efficiencies[46–49] and from these studies it was concluded that, for each genotype two rows of 5 to 6 m in length at each nutrient level and replicated twice were sufficient to give reasonably precise results. It is more desirable to have more replication, rather than more rows of a genotype in the screening experiments. As far as nutrient levels are concerned, three levels are appropriate, i.e., low, medium, and high. However, screening can also be done at two levels (low and high) as well at one level that is neither too low nor too high. If three fertility nutrient levels are used, the best criteria to select these levels is a control (without fertilizer application), level commonly used by farmers for a particular crop and region and the third level may be selected that is based on the soil test calibration curves. In general farmers, especially in developing countries use lower levels of fertilizer than that are recommended by researchers. In screening experiments, one should also use one or two check (nutrient efficient and nutrient inefficient) genotypes under investigation. These genotypes should be planted at a regular interval between other genotypes. If two genotypes are used, one should be a local cultivar and other may have a higher efficiency in nutrient utilization.

Grain yield is the best measure of a genotype evaluation in a screening experiments. Field screening results can be interpreted using the grain yield efficiency index (GYEI):[48]

$$\text{GYEI} = \frac{(\text{Yield at low nutrient level})(\text{Yield at high nutrient level})}{(\text{Experimental mean yield at low nutrient level}) \times (\text{Experimental mean yield at high nutrient level})}$$

The GYEI helps to separate genotypes into high-yielding, stable, nutrient efficient genotypes and low-yielding, unstable, and nutrient inefficient genotypes. Tolerant genotypes have a GYEI of 1 or higher. The susceptible or nutrient inefficient genotypes have a GYEI in the range of 0 to 0.50 and the genotypes between these two limits are considered intermediate types.[48] The GYEI generally used for separating efficient and inefficient genotypes where two nutrient levels have been used. However, this index can also be used in the experiments where three nutrient levels have been used. In this case yield at low nutrient can be compared separately with medium and high nutrient levels.

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SCREENING UNDER CONTROLLED CONDITIONS

Screening of crop genotypes/cultivars for mineral stresses (deficiency/toxicity) can be done under controlled conditions using soil or solution culture as a growth medium. In solution culture, it is possible to manipulate elemental concentrations as desired, but it requires much work in controlling pH and maintaining stable elemental concentrations. It is easier to work with soil as a growth medium as compared with solution culture. The nutrient levels in soil can be manipulated by mixing topsoil and subsoil. Generally, immobile nutrients are concentrated in the top layer, and subsoils have lower concentrations of these nutrients. The level of nutrients required to grow normal plants in a greenhouse is generally high, compared with field conditions.[28] Therefore, one should be careful in selecting nutrient levels in soil under greenhouse conditions.

When screening for a particular nutrient use efficiency, a plant response curve should be developed before starting the mass screening of genotypes. In developing a response curve, a large range of concentrations in selected soil or chosen nutrient culture medium should be used to obtain a quadratic response, and more than one cultivar should be used. From such a curve, two or three nutrient levels (low, medium, and high) can be selected for screening purpose. One of the prerequisites of varietal/genotypic screening for mineral stress is that, the growth medium should have a deficient and/or toxic level of the nutrient/element under study along with sufficient or near sufficient levels of nutrient under consideration. Toxic level is applicable for screening Al or salinity toxicity. It is also applicable for screening lowland rice genotypes for iron toxicity.

Nutrient uptake efficiencies of crop genotypes can be evaluated in solution culture at various concentrations.[34,35] The genotypes can be classified on the basis of dry matter produced per unit nutrient absorbed. Higher dry matter production per unit of nutrient absorbed means greater efficiency of genotype and vice versa.

GENOTYPIC VARIATIONS IN NITROGEN USE EFFICIENCY

Nitrogen is the most yield-limiting nutrient for rice production worldwide[3,9,20,50,51] and because of many opportunities for N losses, especially in the alternating wet/dry cycles in areas where rice is cultivated, and it is also the most difficult nutrient to manage.[50,52] Dobermann et al.[51] reported the results of long-term field experiments conducted at the International Rice Research Institute (IRRI) at Los Baños, Philippines. In these studies, N

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deficiency caused a yield decline from 1968 to 1991, at an annual rate of 1.4 to 2.0%. However, from 1991 to 1995, rate of applied N increased during the dry season and such an improved rate and timing of N application accounted for the restoration of yields. Continuous rice rotations in southeast Asia have resulted in increased levels of soil organic matter, although an apparent N deficiency in the system led to a decline in rice yield.[53]

Grain yield, N content in grain, N harvest index (N uptake in grain/N uptake in grain plus straw), and N use efficiency (APE) were significantly varied among genotypes grown in Oxisol at zero and 304 mg N kg^{-1} of soil levels (Table 4). Grain yield was significantly different among genotypes and varied from as low as 25.43 g per pot produced by genotype, CNA 8619 to as high as 43.0 g per pot produced by genotype, CNA 7556. Values of N uptake in grain varied from 287.60 g per pot to 612.62 g per pot and the lowest grain yield producing genotype, CNA 8619 had the lowest N uptake value. Nitrogen harvest index is a measure of N partitioning in rice, which provides an indication of how efficiently the plant utilized the acquired N for grain production. The lowest grain producing genotype CNA 8619 had the lowest N harvest index, whereas the highest grain producing genotype CNA 7556 had the highest N harvest index. Genetic variability for N harvest index exists within the small grain genotypes and a high N harvest index in the genotypes was associated with efficient utilization of N.[55] Variation in the N harvest index is a characteristic of genotype and such trait may be useful variable for selecting rice genotypes for higher grain yield. Further, importance of this variable is also indicated by a highly significant correlation between N harvest index and grain yield.[56]

Nitrogen-use efficiency (APE) was significantly varied among genotypes and it ranged from 32.57 to 71.47 mg grain produced per mg of N absorbed. Many researchers have reported significant variations of N-use efficiency among lowland rice genotypes.[57,58] Such differences may be related to genetic factors, physiological processes (absorption, translocation, assimilation, N remobilization, and storage), and biochemical processes (enzyme nitrate reductase efficiency).[34,35,59] Based on N-use efficiency and grain yield at a low soil N level, rice genotypes have been classified into four groups. Fageria and Baligar[60] have suggested such classification to categorize crop genotypes for their nutrient use efficiency. The first genotype group was efficient and responsive (ER). Those genotypes which produce above the average yield compared to all the genotypes tested in the experiment at low N level and N-use had higher efficiency than the average of all the genotypes. Genotypes Rio Formoso, CNA 7550, and CNA 7556 fall into this group. The second classification was genotypes that are efficient and nonresponsive (ENR). These genotypes produced more than the average yield of 8 genotypes tested in this study at low N level, but N-use efficiency was lower than the

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Table 4. Grain yield and N uptake parameters of eight lowland rice genotypes across two N levels.

Genotype	Grain yield (g/pot)	N uptake in grain (mg/pot)	N harvest index	N use efficiency (mg grain/mg N uptake in grain plus straw)
Javae	39.90ab	506.22ab	0.60ab	35.86b
Rio Formoso	40.80ab	470.43ab	0.58ab	46.00b
CNA 6343	36.67ab	612.62a	0.61ab	32.57b
CNA 7550	42.22a	573.45a	0.63a	47.10b
CNA 7556	43.00a	522.70ab	0.66a	52.27ab
CAN 7857	40.06ab	419.40ab	0.58ab	71.47a
CAN 8319	30.42ab	402.17ab	0.52ab	37.73b
CNA 8619	25.43b	287.60b	0.44b	40.83b
Average	37.31	474.32	0.58	45.48

Note: Means followed by the same letter in the same column are not significantly different at the 5% probability level by Tukeys test.
Source: Compiled from Fageria and Barbosa Filho.[54]

average of all genotypes classified in this group. The genotype Javae and CNA 6343 fall into this group. The third type of genotypes are known as nonefficient and responsive (NER) are included. The genotypes which produce less than average grain yield of eight genotypes at low N level, but N-use efficiency was above the average of eight genotypes are classified in this group. The only genotype fall into this group was CNA 7857. The fourth group of genotypes is those which produced less than the average yield of eight genotypes at low N level and response to applied N (N use efficiency) was also less than the average of eight genotypes. These type of genotypes were classified as nonefficient and nonresponsive (NENR). The genotypes in this group were CNA 8319 and CNA 8619. From a practical point of view, the genotypes which fall into ER group are the most desirable, because they can produce well at a low soil N levels and also respond well to applied N. Thus, this group can be utilized with low as well as high input technology with reasonably good yield.[60] The second most desirable group is ENR. Genotypes of this type can be planted under low N level and still produce more than average yield. The NER sometimes can be used in breeding programs for their N-responsive characteristics (higher N use efficiency). The most undesirable genotypes are the NENR. These results indicate that lowland rice genotypes differ in their N-use efficiency. Both inter- and intraspecific variation in N nutrition have been recognized among cereal species and genotypes.[1,52] Thus it may be possible to develop cultivars that are efficient at low-nutrient levels or are capable of using N more efficiently when applied as fertilizer.

CONCLUSIONS

Worldwide, N use efficiency in lowland rice is less than 50%. The percentage of N that is unaccounted for represents a heavy loss of applied N fertilizer. Such N loss is not only responsible for higher costs of rice production but may also lead to enhanced environmental pollution. The low recovery of N in lowland rice culture is due to losses through surface runoff, volatilization, denitrification, and leaching. Use of adequate rate and timing of N application improves grain yield potentials and reduces N losses. In addition to this, adaptation of N use-efficient genotypes in combination with integrated nutrient management practices can improve N recovery efficiency. Results obtained in various field trials, clearly showed significant differences in N-use efficiency among lowland rice genotypes. However, for significant improvement in N use efficiency, more work is needed to understand better the physiological or biochemical mechanisms responsible for N-use efficiency. In addition, N-use efficient genotypes should be used in breeding programs to develop agronomically suitable cultivars for different rice producing regions.

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