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A Chemical Index for Predicting Ammonium Production in Submerged Rice Soils

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ABSTRACT

Nitrogen (N) deficiency limits rice production and productivity in tropical soils. The escalating cost of chemical fertilizers warrants an efficient use of external inputs of N. This can be achieved by estimating a soil's indigenous N supply. There is an urgent need for developing simple, rapid and effective methods of assessing N supplying capacity of soils. Ammonium production is the key process in the N nutrition of wetland rice because N mineralization halts at ammonium production in submerged soils. Previous work showed that organic matter and reducible iron control ammonium production in submerged soils. In this paper results are presented for 15 diverse West African rice soils, which show that regression equation connecting organic carbon (C) and reducible iron (extracted by EDTA or ammonium oxalate) with ammonium released under waterlogged condition, can be used for predicting ammonium production in these soils. Soils with higher N supplying capacity had

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relatively higher contents of organic C and reducible iron. There was a close agreement between the observed values of ammonium released and those predicted by organic C and reducible iron for the soils studied. These results suggest that the chemical index based on organic C and reducible iron contents of soils can be used as a simple and rapid index for estimating N supplying capacity of wetland rice soils.

Key Words: Electron acceptors; Nitrogen index; Prediction of ammonium production; Organic matter; Reducible iron; Rice soils.

INTRODUCTION

Nitrogen (N) deficiency is the major constraint to increasing rice production in the tropical regions of Africa. Ever increasing costs of chemical fertilizers warrant a judicious and efficient use of the purchased inputs of N. This can be achieved by regulating N input use based on the soil's N supplying capacity. Little attention has been devoted to developing and testing indices of N supplying capacity for rice,[1] although rice as a food crop is gaining importance in West and Central Africa. Moreover, soil N supply plays a dominant role in N nutrition of the rice plant even in N-fertilized rice paddies.[2] There is an urgent need for developing simple and effective methods of estimating N supplying capacity of soils, which can be used for achieving judicious and efficient use of inputs of N.

The chemistry of submerged rice soils differs considerably from that of their aerobic or upland counterparts and this distinction is mainly caused by the lack of oxygen in the wetland soils.[3] In the absence of oxygen, facultative and obligate anaerobes use nitrate, Mn (IV), Fe (III), sulfate and the dissimilation products of carbohydrates and proteins as electron acceptors in their respiration.[4] Iron (Fe) is present in large amounts in tropical soils[5] and Fe redox chemistry plays an important role in influencing the dynamics of soil fertility in submerged soils through soil reduction and exchange equilibria, which affect the release and availability of plant nutrients to wetland rice.[3,6–8]

Ammonium production is the key process in N nutrition of the rice plant in wetland soils. Lack of oxygen in the submerged soils halts the N mineralization at ammonium. Ammonium accumulation is favored under reduced conditions because ammonium is stable under anaerobic condition.[3] Organic matter is the source of ammonium production as well as the source of energy for the anaerobes operating in the submerged soils. Several authors have reported the importance of soil organic matter for potentially mineralizable N or ammonium production in wetland rice soils.[2,9–12] This is evident from the fact that organic matter content of soil is used as an index of N availability to wetland rice.[2] Sahrawat[7] stressed the importance of the unifying role of role organic matter and reducible Fe in influencing the dynamics of soil chemical fertility in submerged rice soils. Narteh and Sahrawat[8] showed that in 15 diverse West African soils, kept submerged in greenhouse pots, changes in soil solution pH corresponded to changes in soil solution Eh ($r^2 = 0.84$).

In a recent study with West African rice soils, Sahrawat and Narteh[13] showed that ammonium production in submerged soils was significantly correlated to organic C and EDTA or ammonium oxalate-extractable soils. Their results suggested that organic C and reducible iron controlled the release of ammonium in submerged soils. The objective of this paper is to further explore the relationships between organic C and reducible Fe and ammonium released, for predicting potentially mineralizable N in West African wetland rice soils.

MATERIALS AND METHODS

Soils

The soils used in the study were surface (0–0.15 m) samples of soils collected from 15 different locations in five countries (Burkina Faso, Côte d'Ivoire, Ghana, Guinea and Nigeria) of West Africa. The detailed background information about the location, classification and physical and chemical properties is given in an earlier paper.[8] The chemical properties of the soils, relevant to this study, are given in Table 1. Before analyses, soil samples were air-dried and ground to pass a 2-mm sieve. Soil pH was measured by a glass electrode using a soil to water ratio of 1:2.5. Organic C was determined using the Walkley–Black method[14] and total N as described by Bremner.[15] EDTA extractable Fe was determined as described by Borggaard[16] and ammonium oxalate extractable Fe as described by Schwertmann.[17]

Ammonium Production or Nitrogen Mineralization Under Anaerobic Condition

Ammonium production (N mineralization) under waterlogged condition was determined using the anaerobic incubation method described by Waring and Bremner[18] with the modification suggested by Sahrawat and

Table 1. Chemical properties, iron extracted by EDTA (EDTA-Fe) or ammonium oxalate (Amox-Fe), and ammonium N released (Min-N) in 15 West African Soils.

Soil no.	pH	Organic C ($g\,kg^{-1}$ soil)	Total N ($g\,kg^{-1}$ soil)	EDTA-Fe ($mg\,kg^{-1}$ soil)	Amox-Fe ($mg\,kg^{-1}$ soil)	Min-N[a] ($mg\,kg^{-1}$ soil)
1	4.3	7.8	0.75	600	3175	48
2	5.2	11.4	0.60	150	1187	31
3	7.7	46.0	3.30	2200	11412	166
4	4.9	9.8	0.90	550	3400	50
5	5.4	8.8	0.70	350	3562	39
6	5.1	35.2	2.70	325	1100	55
7	6.1	13.4	1.10	575	3052	77
8	5.6	9.2	0.80	800	6750	55
9	5.4	20.0	1.50	1275	10737	94
10	5.6	25.2	1.80	1375	9812	86
11	5.5	23.2	1.50	800	5837	65
12	5.3	19.6	1.20	450	1562	65
13	6.1	23.0	1.80	150	1875	86
14	6.3	7.4	0.50	125	925	21
15	5.0	15.6	1.20	125	1525	36

[a] Ammonium N released under anaerobic (waterlogged) incubation of soil samples at 30°C for 2 weeks.

Ponnamperuma.[19] In the modified method used, instead of directly distilling the incubated samples with MgO, they were first extracted with 2 *M* KCl, and the filtered extracts of incubated soils were used for the determination of ammonium released in soils.[20] Soil samples, in triplicate, were incubated at 30°C for 2 weeks in test tubes under waterlogged condition with a standing water layer of 2 to 3 cm. Mineralized N values reported are the net amounts of ammonium N released during incubation, expressed on a dry soil weight basis.

Regression analysis was used to determine relationship between mineralizable N and organic C and reducible Fe extracted by EDTA or ammonium oxalate extractants. Multiple regression analysis was carried out to develop equations showing the relationship between ammonium N produced and organic C and reducible Fe contents of soils.

RESULTS AND DISCUSSION

The soils used in the study captured the range in variability of soils used for rice cultivation in West Africa. They had a wide range in pH, organic C, total N and EDTA or ammonium oxalate extractable Fe. The soils also differed widely in the mineralizable N (ammonium N) released under anaerobic incubation, which ranged from 21 to 166 mg N kg^{-1} soil (Table 1).

The distribution of the 15 soils studied according to the amount of ammonium N produced, organic C and EDTA (EDTA-Fe) or ammonium oxalate extractable Fe (Amox-Fe) is shown in Table 2. The association between mineralizable N and organic C seemed closer than with reducible Fe. However, it is not easy to separate the effects of organic matter as the source of potentially mineralizable N and its role in the reduction of Fe. Soils high in both organic C and reducible Fe showed higher amounts of mineralizable N. On the other hand, soils low in organic C or reducible Fe had relatively lower contents of mineralizable N. Highly significant correlations between mineralizable N and organic C ($r = 0.79$, $P = 0.0005$), EDTA-Fe ($r = 0.86$, $P = 0.0001$) or Amox-Fe ($r = 0.75$, $P = 0.0014$) support these results.

Several authors have suggested that EDTA and ammonium oxalate solutions extract fractions of amorphous Fe that are easily reducible and thus can be utilized as the measure of the activity of poorly crystalline iron oxides in soils.[16,17] Moreover, research has shown that the amorphous Fe fractions contribute to Fe (II) formation in reduced conditions, and the intensity of Fe (II) production increases with a decrease in the crystallinity of the pedogenic Fe (III)-oxides and hydroxides and with an increase in the easily mineralizable soil organic substances.[21–24]

The correlations between mineralizable N and organic C and reducible Fe were high, multiple regression analysis of the data showed that the prediction of mineralizable N was further improved by combining organic C and

Table 2. Distribution of 15 West African soils according to mineralizable N (Min-N) released under anaerobic incubation and associated organic C and EDTA-Fe or Amox-Fe contents.

Min-N (mg kg^{-1} soil)	No. of soils	Organic C (g kg^{-1} soil)	EDTA-Fe (mg kg^{-1} soil)	Amox-Fe (mg kg^{-1} soil)
86–166	4	23.0–46.0	150–2200	1875–11412
55–77	5	9.2–23.2	325–800	1100–6750
21–50	6	7.4–15.6	125–600	925–3562

reducible Fe. Multiple regression analysis of the results showed that improved mineralizable N or ammonium N produced in the submerged soils studied can be predicted from organic C and EDTA or Amox-Fe by the following regression equations:

$$\text{Mineralizable N (mg kg}^{-1}\text{ soil)} = 16.4 + 1.320\ \text{Organic C (g kg}^{-1}) + 0.0369\ \text{EDTA–Fe (mg kg}^{-1})\quad R^2 = 0.85 \tag{1}$$

$$\text{Mineralizable N (mg kg}^{-1}\text{ soil)} = 11.14 + 1.805\ \text{Organic C (g kg}^{-1}) + 0.00469\ \text{Amox–Fe (mg kg}^{-1})\quad R^2 = 0.81 \tag{2}$$

The values of ammonium N produced under anaerobic incubation, were in close agreement with those predicted by using regression Eq. (1) (for organic C and EDTA-Fe) or 2 (organic C and Amox-Fe) (Table 3). These results presented in Eqs. (1) and (2) need to be tested with an independent data. In the present study, the results with 15 West African soils were used to predict mineralizable N as well as to construct the regression Eqs. (1) and (2). These results, however, are significant as they show that a simple chemical index based on organic C and reducible Fe can be used for predicting potentially mineralizable N (ammonium N) in wetland rice soils.

As pointed out by Patrick and Reddy,[6] the Fe redox reactions dominate in submerged soils due to Fe reduction and this Fe influence exceeds the total amounts of other redox elements by a factor of 10 or more. Easily reducible Fe plays an important role in the sorption–desorption of ammonium and its exchange under reduced conditions as found in wetland rice soils. For example, Sahrawat[25] showed that ammonium fixation in tropical soils was significantly correlated to easily reducible Fe, and it was suggested that ammonium dynamics in submerged soils are greatly influenced by Fe redox reactions. Under reduced soil condition, the sorbed ammonium is released due to Fe reduction as well as due to exchange with Fe (II)[25–27] resulting in increased amounts of ammonium in soil solution.[3,8]

The results presented in this paper along with earlier research suggest that ammonium production or potentially mineralizable N in submerged rice soils

Table 3. Observed values of ammonium N produced (Min-N) under anaerobic incubation and those predicted by organic C and reducible Fe (EDTA-Fe or Amox-Fe) for 15 West African soils.

		Predicted Min-N (mg kg^{-1} soil)	
Soil no.	Observed Min-N (mg kg^{-1} soil)	Organic C and EDTDA-Fe	Organic C and Amox-Fe
1	48	49	40
2	31	37	37
3	166	158	158
4	50	50	45
5	39	41	44
6	55	75	45
7	77	55	50
8	55	58	59
9	94	90	98
10	86	100	103
11	65	76	80
12	65	59	54
13	86	52	61
14	21	31	29
15	36	42	46
Mean	65	65	63
SD[a]	25	23	25

[a] SD is standard deviation of mean.

can be estimated using the chemical index based on organic C and reducible Fe contents of soils. The method is simple and rapid for routine estimation of N supplying capacity of the soils.

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