

Ammonia Volatilization Losses from Flooded Rice Soils¹

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ABSTRACT

The pH of the flood water in rice fields is largely determined by the chemical equilibria that exist between the CO₂ balance achieved by the aquatic biota and the various solutes, solids, and gases in the water. Water pH values undergo diurnal changes, increasing by midday to values as high as pH 9.5–10 and decreasing as much as 2–3 pH units during the night. The pH of shallow flood water is greatly affected by the total respiration activity of all the heterotrophic organisms and the gross photosynthesis of the species present.

Ammonium form fertilizers broadcast into a high pH water are highly susceptible to direct NH₃ volatilization losses. Nitrogen losses from fertilizer broadcast into flood water on a fertile, neutral-pH Maahas clay were as high as 20% of the amount applied, but losses varied depending upon water pH, the nitrogen source, and rate, time, and method of application. Losses from an acid Louisiana clay, where the flood water was not conducive to algal growth and did not exceed pH 6.8, produced NH₃ volatilization losses consistently less than 1% of the total N applied. Placement of N fertilizer in the soil at depths of 10–12 cm reduced NH₃ volatilization losses to less than 1% of the total N applied.

Additional Index Words: nitrogen losses, diurnal pH variations, (NH₄)₂SO₄, urea, N use efficiency, carbonic acid equilibrium.

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THE AGRONOMIC significance of the high pH that develops in ponds or rice flood water has largely been neglected as a factor in the direct volatilization loss of NH₃. Biologists have long been aware that the pH of water in natural systems rise to values as high as pH 10 in a regular diurnal pattern, which is determined by the chemical equilibria that exist between all aquatic organisms, their CO₂ metabolism, and the various solutes, solids, and gases in water systems. Park et al. (6) reviewed the diurnal pH variations in a variety of natural waters showing changes of as much as 3.5 pH units, rising in midday when the photosynthetic process is actively withdrawing CO₂ from the ecosystem and falling at night when respiratory activities liberate free CO₂ into the water.

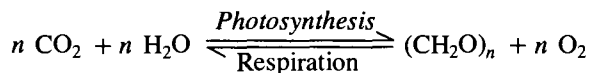
The correlation between water pH and the carbonic acid system in natural waters is complex (8), but in its simplified form can be characterized by the proton condition

$$[H^+] = [HCO_3^-] + 2 [CO_3^{2-}] + [OH^-]$$

and equilibrium concentrations

$$\begin{aligned} -\log [H^+] &= -\log [HCO_3^-] = 5.65; \quad -\log [CO_2 \text{ aq.}] = \\ -\log [H_2CO_3] &= 5.0 \text{ (as a non volatile acid); } \quad -\log \\ [H_2CO_3] &\approx 7.8; \quad -\log [CO_3^{2-}] = 8.5. \end{aligned}$$

The relationship between pH and the mole fraction of dissolved carbonic acid, HCO₃⁻ and CO₃²⁻, from data of Saruhashi (7) is shown in Fig. 1. The pH values different from those in a pure CO₂ system relate to either alkalinity or the mineral acidity inherent in the water, biochemical variances among the aquatic biota, and such factors as temperature, pressure, and air movement. Of particular interest in the shallow-water systems found in flooded rice culture is the CO₂ balance existing among the various submersed aquatic plant species, particularly algal forms, which develop quickly into a large biomass. The generalized reaction involving the plant biochemistry of CO₂ (i.e.)



is very significant. The photosynthetic process decreases the net concentration of [CO₂ (aqueous)] + [H₂CO₃] during favorable daylight periods but when respiratory activity exceeds photosynthesis both H₂CO₃, acidity, and the total concentration of dissolved carbonic acid increase. A number of complex relationships exist in the system. Reactions of CO₂ with alkaline earth minerals, carbonates, divalent cations, and with various components of the external environmental system affect the solubility of gases, their dissociation, and the relative activity of the entire system. Water pH in flooded rice is also affected to some extent by the soil type, its pH, electrical conductivity, previous cropping history, and soil management practices such as puddling. The quality of the irrigation water, its origin either from rainfall, wells, run-off, or streams and its silt load, may also influence the initial pH of paddy water.

Ammonia and its ionized form (NH₄⁺) are readily identifiable products of the decomposition of soil organic matter, and the micro and macro plant residues occurring in natural waters. Use of N fertilizers on rice also contributes large concentrations of dissolved NH₄⁺-N salts. Ammonium-form fertilizers may dissociate directly, or like urea may decompose by catalytic hydrolysis to produce NH₄⁺ ions in water. Ammonium ions, loosely bound to water molecules, predominate in water at a pH above 7.2. With increasing hydroxyl-ion concentrations in the water, ionized NH₄⁺ increasingly converts to nonionized NH₃, which may escape from the water as a gas.

Losses from flooded soil systems are affected by a number of variables in a manner similar to direct NH₃ volatilization losses from upland soils. Particularly critical is a high level of solar radiation, the nature and numbers of aquatic plants, indirectly the CO₂ balance between photosynthesis and respiration, and other factors such as the influence of temperature on CO₂ solubility in the water and carbonic acid equilibria.

Losses of volatile NH₃ from flooded rice soils reported by MacRae and Ancajas (4) are calculated as 7% of the ammonium sulfate applied and as much as 19% of the urea

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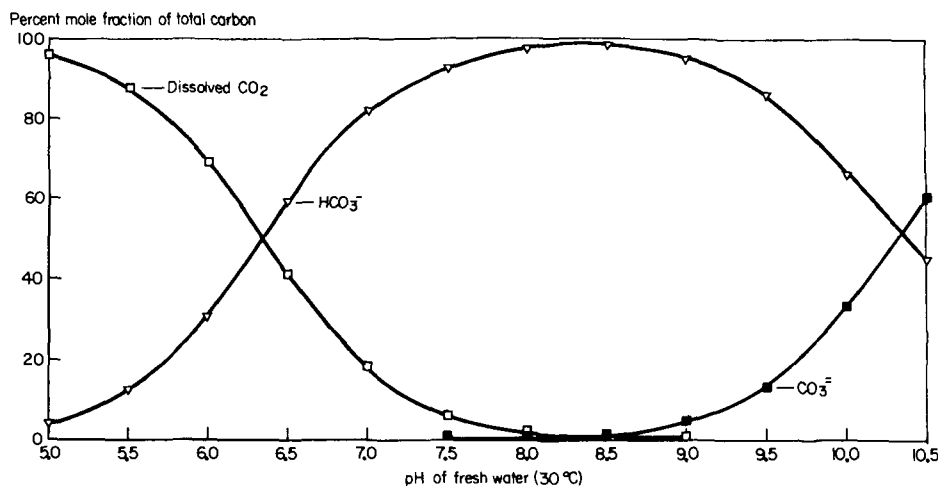


Fig. 1—Relation between pH and percent of total "CO₂" as dissolved CO₂, HCO₃⁻ and CO₃²⁻. (Data from K. Saruhashi (1953), Pap. Met. Geophys. Tokyo 3:202)

within 7 weeks, at rates of 50 and 200 kg N/ha. Ventura and Yoshida (9) measured NH₃ volatilization losses from different N sources on a flooded Maahas clay soil, and reported that NH₃ losses occurred principally during the first 9 days after N application. Losses were small when soil pH was adjusted below pH 7.4. Their field experiments showed N losses of 3.8% from ammonium sulfate and 8.2% from urea during a 21-day sampling period, when broadcast at 100 kg N/ha. Ammonia volatilization losses were reduced by 50% when N fertilizer was incorporated into a puddled soil.

No relationship has been shown, however, between the pH of rice flood water and NH₃ volatilization losses. Our study measured the diurnal changes in water pH occurring in the flood water of typical tropical rice soils and changes in the components of the carbonic acid system. The magnitude of direct NH₃ volatilization losses as a consequence of pH change was evaluated as determined by N source, time, and method of N application on both a neutral and an acid rice soil.

MATERIALS AND METHODS

During the 1976 wet season (June–December), diurnal changes in pH of rice flood water was characterized in a field simulation study.

Steel drums, 57 cm diam. by 60 cm deep were filled 40 cm deep with Maahas clay (an isothermic clayey mixed Aquic Tropudalf, pH 7.0, total N 0.19%, organic matter 2.11%, CEC 40 meq/100 g soil, predominant clay mineral montmorillonite) or Louisiana clay (clayey acid mixed, Typic Tropaquept, pH 5.7, total N 0.17%, organic matter 2.60%, CEC 24 meq/100 g soil, predominant clay mineral kaolinite) and flooded with tap water or deionized water, respectively, to simulate natural rice environments. Phosphorus and K were applied to each soil at a rate of 60 kg P₂O₅/ha and 30 kg K₂O/ha before the soils were puddled 20 cm deep. Subsequently, ammonium sulfate and urea were broadcast in separate treatments at the rate of 60 kg N/ha into 2 cm of water, followed by mixing to simulate field harrowing. The drums were flooded and maintained with 4–6 cm of water. For a period of 8 days, the water pH and components of the carbonic acid system in the water were monitored by sampling at 8-hour intervals, except for the 3rd and 4th day after N application, when sampling was at 2-hour intervals. Replications of each soil-water system were also treated with copper sulfate to prevent the growth of algae and

determine if algal CO₂ metabolism was responsible for pH changes in the systems. Water samples were examined by the standard methods (1). The amount of CO₃²⁻ + OH⁻ was determined by titration with acid to ≈ pH 8.3, the end point detected with phenolphthalein. The HCO₃⁻ concentration was determined by further titration with acid to an end point pH between 4.2 and 5.4 with mixed indicator. Carbonate alkalinity and total CO₂ were calculated from the total alkalinity values, the pH, and the total filtrable residue of the original water samples. Water pH was determined *in situ* with a portable pH meter. Four replications of each treatment were measured in a randomized block design.

During the experiment there was an average sunshine hours of 6 hours/day and average solar radiation of 317 g cal/sq cm per day. Water temperature ranged from 24 to 32°C from night to day.

During the same season (1976 wet), a field study was conducted on the nitrogen source and placement of nitrogen fertilizer on NH₃ volatilization losses from flooded Maahas clay soil at the IRRI farm. The design was randomized block with individual plot size of 3 by 5 m.

Losses of NH₃ through volatilization in transplanted rice were determined following application of 90 kg N/ha as (NH₄)₂SO₄ and urea. Mudballs containing N were made from Maahas clay. These mudballs were used to place 100, 75, 50, 25, and 0% of the applied N between the hills of transplanted rice (20 by 20 cm), while the remaining percentage was applied broadcast on the puddled soil (5–8 cm of standing water) just after transplanting. Wire cylindrical frames (12.5 cm diam. by 30 cm height) covered with 5 mil plastic bags that had previously been examined for NH₃ leakage were placed in the soil between the rice plants after N fertilizer application. The plastic bags were about 5 cm above the standing water to allow the air to flow in and out of the system. Inside the collector, a 12-cm petri dish was suspended and filled with 100 ml of 0.1N H₂SO₄. A distance of 9 cm separated the petri dish and the water surface within the cylindrical frames. The petri dishes were emptied and replaced every 3 days over a 12-day period. The collected samples were transferred to volumetric flasks, adjusted to volume and an aliquot taken for micro-Kjeldahl distillation with MgO.

During the wet season, skies were cloudy about 50% of the time, and water temperatures were between 24–30°C. The biomass of algae and other aquatic species as determined by visual inspection was low and this was also reflected in the carbonic acid constituents, and the pH value changes. Direct measurements of the algal biomass was not possible since the population was distributed both in the water and on the soil surface.

These two experiments were followed by two greenhouse studies during the 1977 dry season (January to May) to further

detect the effects of nitrogen sources, placement, and method of N fertilizer application on NH_3 losses from flooded soils.

The drums described in the first experiment, filled with Maahas or Louisiana soil and flooded with water, were used to compare the NH_3 volatilization losses from $(\text{NH}_4)_2\text{SO}_4$ and urea when different proportions of the total N application were applied either broadcast or placed in the reduced soil layer. Gelatin capsules were used to place 100, 66, 33, or 0% of 90 kg N/ha 10–12 cm deep in the soil, and the remaining portion broadcast into the flood water. Bell jars (2.5 liters), pressed into the soil, were equipped with an inlet for acid- and water-scrubbed compressed air and an outlet connected to a 2% boric acid trap provided with gas diffusers. Air flow was regulated at about six air exchanges per hour and trapped NH_3 was collected at 3-day intervals for 12 days. Ammonia nitrogen was analyzed (10) colorimetrically by the indophenol blue procedure (alkaline phenol and sodium hypochlorite) using an autoanalyzer.

Sunshine hours (9 hours/day), solar radiation (420 g cal/sq cm per day) and water temperature (24–39°C) during the experiment (dry season) were higher than in the previous experiments conducted in the wet season.

The procedure described for the third experiment was used in this experiment. Except that 0.1N H_2SO_4 was used as the absorbing solution for volatile NH_3 and the soil was in large pots (57 cm diam). Ammonium sulfate was applied at rates of 15, 30, 60, and 90 kg N/ha broadcast into 5–8 cm of water contained in 2.5-liter bell jars pressed into the mud of each pot. Mechanical incorporation was accomplished by stirring the soil in each bell jar for 30 sec with an electric-powered mechanical stirrer. The stirring was thorough, and completely mixed the soil and water in each bottle to a depth of about 10–12 cm. The degree of incorporation exceeded that achieved by Asian rice farmers who incorporate fertilizer by harrowing.

Finally, effects of methods and time of N application on NH_3 losses were determined at two different sites during the 1977 dry season.

Nitrogen as ammonium sulfate was applied at rates from 20–120 kg N/ha. Preplant (basal) N was broadcast into 5–8 cm of water and incorporated at rates of 20, 30, 40, and 90 kg N/ha, top-dressing was at the rate of 30 kg N/ha 10 days after transplanting and placement in mudballs 10–12 cm deep between rows of rice transplanted on a 20- by 20-cm grid. The collection of NH_3 and the method of chemical analysis were the same as reported in the previous experiments.

RESULTS AND DISCUSSION

The pH of the water in flooded rice systems is dominated by aqueous carbonic acid in the water and influenced to a large extent by the balance between opposing biological processes of respiration and photosynthesis. The diurnal changes in pH of rice flood water on two different soils receiving 60 kg N/ha as $(\text{NH}_4)_2\text{SO}_4$ and urea are shown in Fig. 2. The pH decreased about 0.6 during the initial 12-hour period after $(\text{NH}_4)_2\text{SO}_4$ application, but increased about 1.5 units after urea application. After 24 hours a rhythmic pattern of diurnal pH variation became apparent, and was measured for 8 days. The largest changes occurred after about 36 hours when green algae became noticeably apparent in the treated water on Maahas clay. There was less development of green algae on Louisiana clay. During daylight the removal of dissolved CO_2 from the water by photosynthesizing plants shifted the carbonic acid equilibrium and increased the pH of the water. During the night, respiration exceeded photosynthesis and the pH of the water decreased. With the addition of Cu^{2+} to the flood water, which inhibited algae growth, only small changes in dissolved CO_2 occurred in Louisiana clay. This suggests that

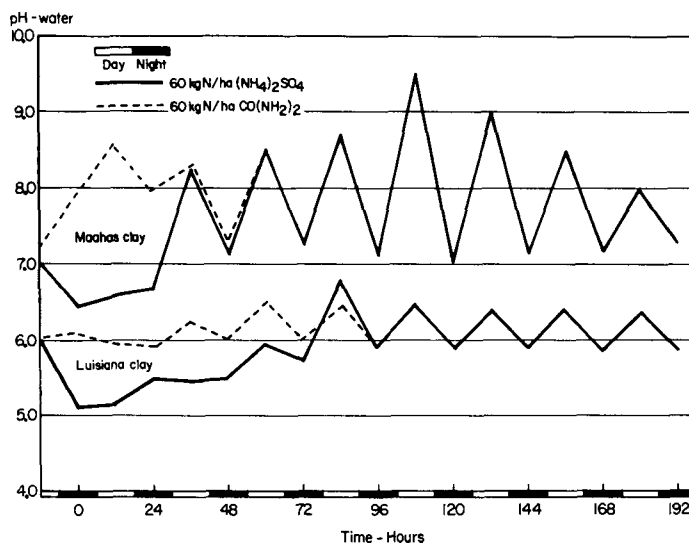


Fig. 2.—Diurnal changes in the pH of rice flood water as affected by two N sources on Maahas and Louisiana clay. IRR, 1976 wet season.

the algae population is the major factor affecting the CO_2 equilibrium.

Changes in the carbonic acid systems of the flood water on Maahas and Louisiana clay the third day after broadcast 60 kg N/ha are shown in Fig. 3 and 4, respectively.

pH of the flood water on Maahas clay varied from 7.2–9.0 between 0600 and 1600 hours daily when solar radiation was high and the aquatic biota were biologically active. Free CO_2 in the system declined rapidly after 0600 hours, reached a low point from 1200 to 1800 hours, then increased until 2200 hours. The percent mole fraction of carbonic acid decreased in direct proportion to the free CO_2 content of the water, with a similar effect noted for the HCO_3^- and CO_3^{2-} ion fractions (Fig. 3).

Water on the Louisiana clay had a pH range from 5.7–6.8 between 0600 and 1400 hours (Fig. 4). Even though the soil had been fertilized with P and K, and N was added to the flood water, the development of algae on this acid soil was not nearly as great as that on Maahas clay. Either the algae inoculum level was inherently low on this soil or some factor(s) inhibited algae development. The mole fraction of carbonic acid decreased from 0600 to 1400 hours, while the HCO_3^- mole fraction increased proportionately. The free CO_2 content varied from 42–370 mg/liter and paralleled the percentage mole fraction of carbonic acid in the system (Fig. 4). The diurnal fluctuation of water pH with midday values as high as 10, and 2 to 3 units lower at night, provide unusual water-chemistry and promote rapid volatilization of NH_3 from rice flood waters.

A field experiment was conducted on Maahas clay at the IRR farm in the wet season to evaluate NH_3 losses from $(\text{NH}_4)_2\text{SO}_4$ and urea with variable proportions broadcast and placed in the soil in mudballs. The field study had poorer light and lower algal populations than the comparable pot experiment on Maahas clay. The NH_3 volatilization losses were highest when all the N was broadcast into the water and lowest when all the N, regardless of source, was placed in the soil. These field results (Fig. 5) show that higher concentrations of NH_4^+ in rice flood water

increase NH_3 volatilization losses. In this field experiment, results were that the initial rate of NH_3 loss from urea was slower than from $(\text{NH}_4)_2\text{SO}_4$, and although the differences in total NH_3 losses between the two N sources were small, $(\text{NH}_4)_2\text{SO}_4$ contributed slightly larger losses except where all the fertilizer was placed in the soil.

Greenhouse studies were conducted to further detect the effects of N source, placement, and method of application on ammonia volatilization from the flood water of Maahas clay. NH_3 losses from urea were generally greater than

from $(\text{NH}_4)_2\text{SO}_4$ during a 12-day period (Fig. 6). Maximum NH_3 volatilization losses amounted to 18% of the urea N and 15% of the $(\text{NH}_4)_2\text{SO}_4\text{-N}$ when they were applied entirely broadcast during periods of high light intensity and active algae growth. The rate of NH_3 volatilization was initially faster from $(\text{NH}_4)_2\text{SO}_4$ than urea. During the first 3 days of measurement, losses from urea were about 5%, and from $(\text{NH}_4)_2\text{SO}_4$ 9.2% of the total N applied. Nine days after N application, however, the total loss from urea exceeded that of $(\text{NH}_4)_2\text{SO}_4$. The delayed loss of NH_3 from urea differs from results reported by other investigators (9), who found that urea is rapidly hydrolyzed in water to $(\text{NH}_4)_2\text{CO}_3$ creating a high water pH, faster initial rates of NH_3 loss, and higher total levels of induced NH_3 volatilization than from $(\text{NH}_4)_2\text{SO}_4$. In our experiment, urea hydrolysis was delayed for a period of about 5–6 days, probably due to low levels of the urease enzyme in the flood water. Where 60 kg N/ha was broadcast into water and 30 kg N/ha in gelatin capsule placed at 10–12 cm soil depth, the NH_3 volatilization loss was reduced from 15% to 10% with $(\text{NH}_4)_2\text{SO}_4$ and from 18%–12% with urea. Where either urea or $(\text{NH}_4)_2\text{SO}_4$ was placed 10–12 cm deep in the reduced soil layer, NH_3 volatilization losses were nearly eliminated. This suggests that fertilizer application techniques such as soil injection, banding, or mudball-placement are effective in increasing fertilizer efficiency in rice because NH_3 volatilization and denitrification losses are both minimized.

A similar experiment conducted on the acid Louisiana clay showed that NH_3 volatilization losses from the same treatments as described above were negligible. Apparently, the maximum water pH of 6.8 was not sufficient to volatilize measureable amounts of NH_3 . One may conclude that if the flood water pH stays below pH 7.0 NH_3 losses from broadcast applications of N are likely to be of little agronomic significance in lowland rice production.

The different magnitudes of NH_3 volatilization losses from field plots and large pot experiments suggest the

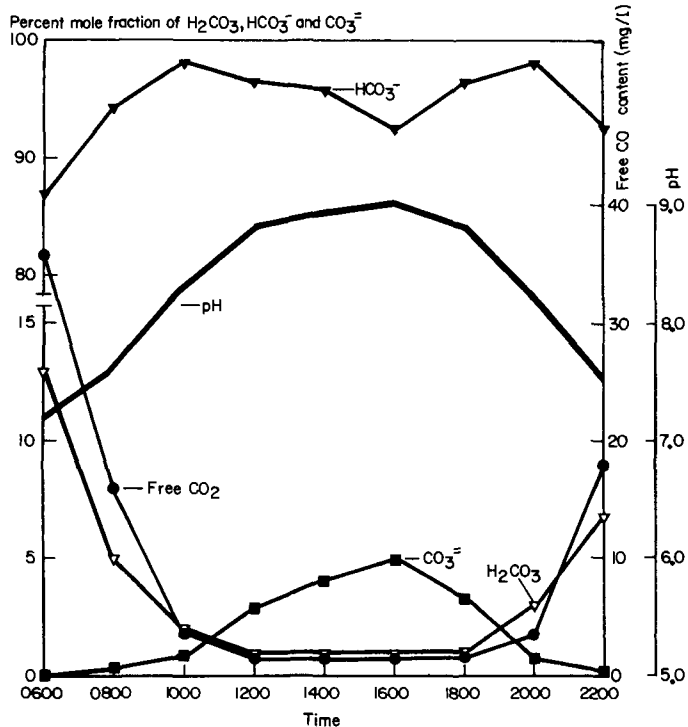


Fig. 3—Changes in the pH and components of the carbonic acid system of rice flood water 3 days after N fertilization on Maahas clay. IRRI, 1976 wet season.

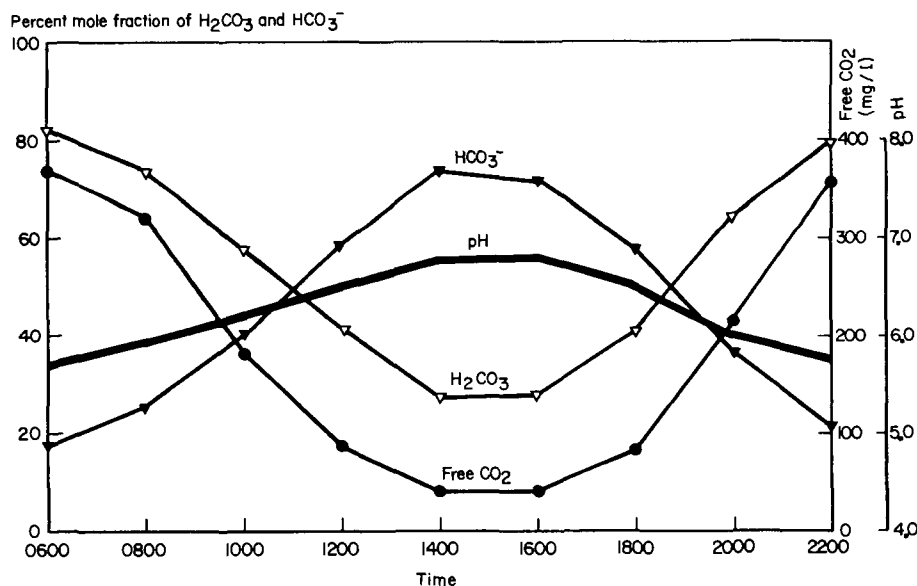


Fig. 4—Changes in the pH and components of the carbonic acid system of rice flood water 3 days after N fertilization on Louisiana clay. IRRI, 1976 wet season.

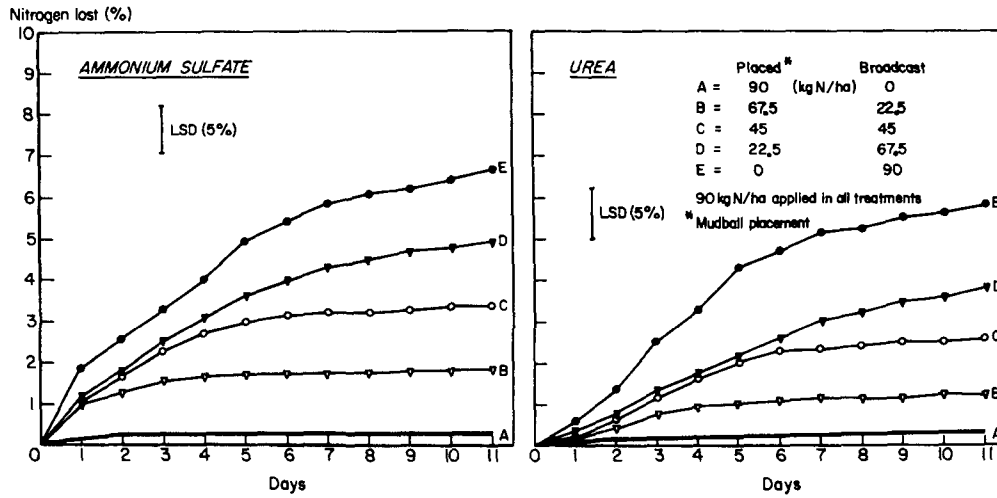


Fig. 5—Ammonia volatilization loss as percent of total N application as affected by source and placement on Maahas clay. Field experiment. IRRI, 1976 wet season.

effects of environmental factors such as solar radiation, temperature, wind velocity, air and water mixing, and variables of water quantity, differences in aquatic species and populations, and various growth limiting factors that may all contribute to variable NH₃ losses from natural aquatic ecosystems.

Much of the fertilizer N applied to rice in Southeast Asia is either broadcast directly onto wet flooded soil and incorporated by harrowing, or broadcast directly into shallow water after transplanting. Results presented in Fig. 7 show the cumulative loss of NH₃ from these two methods of N application with rates of 15, 30, 60, and 90 kg N/ha applied as (NH₄)₂SO₄.

Ammonia volatilization losses from 90 kg N/ha broadcast into water as (NH₄)₂SO₄ accounted for 4.7% of the total N applied or the equivalent of 4.2 kg N/ha; at application rates of 60 kg N/ha, 5.8% of the total N was volatilized in 9 days. During the same time 6.2% and 6.5% of 30 kg N/ha and 15 kg N/ha treatments were volatilized, respectively (Fig. 7).

Incorporation of the surface broadcast N with a mechanical stirrer reduced the NH₃ volatilization loss to less than 1% at all rates of application, approaching the levels of soil retention achieved by placement. Naturally, field incorporation of fertilizer N cannot be as thorough as attained in our treatments, but the results suggest that more complete field incorporation of the N could conserve considerable quantities of fertilizer N.

Experiments on Maahas clay and Luisiana clay determined NH₃ volatilization field losses as influenced by a variety of methods and timing of N application. Ammonia volatilization losses from water on the Luisiana clay (Fig. 8) were about 1% of preplant basal application (topdress and incorporate) and significantly higher than topdressing at 10 days after transplanting at the same N rate. Losses from mudball placement application were lowest and did not exceed 0.25% of the total N applied.

The Maahas soil contributed the largest volatilization losses because the water pH was in the 7.2–10 range in diurnal fluctuations (Fig. 8). Losses of N from topdressed fertilizer applied 10 days after transplanting amounted to

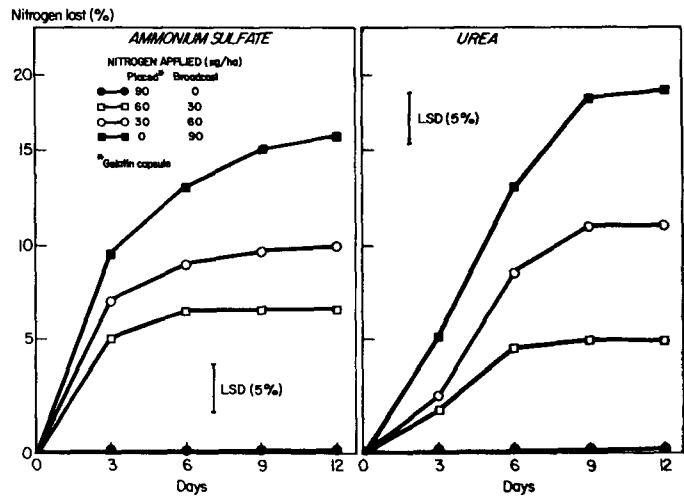


Fig. 6—Ammonia volatilization loss as percent of total N application as affected by N source and placement on Maahas clay. Large pot experiment. IRRI, 1977 dry season.

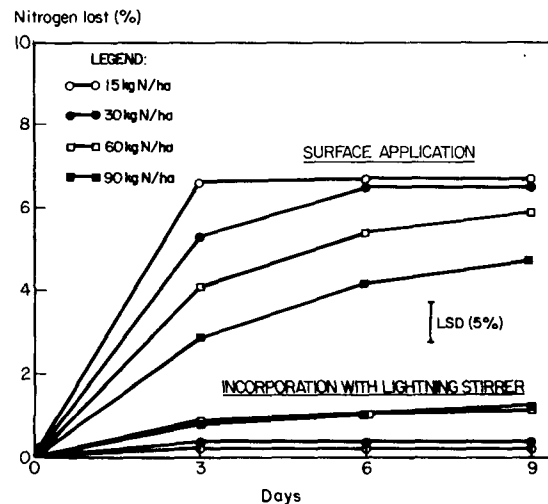


Fig. 7—Ammonia volatilization loss as percent of total N application as affected by N rate and method of application on Maahas clay. Large pot experiment. IRRI, 1977 dry season.

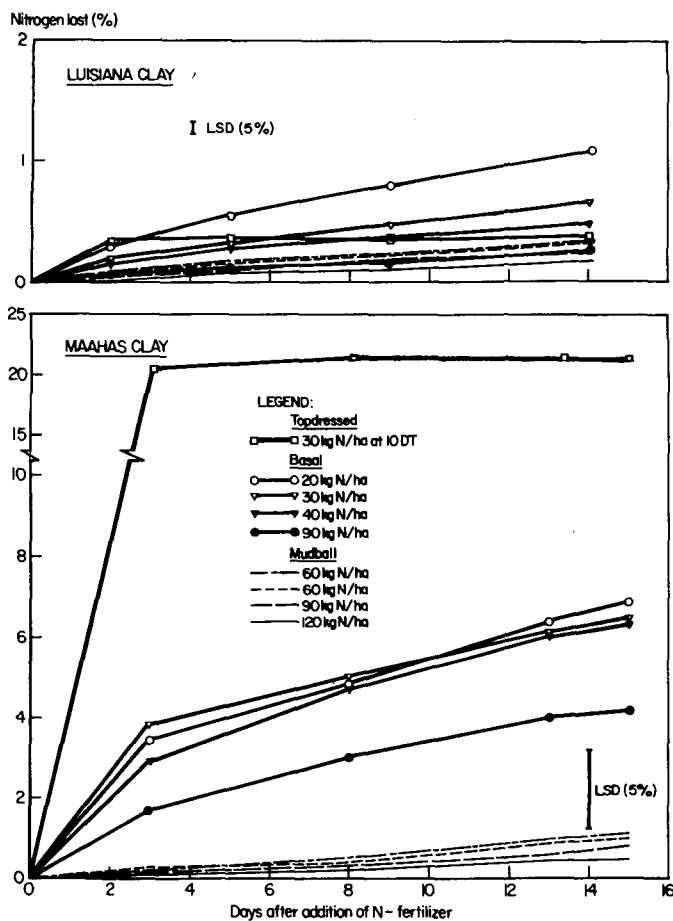


Fig. 8—Ammonia volatilization loss as percent of total N application as affected by time and method of application on Maahas and Louisiana clay. Field experiments. IRRI, 1977 dry season.

about 20% with most of the NH_3 lost during the first 3 days after application. Preplant basal (topdress and incorporate) applications contributed about 6–7% loss during a 15-day period, with losses greatest during the first 3 days, but continuing as long as 15 days. Placement as mudballs allowed less than 1% loss of total N through NH_3 volatilization.

These field experiments are in substantial agreement with other data reported here; placement of N fertilizer in the soil greatly minimizes NH_3 losses. Numerous field studies also demonstrate that placement of N substantially increases grain yields over other methods of application (2,3,5). It is also observed that the losses of fertilizer N applied in water or on the soil surface are dependent, among other factors, on the pH of the flood water.

It is evident from this research that the flood water of

lowland rice, inhabited by aquatic biota, is highly susceptible to large diurnal variations in pH. Carbon dioxide in solution, as a product of the photosynthesis and respiratory balance of aquatic organisms and occurring as undissociated carbonic acid, bicarbonate, and carbonate ions, is the buffering system that regulates water pH. Water pH values as high as 9.5–10.0 can occur in shallow flood waters populated by aquatic biota under high solar radiation, rising during midday and dropping at night. Diurnal pH variations of 2–3 units are not uncommon when fertilizer N is broadcast for rice production and stimulates the development of blue and blue-green algae. A more complete definition of the physical chemistry of the carbonic acid in rice flood water and the metabolism of the inhabiting aquatic organisms is required to fully characterize the rice flood water ecosystem and its effect on NH_3 volatilization.

Ammonium-form fertilizers, such as $(\text{NH}_4)_2\text{SO}_4$ and urea, broadcast into water are highly susceptible to NH_3 volatilization. The magnitude of losses vary particularly with the NH_4^+ concentration, water pH as affected by the biochemical activity of aquatic plants, N source, and time and method of application. Losses of N from flooded rice systems varied from 0.25–20% of the total N applied by broadcast techniques. Proper N placement 10–12 cm deep in the soil, greatly reduces NH_3 volatilization losses. Thorough incorporation of ammonium-form N fertilizers into the soil also minimizes volatilization losses.

LITERATURE CITED

1. American Public Health Association. 1971. Standard methods for the examination of water and wastewater. 13 ed. Am. Public Health Assoc., Inc., New York.
2. De Datta, S. K., C. P. Magnaye, and J. C. Moomaw. 1968. Efficiency of fertilizer nitrogen (^{15}N -labeled) for flooded rice. Int. Congr. Soil Sci., Trans. 9th (Adelaide, Austr.) 4:67–76.
3. De Datta, S. K., F. A. Saladaga, W. N. Obcemea, and T. Yoshida. 1974. Increasing efficiency of fertilizer nitrogen in flooded tropical rice. Proc. FAI-FAO seminar on optimising agricultural production under limited availability of fertilizers, New Delhi. pp. 265–288.
4. MacRae, I. C., and R. Ancajas. 1970. Volatilization of ammonia from submerged tropical soils. Plant Soil 33:97–103.
5. Mikkelsen, D. S., and D. C. Finfrock. 1957. Availability of ammoniacal nitrogen to lowland rice as influenced by fertilizer placement. Agron. J. 49:296–300.
6. Park, K., D. W. Hood, and H. T. Odum. 1958. Diurnal pH variations in Texas bays and its application to primary production estimates. Ints. Mar. Sci. 5:47–64.
7. Saruhashi, K. 1953. Carbon dioxide solubility in fresh water and sea water. Pap. Met. Geophys. Tokyo 3:202–273.
8. Stumm, W., and J. J. Morgan. 1970. Aquatic chemistry: An introduction emphasizing equilibria in natural waters. Interscience, New York.
9. Ventura, W. B., and T. Yoshida. 1977. Ammonia volatilization from a flooded tropical soil. Plant Soil 46:521–531.
10. Zadorojny, C., S. Saxton, and R. Finger. 1973. Spectrophotometric determination of ammonia. J. Water Poll. Control Fed. 45:905–912.