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Review Article

THE ROLE OF FRESH *AZOLLA LOCAL BESUKI'S* IN IMPROVING THE NITROGEN USE EFFICIENCY OF PADDY FIELD

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Abstract

The development of management techniques to improve the poor N use efficiency by lowland rice (*Oryza sativa* L.) and reduce the high N losses has been an important focus of agronomic research. The potential of an *Azolla* cover in combinationwith urea was assessed under field conditions in Jember, East Java,Indonesia. Two on-station field experiments were established in the 1998–1999 dry season and eight on-farm experiments per season were carried out in the 2000–2001 wet and dry seasons. Treatment combinations consisting of N levels applied alone or combined with *Azolla* were evaluated with respect to floodwater chemistry, ^{15}N recovery, crop growth, and grain yield. A full fresh *Azolla* cover on the floodwater surface at the time of urea application prevented the rapid and large increase in floodwater pH and floodwater temperature. As a consequence, the partial pressure of ammonia (ρNH_3), which is an indicator of potential NH_3 volatilization, was significantly depressed. ^{15}N recovery was higher in plots covered with *Azolla* where the total ^{15}N recovery ranged between 77 and 99%, and the aboveground (grain and straw) recovery by rice ranged between 32 and 61%. The tiller count in *Azolla*-covered plots was significantly increased by 50% more than the uncovered plots at all urea levels. Consequently, the grain yield was likewise improved. Grain yields from the 16 on-farm trials increased by as much as 40% at lower N rates (40 and 50 kg N ha^{-1}) and by as much as 29% at higher N rates (80 and 100 kg N ha^{-1}). In addition, response of rice to treatments with lower N rates with an *Azolla* cover was comparable to that obtained with the higher N rates without a cover. Thus, using *Azolla* as a surface cover in combination with urea can be an alternative management practice worth considering as a means to reduce NH_3 volatilization losses and improve N use efficiency.

Key words: ammonia volatilization, fresh *Azolla* cover, lowland rice, ^{15}N, N-use efficiency

INTRODUCTION

Nitrogen is the most essential element influencing rice productivity. The recovery, however, of applied N by lowland rice (*Oryza sativa* L.) is very inefficient (Craswell and Vlek, 1979; Vlek and Byrnes, 1986; Vlek and Fillery, 1984). In Asia, the average N fertilizer recovery efficiency in farmers' fields is currently only about 30% (Dobermann et al., 2002). Ammonia volatilization, the gaseous emission of NH_3 to the atmosphere, is reportedly the major cause of this low N fertilizer efficiency and an important mechanism for N losses in lowland rice fields (Freney *et al.,* 1993;Jayaweera and Mikkelsen, 1990; Reddy *et al.,* 1990; Vlek and Craswell, 1981). Earlier studies have shown that the total N losses due to NH_3 volatilization are in the range of 20 to 80% (De Datta *et al.,* 1989; Freney *et al.,* 1990; Rao, 1987). Aside from high losses as gas, N is also transported to the ground and surface waters. These factors cause substantial economic loss to farmers and create negative impacts on the atmosphere and water quality (Xing and Zhu, 2000). As such, the inefficient use of N by lowland rice is a matter of concern not only to farmers but to researchers and environmentalists as well. In the past, the use of urease inhibitors (Freney *et al.*, 1993), algicides (Simpson *et al.*, 1988) and monomolecular surface films (Cai *et al.*, 1987) have been employed to control NH_3 volatilization losses and improve N use efficiency. Most of them, however, are expensive (Damodar Reddy and Sharma, 2000) and entail costs to farmers in excess to their savings. Recently, the use of the aquatic fern *Azolla* in improving the efficiency of applied urea has generated interest. Results from laboratory and greenhouse experiments in Germany and in the Indonesia using *Azolla* to reduce NH_3 losses and increase the low N fertilizer use efficiency seem promising (Cissé and Vlek, 2003a; Vlek *et al.,* 1992, 1995; Villegas and San Valentin, 1989) but this has not yet been thoroughly explored under field conditions. Field research verifying these results is very limited and the results obtained were inconclusive. It is necessary, therefore, to verify and provide concrete evidence of the positive impacts of an *Azolla* cover with regards to minimizing NH3 volatilization losses and enhancing urea efficiency under field conditions, in order to promote the adoption of this management approach to farmers. Thus, the study was conducted to assess the influence of an *Azolla* cover on the floodwater chemistry and its relation to NH3 volatilization losses; to compare the N recoveries from urea-amended, *Azolla*-covered treatments with those of urea applied alone using the ^{15}N tracer technique; and to evaluate the response of rice to the presence of an *Azolla* cover in terms of crop growth and yield.

MATERIALS AND METHODS

The study was conducted in Jember, the province of East Java, Indonesia. Two field experiments were carried out at Jember during the 2008/2009 dry season to evaluate the use of fresh *Azolla* in combination with urea with respect to floodwater chemistry and ^{15}N recovery. The fresh *Azolla*-cover technique was subsequently evaluated in terms of crop growth and grain yield in 16 farmers' fields with low N status. Two experiments each were established in 4 municipalities in Besuki area namely, IR64, Ciherang, during the wet season

(May to October) and during the dry season (November to April) of 2008–2009. The soils of the area varied in top-soil pH from 5.5 to 6.5 and in CEC from18 to 45 $cmol^{+}kg^{-1}$.

Ten treatment combinations consisting of five N levels (0, 40, 80, 120, and 160 kg N ha^{-1}) applied alone or combined with *Azolla* were laid out in a randomized complete block design with four replicates for on-station trials. In the on-farm trials, N rates were reduced to the levels where the benefits of the *Azolla* cover are visible i.e., 0, 40 and 80 kg N ha^{-1} during the wet season and 0, 50 and 100 kg N ha^{-1} during the dry season.

Rice plant. Rice variety Ciherang (114-day maturity) was planted during the 2008/2009 dry season on paddy field. Experiment 1 was initiated in November 2006, and experiment 2 in February 2007. Similarly variety Ciherang (112-day maturity) was planted during the 2008–2009 wet and dry season on-farm experiments. Azolla. *Azolla* was multiplied in propagation ponds. It was harvested, drained and weighed a day before the scheduled inoculation time, i.e., four days before the first urea application. Fifty percent of the floodwater surface was inoculated with *Azolla* at the rate of 5 t ha^{-1} (0.5 kg m^{-2}) in plots with *Azolla* treatments. The aim was that at the time of urea application, the floodwater surface would be completely covered with *Azolla*.

Inorganic fertilizer

Based on the farmers' N application schedule, two thirds of the urea was top-dressed 7 days after transplanting and the remaining one third at 7 days before panicle initiation. Phosphorus and K were broadcast at a uniform dose of 30 kg P_2O_5 ha−1 and 30 kg K_2O ha−1 at the time of transplanting in the on-station experiments. For experiments carried out in farmers' fields, 60 kg P2O5 ha−1 and 90 kg K2O ha−1 were applied.

^{15}N balance determination

The effect of the *Azolla* cover on the recovery of applied N was assessed using the ^{15}N tracer technique in the on-station experiments. Microplots enclosed in polyethylene plastic sheets (1.0 m × 1.0 m × 0.3 m) were inserted in the center of each main plot. The sheets were embedded approximately 15 cm below the soil surface, leaving approximately 15 cm projected above the soil surface, to prevent possible run-off. Except for the 160 kg N ha−1 treatment and the control plots, each microplot received ^{15}N-labeled urea applied at the same rate and in the same way as the non-labeled urea for the first urea application in the main plots. *Microplot sampling.* Plant and soil samples were taken at harvest for ^{15}N analysis. Four hills from the center of the microplot were cut at ground level and washed to remove any adhering soil. Grains were threshed and the chaff added back to the straw. Straw and grain samples were placed in separate bags and dried to constant weight at 80 ˚C in a forced-draft oven. Dry weights were recorded and samples were ground with a grinder. Composite soil samples were taken from 0- to 15- and 15- to 30-cm depth using an auger and placed in plastic bags. They were spread on a paper in a room until they were air-dried. The clods were pulverized using a mallet and passed through a 2-mm sieve.

***^{15}N analysis**.*

A small portion each of the *Azolla*,straw, grain, and soil samples were weighed in tin cups, ball-milled, and placed into the auto sampler of the mass spectrometer (ANCA SL coupled to 20–20 stable isotope analyzer IRMS). The %^{15}N recovery by the plant, *Azolla*, and soil was then computed using the formula of Zapata (1990).

Sampling methods and analyses

Floodwater measurements (2008/2009 dry season).

Floodwater samples of about 200 mL were collected daily between 12.00 and 14.00 h from the day of the initial urea application up to day 10. The concentration of ammoniacal-N in the floodwater was determined colorimetrically using the salicylate method (Keepers and Zweers, 1986). Simultaneously, floodwater pH and temperature were measured *in situ* with a portable pH meter (Milwaukee/Cole Parmer pH meter-pen type) and a mercury-in-glass thermometer (maximum of 100 ◦C). The partial pressure of ammonia (ρNH3) in the floodwater was then calculated from total ammoniacal-N concentration, floodwater pH, and temperature using the corrected equation of Denmead *et al.* (1983): $\rho o = 0.00594AT/10(1477.8T-1.6937)$, (1) where, ρo = partial pressure of ammonia in Pascals, A = aqueous NH3 concentration in the floodwater in g N m^{-3}, T = floodwater temperature in degrees Kelvin.

Plant samples.

On-farm data clearly reflected the benefits of having an fresh *Azolla* cover on the floodwater surface. At harvest, tiller number was measured from 12 random hills. At maturity, 125 hills (5 m^2) from each plot were cut at the base and threshed to separate the grains. Grain samples were cleaned and sun-dried. The plot grain yield (PlotGY) was then weighed and the grain moisture content (MCPlotGY) measured with a moisture tester. The plot grain yield from the harvest area was corrected to 14% moisture content (PlotGY14) using the formula: PlotGY14 = PlotGY × [$(100 - MCPlotGY)/86$] *(2)* (Soil and plant sampling and measurements, 1994)

Statistical analysis

A two-factorial analysis of variance and the LSD comparison of treatment. The significance of the presence of an fresh *Azolla* cover, N rate and *Azolla* × N interaction on the floodwater chemistry, crop growth, and grain yield were determined.

RESULTS AND DISCUSSION

On-Field experiments: Floodwater chemistry ,Floodwater pH.

The presence of an *Azolla* cover on the floodwater surface significantly lowered ($P < 0.01$) the floodwater pH (Figure 1). At the time of urea application, the presence of an *Azolla* cover reduced pH values by 0.1 to 0.3 units in experiment 1. In experiment 2, floodwater pH was maintained below 8.0 in the *Azolla*-covered plots. On day 2, floodwater pH without an *Azolla* cover rapidly increased by 0.9 to 1.6 pH units in Exp. 1. In contrast, in the presence of an *Azolla* cover, the rise in the floodwater pH was less than 1.0 pH unit. In experiment 2, floodwater pH without an *Azolla* cover increased by 0.2 to 0.4 units while that with an *Azolla* cover increased only by 0.1 to 0.2 units. During the entire sampling period, the presence of an *Azolla* cover reduced floodwater pH by as much as 1.8 units and 1.9 units in the first and second experiments, respectively. Fertilization of urea stimulates the growth of algae and increases their photosynthetic activity (Simpson *et al.,* 1994). In turn, the dissolved CO_2 in the floodwater is reduced during the daytime leading to a rise in the floodwater pH (Thind and Rowell, 1997).

The higher the floodwater pH, the higher is the potential for NH_3 volatilization losses. The lower floodwater pH in the presence of an *Azolla* cover is partly explained in terms of the absorption of available light (Vlek *et al.,* 2002). With *Azolla* covering the floodwater surface, less light penetrated the floodwater. *Azolla* absorbs incoming solar radiation, reducing light intensity (Kröck *et al.,* 1988a). As shading is one of the most important factors limiting the photosynthesis of algae in lowland rice fields (Saito and Watanabe, 1978), its photosynthetic activity was reduced in the presence of an *Azolla* cover thus preventing the rapid rise in floodwater pH. *Floodwater temperature.* The floodwater temperatures of the *Azolla*-covered plots were significantly lower ($P < 0.05$) than those in the *Azolla*-free plots. In the presence of an *Azolla* cover, the rapid heating of the floodwater from morning until midday was prevented. An *Azolla* cover resulted in a mean floodwater temperature reduction of 0.6 to 2.6 ˚C and the maximum floodwater temperature difference between *Azolla*-covered and *Azolla*-free plots was 5 ˚C. On average over the 10 days of monitoring, the temperatures of the floodwater from the two experiments were similar, around 29 ˚C. Floodwater temperature affects the relative proportion of NH_3 to NH_4 present at a given pH. An increase in the temperature from 20 to 30 ˚C doubles the initial aqueous NH_3 in a system (Peoples *et al.,* 1995) which in turn increases the potential of NH_3 loss.

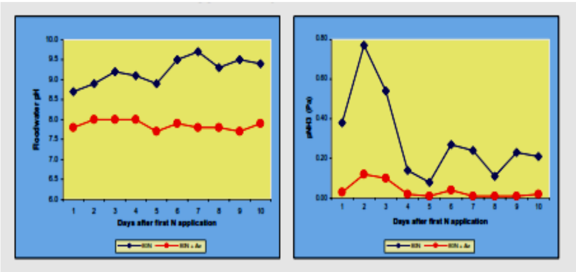

Fig. 1. Effect of fresh Azolla cover on floodwater pH and NH_3 partial pressure following the application of 80 kg N ha^{-1} on field experiment

Floodwater total ammoniacal-N.

In general, treatments with an fresh *Azolla* cover contained more total ammoniacal-N (NH_3 + NH^{4}-N) (P < 0.05) than treatments without cover during the entire sampling period. A similar pattern was reported by Villegas and San Valentin (1989) under screenhouse conditions. *Azolla*-covered plots contained, at the maximum, 5.5 g Nm^{-3} more total ammoniacal-N than the *Azolla*-free plots. This could be due to the reduction in the NH3 volatilization losses. Peak concentrations of up to 9 g N m^{-3} on the day 4 in experiment 1 and 16 g N m^{-3} on day 2 in experiment 2 were observed when a cover of *Azolla* was present. Without a cover, such high total ammoniacal-N can result in substantial NH_3 losses.

Partial pressure of ammonia.

Despite this higher concentration of total ammoniacal-N, the partial pressure of ammonia (ρNH_3) in *Azolla*-covered plots was significantly reduced (P < 0.01) from day 2 to 10 in both experiments. A built-up of ρNH_3 was prevented due to the low pH effected by the *Azolla* cover (Vlek et al., 1995). The highest ρNH_3 calculated were 0.66 and 0.92 Pa in experiments 1 and 2, respectively (Figure 3). These high ρNH_3 values indicate a high potential for NH_3 volatilization (Simpson et al., 1984, Vlek and Craswell, 1981).

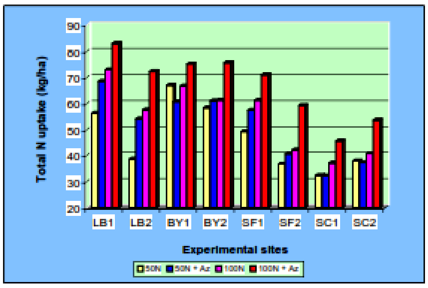

Fig. 2. Effect of Azolla cover on total N uptake on field experiment

Covering the floodwater surface with *Azolla* markedly reduced these ρNH_3 values by more than 85%. Overall, the calculated ρNH_3 in plots covered with *Azolla* was very low, virtually eliminating the danger of NH_3 losses. The low ρNH_3 in *Azolla*-covered treatments suggest that, under the conditions of our field experiments, *Azolla* is capable of curtailing NH_3 volatilization losses. In contrast, the high floodwater pH and temperatures in *Azolla*-free plots that led to a high ρNH_3, could result in high N losses via NH_3 volatilization. If so, this must be reflected in the ^{15}N balance of applied N in these experiments.

^{15}N recovery at harvest: ^{15}N recovery by rice.

The presence of an fresh *Azolla* cover on the floodwater surface before the initial urea application resulted in a significantly higher ^{15}N recovery (P <0.01) by the aboveground biomass (grain plus straw) at harvest in experiment 2 where 15N recovery by rice increased by approximately 25 to as much as 95% in the *Azolla*-covered plots. The improved ^{15}N recovery by the rice in the *Azolla*-covered treatments is partly attributed to the lower NH3 volatilization losses in the earlier stage of rice as supported by the low ρNH_3 in the floodwater. Furthermore, *Azolla*, upon its decomposition could have released part of the ^{15}N it initially absorbed and its availability would have contributed to the better 15N utilization by the crop (Cissé and Vlek, 2003a).

^{15}N recovery by Azolla.

Indeed, the aquatic fern assimilated a fraction of the applied ^{15}N. At harvest, 5 to 14% of the ^{15}N-labeled urea applied was found in the *Azolla* plant (figure 3). This is consistent with greenhouse experiments in which *Azolla* immobilizes up to 68% of applied ^{15}N within six weeks after application, of which up to 45% was re-mineralized by harvest time (Cissé and Vlek, 2003a). Thus, nitrogen might be temporarily locked up in the *Azolla*, which limits availability of N to rice plants. In the process, however, this protectsN from immediate gaseous losses, as it is conserved within the system and is mineralized later, becoming available for plant use (Keeney and Sahrawat, 1986).

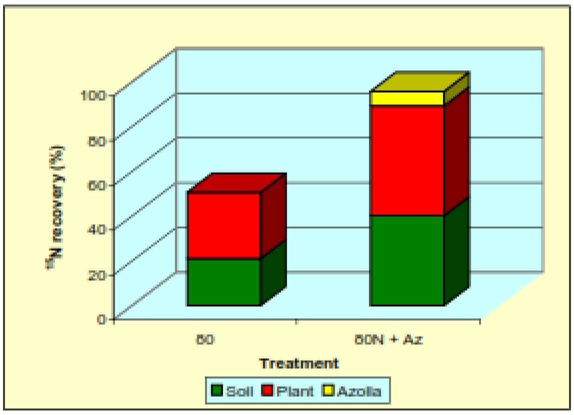

Fig. 3. Effect of Azolla cover on ^{15}N recovery by Azolla

Total ^{15}N recovery in the Azolla-plant-soil system.

In general, the presence of an fresh *Azolla* cover markedly improved the total ^{15}N recovery in the rice-soil system. In experiment 1, the recovery of applied ^{15}N significantly increased (P < 0.05) from an average of 66.4% in treatments without *Azolla* cover to an average of 83.3% with *Azolla* cover. In experiment 2, the average ^{15}N recovery of 62.0% on *Azolla*-free plots was significantly increased (P <0.01) to 92.1% when *Azolla* was present. An *Azolla* cover increased ^{15}N recovery in the 80 kg N ha^{-1} level by as much as 78% in experiment 1 and by as much as 89% in Exp. 2. The improvement in the ^{15}N recovery in the presence of an *Azolla* cover indicates the important contribution of *Azolla* to the fertilizer-N economy in rice fields. Its beneficial effects on the floodwater chemistry, and its assimilation and conservation of N led to an enhancement in the ^{15}N recovery. Unfortunately, the grain yields (data not shown) of the on-field experiments did not reflect the improved N recovery or tiller counts, due largely to adverse weather conditions at the time of grain ripening. In order to as certain whether grain yield responses, as reported by Cissé and Vlek (2003a) and Vlek *et al.* (1995) under greenhouse conditions, are indeed possible under field conditions, an on-farm campaign was undertaken in 2000–2001 with a larger number of sites to reduce the risk of adverse weather conditions.

On-field experiments : Tiller count at harvest

At harvest, all treatments with an *Azolla* cover had a significantly higher (P < 0.01) number of tillers than the uncovered treatments in both seasons (Figure 4). The *Azolla* cover in the non-fertilized plots increased the tiller number at harvest by as much as 64.5 and 20.8% over the control plots in the wet and dry seasons, respectively. In the wet season, five sites (Jember, Banyuwangi, Kalibaru, Bondowoso, and Besuki,Situbondo) showed a significant positive *Azolla* × N interaction, with 27.9 to 44.8% more tillers with *Azolla* at 40 kg N ha^{-1} and 7.5 to 28.7% more at 80 kg N ha^{-1}. In the dry season, this significant interaction effect (P <0.01) was observed in 4 out of 8 sites (LB1, LB2, SC1, and SC2). This observed significant *Azolla* × N interaction indicates the positive synergistic effect of an *Azolla* cover (Vlek *et al.,* 1995). The magnitude of increase in the tiller count due to an *Azolla* cover in the dry season was greater than that in the wet season. At 50 kg N ha^{-1} plus *Azolla*, the tiller count increase ranged from 36.1 to 51.7%, whereas at 100 kg N ha^{-1} plus *Azolla*, increase was 8.3 to 25.1%. The *Azolla*-covered plot with 40 kg N ha^{-1} in the wet season and 50 kg N ha^{-1} in the dry season produced tiller numbers comparable to those of 80 and 100 kg N ha^{-1}.

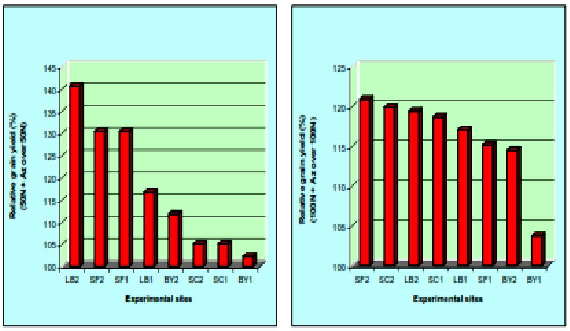

***Fig. 4.* Effect of an *Azolla* cover on the tiller count at harvest On-farm field experiments**.

Hasbi *et al.* (2008) reported that the number of tillers is closely related to the amount of N absorbed during the vegetative period. Thus, the N conserved by the reduction of NH_3 volatilization in the beginning in the presence of an *Azolla* cover (Vlek *et al.,* 1995), and presumably the N fixed and supplied by the *Azolla* (Parot, 1991) contributed to the increase in the tiller number. Tillering ability is one of the most important traits of rice as it significantly influences the production of panicles, which in turn is highly correlated with grain yield (Hasbi *et al.,* 2008).

Grain yield

The influence of an *Azolla* cover on grain yield was clearly manifested in the on-farm field experiments' results, where most of the sites had insufficient levels of N. Since N was limiting, yield responded better to the combined treatment of urea and *Azolla* cover. The presence of an *Azolla* cover in combination with urea produced consistently higher grain yields than that with urea alone. At lower N rates (40 and 50 kg N ha^{-1}), the relative grain yield of rice in plots covered with *Azolla* was higher by approximately 2 to 41% than those obtained in the uncovered treatments (Figure 5). At higher N rates, an *Azolla* cover in combination with urea increased the grain yield by approximately 4 to 29% over the urea applied alone in both seasons.

Earlier studies on the dual cropping of *Azolla* with rice attributed this increase mainly to the N fixed and released by *Azolla*. In the present experiments, we attribute the increase in part due to a greater availability of urea because of the reduced potential for NH3 volatilization losses (Figure 3) and an increase in fertilizer efficiency. In addition, besides the N fixed by the fern from the atmosphere, *Azolla* took up N from the urea that was applied, conserving it in the process and presumably releasing the urea-N during its growth together with rice or after its decomposition. Part of this relative-grain-yield increase is due to an *Azolla* × N interaction as indicated by the light-shaded portion in each bar. Grain yield increased by as much as 1.7 t ha^{-1} due to a positive interaction of *Azolla* and urea, at lower N rates and as much as 1.0 t ha^{-1} at higher N rates. This positive interaction effects indicate greater benefits from the combined *Azolla* and urea treatments than for the sum of the treatments alone.

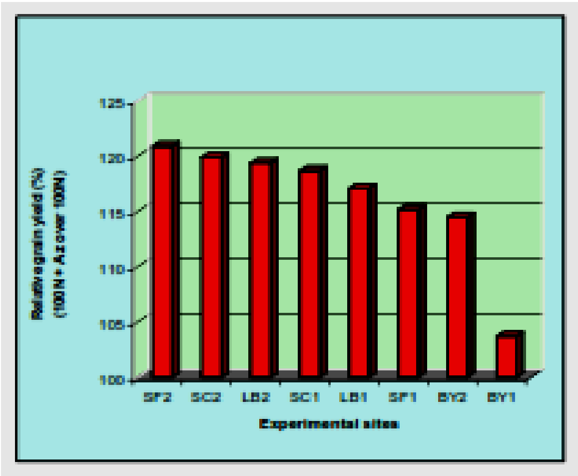

***Fig. 5.* The relative grain yield of rice at 40 and 50 kg N ha−1 with fresh *Azolla* cover over the 40 and 50 kg N ha−1 applied alone on-farm field experiments.**

More than half of the sites in both seasons yielded 10% higher in treatments with urea and fresh *Azolla* cover than plots with only urea. An *Azolla* cover together with 40 kg N ha^{-1} in the wet season and 50 kg N ha^{-1} in the dry season produced a grain yield response comparable with that obtained in the 80 and 100 kg N ha^{-1} without *Azolla*.Whether the benefit of an *Azolla* cover will be pronounced or not depends on the quality of irrigation water used and the incidence of rainfall in the days following urea application. These conditions differed among the farm sites investigated leading to a differential effect of fresh *Azolla*.

The results of this experiments suggest that the higher grain yield obtained in the *Azolla*-covered plots can mainly be attributed to the production of a significantly higher tiller number, presumably because of the adequate N supply during the vegetative and reproductive stages of the rice. Bronson *et al.* (2000) found a positive correlation between productive tillers and grain yield. Unfortunately, the determination of the N fixed by the *Azolla* was not included in the present investigation. Past studies however, reported a N_2-fixation rate ranging from 0.4 to 3.6 kg N ha−1 day−1 (Oliveros *et al.,* 1983; Roger and Ladha, 1992; Singh and Singh, 1987; Watanabe, 1982) depending on several factors, one of which is N fertilizer. The influence of fertilizer N on theN_2-fixation of *Azolla* varies. Singh and Singh (1988) noted a significant reduction in the growth and N_2 fixation by the fern with an increase in the rate of fertilizer N. Yanni (1992) had similar findings, but noted that with split application of urea, *Azolla* can still maintain its N contribution to the rice plants, even at N rate of 144 kg N ha^{-1} despite the inhibition of N_2 fixation.

The occurrence of an *Azolla* × N interaction effect on the grain yield indicates that the influence of an *Azolla* cover in the enhancement of the response of rice to the applied urea-N was not only additive in nature, but synergistic as well. This means that, besides the benefits achieved with the application of urea-N alone or from the N fixation by *Azolla*, an additional benefit was gained that could not be obtained from the separate treatments. This would have been the conservation of applied N by the *Azolla* cover. In fact, it appears that the latter effect might in some cases exceed the main effects of urea, and *Azolla* through N fixation (Vlek *et al*., 1995).

CONCLUSIONS

The results from field experiments provided convincing evidence that *Azolla* used as a cover on the floodwater of rice could help curb NH_3 volatilization losses.

Under the conditions of the experiments, showed that a full fresh *Azolla* cover at the time of urea application effectively prevented the sudden rise in the floodwater pH. As a result, the large NH_3 losses that often occur when urea is broadcast onto the floodwater of rice shortly after transplanting were reduced.

In minimizing NH_3 volatilization losses, the N On-farm field experiments,use efficiency was improved. *Azolla* likewise brought about appreciable changes with regard to the availability of N, which influences the growth and mineralnutrition of the rice plants.

The relative grain yield of rice at 80 and 100 kg N ha^{-1} with fresh *Azolla* cover over the 80 and 100 kg N ha^{-1} applied alone at harvest.

With an fresh *Azolla* on the floodwater surface, a higher grain yield can be achieved with a reduced rate of urea applied.

In the present farmer-field investigations, combining *Azolla* with urea produced yields, which were generally higher by 10% or more than those without cover. This prospect is especially attractive in light of the high cost of N fertilizer and the growing need to improve grain yield with minimum adverse environmental effects associated with the intensive use of N fertilizer.

The combined application of urea with *Azolla* thus can (1) be an efficient fertilizermanagementmethod to reduce NH_3 losses from urea applied to lowland rice in areas prone to such losses (2) introduce an N-fixing species into the system; and (3) can lead to increased grain yields. These benefits can surpass those from either urea or *Azolla* alone.

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