

Comissão 2.4 - Química do solo

DYNAMICS OF AMMONIUM AND pH IN THE SOLUTION OF SOILS WITH DIFFERENT SALINITY LEVELS, GROWING IRRIGATED RICE⁽¹⁾

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SUMMARY

Rice in Rio Grande do Sul State is grown mostly under flooding, which induces a series of chemical, physical and biological changes in the root environment. These changes, combined with the presence of rice plants, affect the availability of exchangeable ammonium (NH_4^+) and pH of soil solution, whereas the dynamics of both variables can be influenced by soil salinity, a common problem in the coastal region. This study was conducted to evaluate the dynamics of exchangeable NH_4^+ and pH in the soil solution, and their relation in the solution of Albaqualf soils with different salinity levels, under rice. Four field experiments were conducted with soils with exchangeable Na percentage (ESP) of 5.6, 9.0, 21.2, and 32.7 %. Prior to flooding, soil solution collectors were installed at depths of 5, 10 and 20 cm. The soil solution was collected weekly, from 7 to 91 days after flooding (DAF), to analyze exchangeable NH_4^+ and pH in the samples. Plant tissue was sampled 77 DAF, to determine N uptake and estimate the contribution of other N forms to rice nutrition. The content of exchangeable NH_4^+ decreased over time at all sites and depths, with a more pronounced reduction in soils with lower salinity levels, reaching values close to zero. A possible contribution of non-exchangeable NH_4^+ forms and N from soil organic matter to rice nutrition was observed. Soil pH decreased with time in soils with ESP 5.6 and 9.0 %, being positively correlated with the decreasing NH_4^+ levels at these sites.

Index terms: nitrogen, acidity, exchangeable sodium percentage.

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RESUMO: *DINÂMICA DO AMÔNIO E DO pH NA SOLUÇÃO DE SOLOS COM DIFERENTES NÍVEIS DE SALINIDADE, CULTIVADOS COM ARROZ IRRIGADO*

O arroz no Rio Grande do Sul é cultivado sob alagamento, o que causa uma série de alterações químicas, físicas e biológicas no ambiente radicular, ocasionando efeitos sobre a disponibilidade de amônio trocável (NH_4^+) e a acidez da solução do solo. Essa dinâmica pode ser influenciada também pela salinidade do solo, um problema comum na região costeira do Estado. Este trabalho teve como objetivo avaliar as alterações do NH_4^+ trocável e do pH e a relação entre ambos na solução de um Planossolo Háptico com diferentes níveis de salinidade, cultivado com arroz irrigado. O trabalho foi realizado a campo, em solos com percentagem de sódio trocável (PST) de 5,6, 9,0, 21,2 e 32,7 %. Previamente ao alagamento das áreas experimentais, instalaram-se coletores de solução do solo nas profundidades de 5, 10 e 20 cm. Realizaram-se coletas semanais de solução entre 7 e 91 dias após o alagamento (DAA), sendo analisados os teores de NH_4^+ trocável e o pH. Foi feita a coleta de plantas aos 77 DAA, para determinação da absorção de N e estimativa da contribuição de outras fontes desse nutriente na nutrição do arroz. Os teores de NH_4^+ trocável diminuíram ao longo do tempo em todos os locais e profundidades, sendo essa diminuição mais acentuada nos menores níveis de salinidade, com valores próximos a zero. Houve possível contribuição de formas não trocáveis de NH_4^+ e provenientes da matéria orgânica do solo na nutrição das plantas. Já o pH diminuiu com o tempo nos solos com PST de 5,6 e 9,0 %, correlacionando-se positivamente com a diminuição dos teores de NH_4^+ nesses locais.

Termos de indexação: nitrogênio, acidez, percentagem de sódio trocável.

INTRODUCTION

Growing rice in Rio Grande do Sul is one of the main agricultural activities of the State. In the 2010/11 growing season, 1,171,600 ha were cultivated (CONAB, 2011), of which virtually 100 % were irrigated (Oliveira, 2006). Flooding, which can occur before (pre-germinated system) or up to 30 days after sowing (sowing on dry soil), promotes a series of physical, chemical and biological changes in the soil and rhizosphere. Changes in this environment are caused mainly by the lack of oxygen in the system, inducing a series of reductive processes in the soil. This dynamic is regulated by the presence and availability of electron acceptors and donors (organic matter) and is accompanied by changes in pH, redox potential (Eh), electrical conductivity (EC) and phenomena of sorption-desorption and ion exchange, influencing the nutrient availability in soil and nutrient uptake by plants (Camargo et al., 1999).

Nitrogen is an essential element in plant nutrition and its particular dynamics is altered in rice soils. Nitrogen gain and loss in flooded soils are regulated by a number of biological and physical-chemical processes. Nitrogen in the soil is mainly supplied by fertilizers and crop residues, biological N_2 fixation, irrigation water, dry depositions and rainfall. On the other hand, losses from the system are associated with removal in crops, simultaneous occurrence of nitrification-denitrification reactions, NH_3 volatilization, irreversible retention between

mineral layers, leaching and runoff (Reddy & Patrick, 1976). Ammoniacal N is one of the preferential N forms taken up by rice (Holzschuh et al., 2009) and may account for up to 60 % of the crop demand. Compared to the mineralization in oxidic soils, ammonification in waterlogged soils occurs more slowly. In flooded soils of Louisiana, for example, the daily NH_4^+ accumulation rate in the soil reached 0.22 mg kg^{-1} of dry soil (Reddy & Patrick, 1976). The NH_4^+ concentration in the soil solution is influenced not only by root uptake, but also by its movement in the soil profile. Losses of NH_4^+ may occur, mainly by diffusion from anaerobic to aerobic soil layers, since the presence of aerobic microorganisms in the topsoil favors nitrification and subsequent denitrification of N.

In saline soils, as those found on the coastal plains of Rio Grande do Sul (Carmona et al., 2011), the variation of NH_4^+ concentration in the soil solution can be affected by a number of factors. The physical destructuring of soil, caused by clay dispersion in soils with exchangeable Na percentage (ESP) above 15 % (Ayers & Westcot, 1999), changes the profile porosity and can interfere with the upward movement of NH_4^+ towards the limiting oxidized layer. Moreover, the damage caused by salinity to the NH_4^+ root uptake sites can cause a decrease in nutrient uptake, slowing down the ion depletion in the soil solution.

Sodium chloride (NaCl) is known to inhibit NH_4^+ uptake by wheat (Hawkins & Lewis, 1993) and fescue (Bowman et al., 2006), for example. Another

factor that may contribute to maintain NH_4^+ in the soil solution is the fact that high sodium ion concentrations decrease NH_4^+ activity, reducing its availability to plants due to a high chemical competition. Soil salinity also affects root growth, reducing the length (Welfare et al., 1996) and therefore the possibility of roots to take up NH_4^+ .

A possible indicator of NH_4^+ depletion in the soil may be the pH. Changes in soil pH after flooding are attributed to several factors, such as the reduction of Fe^{3+} to Fe^{2+} , SO_4^{2-} to H_2S and CO_2 to CH_3 , aside from NH_4^+ accumulation (Camargo et al., 1999). Ishizuka & Tanaka (1969) observed a marked reduction in the rhizosphere pH, caused by NH_4^+ uptake by rice. Thus, a pH reduction may indicate the intensity of NH_4^+ uptake by roots, whose ion carriers excrete H^+ protons as compensation for NH_4^+ uptake. This proton excretion may change not only the rhizosphere pH, but the whole soil layer influenced by the root system (Nye, 1981).

This study aimed to evaluate the NH_4^+ dynamics and pH and the relationship between them at different depths in soil solution with increasing salinity levels, under irrigated rice.

MATERIAL AND METHODS

The study was carried out on the Fazenda Cavalhada (30° 29' 45" S, 44° 34' 32" W), municipality of Mostardas, State of Rio Grande do Sul, Brazil. Four Albaqualfs were selected, with different salinity levels in the 0–20 cm layer, expressed by the exchangeable Na percentage (ESP), according to equation 1.

$$\text{ESP (\%)} = [(\text{Na}^+ / \text{CEC}_{\text{pH } 7.0})] \times 100 \quad (1)$$

The ESP levels of the selected soils were 5.6, 9.0, 21.2 and 32.7 % (Table 1). Rice was sown on different dates, i.e, the area with ESP 9.0 % on November 1, 2008 (cultivar IRGA 417), the areas with ESP 21.2 and 32.7 % on November 8, 2008 (cultivar IRGA 417) and the area with ESP 5.6 % on November 17, 2008 (cultivar IRGA 422 CL). Cultivar IRGA 422 CL was used at one of the sites due to high red rice infestation. IRGA 417 and IRGA 422 CL have very similar genetic characteristics (Lopes et al., 2003). The management system used was half-tillage cultivation. The seeding rate was 120 kg ha⁻¹, in rows spaced 0.2 m apart. The seeds were treated with the insecticide fipronil to prevent infestation of *Oryzophagus oryzae* and weeds were controlled with specific herbicides (Penoxulam + Clomazone in the areas cultivated with IRGA 417 and Imazethapyr + Imazapic in the area cultivated with IRGA 422 CL) applied at growth stage V4 (Counce et al., 2000). The experiments were conducted on 12 m² plots (4 x 3 m), spaced 0.5 m apart and three replications per site. The experiment was arranged in a completely randomized block design.

The soil properties at the four sites were analyzed according to Tedesco et al. (1995) (Table 1). The plots received N at rates of 120 kg ha⁻¹, in the form of urea (45 % N) before flooding in the V4 stage (Counce et al., 2000). Due to the sufficiency of P and K (SOSBAI, 2007) at all sites (Table 1), no fertilizer containing these nutrients was supplied. Two water sources were used: Lagoa do Casamento, to irrigate the experiments in the soils with ESP 5.6 and 9.0 %, and Lagoa dos Gateados, for soils with ESP 21.2 and 32.7 %. A water table of 10 cm was maintained until grain harvest.

Table 1. Soil properties at different sites and depths

ESP ⁽¹⁾	Layer	pH H ₂ O	Clay	Organic matter	P ⁽²⁾	NH ₄ ⁽³⁾	K ⁺⁽⁴⁾	Na ⁺⁽⁴⁾	Ca ²⁺⁽⁴⁾	Mg ²⁺⁽⁴⁾	H + Al	CEC _{pH 7}	EC
%	cm	1:1	— g kg ⁻¹ —	— mg dm ⁻³ —	—	—	—	—	—	—	—	—	dS m ⁻¹
5.6	0–5	4.4	140	24	34	15.2	70	0.40	2.50	1.40	4.67	9.2	2.23
	5–10	4.6	140	22	37	9.8	51	0.41	2.51	1.45	4.54	9.0	1.61
	10–20	4.9	140	15	28	23.0	23	0.51	2.16	1.47	3.57	7.8	1.46
9.0	0–5	4.6	150	18	36	19.4	81	0.40	1.81	1.50	2.53	6.5	2.01
	5–10	4.6	150	15	39	18.6	43	0.47	1.63	1.50	3.27	7.0	1.53
	10–20	5.7	130	11	70	18.0	62	0.87	2.03	2.42	2.14	7.6	1.86
21.2	0–5	4.9	140	19	31	20.1	90	1.58	2.03	1.80	2.56	8.2	6.34
	5–10	5.2	160	19	34	15.4	82	1.35	2.01	1.68	2.28	7.5	5.82
	10–20	6.3	160	9.5	20	17.3	82	1.80	2.07	1.79	1.63	7.5	5.40
32.7	0–5	5.1	130	14	47	17.2	152	5.04	1.77	3.41	2.51	13.1	15.54
	5–10	5.6	120	14	45	20.4	148	3.63	2.20	3.12	2.29	11.6	9.03
	10–20	6.3	130	10	26	14.6	160	3.30	2.34	3.01	1.93	11.0	6.87

⁽¹⁾ Exchangeable sodium percentage in the 0–20 cm layer. ⁽²⁾ Mehlich 1 method. ⁽³⁾ KCl 1.0 mol L⁻¹ extractant; ⁽⁴⁾ Ammonium acetate extractant, 1.0 mol L⁻¹.

Prior to soil flooding, soil solution collectors were installed at depths of 5, 10 and 20 cm. The device consisted of a plastic tube (diameter 5 mm) connected to a PVC collector (diameter 25 mm, length 40 m), covered at the ends with nylon mesh (Silva et al., 2003). From the surface end of the hose, approximately 40 mL solution was extracted per depth, with a 60 mL syringe. After sampling, the aliquots were placed in plastic tubes with a vacuum cap. Samplings were repeated weekly, from the 7th day until the 91st day after flooding (DAF). After determining the pH, these samples were acidified for later analysis of the NH_4^+ levels (Tedesco et al., 1995).

When the rice plants reached full flowering 77 DAF, the above-ground plant tissues were harvested from one meter in a row. The material was dried in a forced air oven for 72 h to determine dry mass and then total N levels (Tedesco et al., 1995).

The results of pH and NH_4^+ in the soil solution were subjected to regression analysis. Polynomial equations that best fit the data were used, and the significance of the regression coefficients at 10, 5 and 1 % presented, together with the coefficient of determination. Additionally, the association between the variables pH and NH_4^+ at the different sites was determined by Pearson (linear) correlation analysis. To determine the NH_4^+ balance in the soil solution in relation to the plant uptake, the NH_4^+ concentrations in the soil solution 7 DAF were subtracted from the concentrations 77 DAF, a period that coincided with flowering at all sites. The average NH_4^+ concentrations at the depths of 5, 10 and 20 cm were considered, since about 90 % of the rice roots are concentrated in the 0–20 cm layer (Lopes et al., 1994). From the values of total N taken up by plants 77 DAF and the balance in ionic solution between 7 and 77 DAF, it was possible to estimate the contribution of N mineralized by soil organic matter and/or desorbed from the non-exchangeable fraction by plant nutrition.

RESULTS AND DISCUSSION

Levels of exchangeable NH_4^+ in the soil solution and uptake by rice

Several factors are associated with NH_4^+ depletion in flooded soils, and this dynamic is greatly influenced by the presence of rice plants, which absorb mainly inorganic N forms (Ghosh & Bhat, 1998). Plant roots can also stimulate N loss by denitrification, since the metabolism of the root system causes the secretion of organic substances that serve as hydrogen donors for the denitrification process. In addition, high root densities in flooded

soils can increase the total area of aerobic zones and create favorable conditions for nitrification (Reddy & Patrick, 1984). When not taken up by the roots, the nitrate produced can migrate to the adjacent reduced zone and undergo denitrification, which may result in significant N losses in the form of NH_3 (Buresh et al., 1991).

In this study, regardless of the soil salinity level and depth, there was a marked decrease in the levels of exchangeable NH_4^+ during rice growth (Figure 1). At ESP 5.6 % (Figure 1a), despite the initial difference between NH_4^+ concentrations between depths of 5 and 20 cm, this nutrient was almost completely depleted 35 DAF, and thereafter the NH_4^+ concentrations remained low and stable, with little variation at the depth of 5 cm, until the end of the crop cycle. The availability of exchangeable NH_4^+ was therefore still very low from the vegetative stage of rice. Comparing the exchangeable NH_4^+ levels at 7 DAF and 91 DAF at this salinity level (Table 2), it appears that the decrease throughout the rice cycle was higher than 90 % at all depths, on average 96 %.

Likewise, in the soil with ESP 9.0 %, there was a similar depletion pattern at the three depths evaluated. At 5 and 10 cm, the analysis method could hardly detect the presence of exchangeable NH_4^+ . As observed at ESP 5.6 %, the difference between the NH_4^+ concentrations between 7 and 91 DAF in ESP 9.0 % was over 90 % at the three studied depths (Table 2), with on average 97 % during rice growth.

In the two soils with highest salinity levels, the depletion pattern was different. In soil with ESP 21.2 %, at the depth of 5 cm, the presence of exchangeable NH_4^+ was no longer detectable as early as 28 DAF (Figure 1c). Root activity is highest at this depth (Lopes et al., 1994) and would therefore, theoretically, require larger amounts of NH_4^+ to meet the plant demand. However, the difference between the initial and final levels of exchangeable NH_4^+ at this depth was 59 %, which is much lower than at the other depths (Table 2). This was due to the increase of exchangeable NH_4^+ in the last evaluation at this depth (Figure 1c). At greater depths however, exchangeable NH_4^+ was almost completely depleted 42 DAF (Figure 1c). Comparing the initial and final levels of exchangeable NH_4^+ in the soil solution at this salinity level, at the three studied depths, it was observed that, contrary to what occurred at 5 cm, the increase 91 DAF, at depths of 10 and 20 cm, was on a smaller scale, resulting in a higher difference compared to 7 DAF, in the order of 93 and 92 %, respectively (Table 2).

The dynamics of exchangeable NH_4^+ were most differentiated at the site with highest salinity level (Figure 1d). Although there was a considerable decrease in the NH_4^+ levels, especially at 5 and

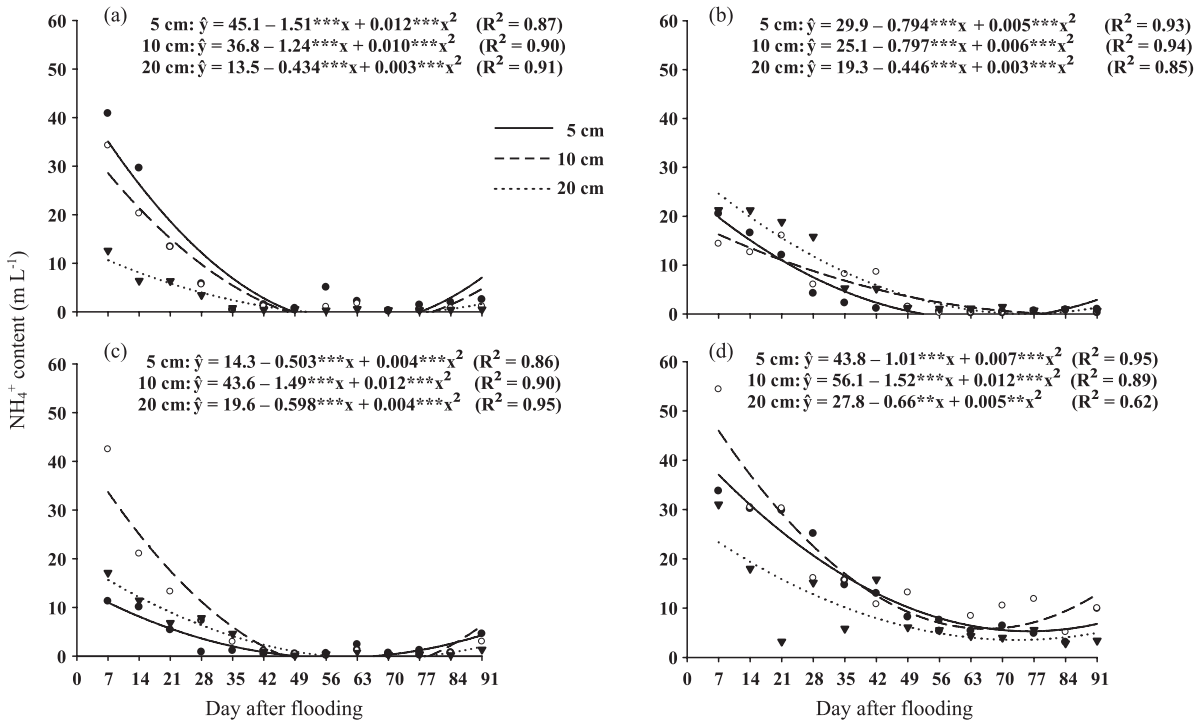


Figure 1. Ammonium contents in the soil solution at different depths and salinity levels: ESP 5.6 % (a), ESP 9.0 % (b), ESP 21.2 % (c), ESP 32.7 % (d). **, ***: significant at 1 and 0.1 %, respectively, by the F test.

Table 2. Percentage reduction in ammonium levels in the soil solution between 7 and 91 days after flooding at three depths in four rice soils, with increasing salinity levels

ESP ⁽¹⁾	Depth (cm)			Average
	5	10	20	
	%			
5.6	94	97	96	96
9.0	95	98	97	97
21.2	59	93	92	81
32.7	71	82	89	81

⁽¹⁾ Exchangeable sodium percentage in the 0–20 cm layer.

10 cm, the levels of exchangeable NH₄⁺ never approached zero, as observed at the other sites (Figures 1a,c). Furthermore, the depletion of exchangeable NH₄⁺ levels between 7 and 91 DAF, at the highest soil salinity level, did not reach 90 % at any of the studied depths (Table 2). As observed in ESP 21.2 %, NH₄⁺ levels increased in the last assessment at depths of 5 and 10 cm (Figure 1d), which explains the lowest differences between the NH₄⁺ levels at the three depths (Table 2). Another similarity observed in relation to ESP 21.2 %, was the average depletion of the evaluation period of 81 %.

Except for the soil with highest salinity level, the difference between the ammonium concentration in

the soil solution between 7 and 77 DAF and the plant uptake of this ion was always negative (Table 3). This indicates that the plants absorbed NH₄⁺ ions from the N mineralized from organic matter and/or from the non-exchangeable soil fraction. The ammonification from soil organic matter, although reduced in anaerobic soils, can occur at rates of 0.22 mg kg⁻¹ day⁻¹ dry soil (Reddy & Patrick, 1976), which reinforces the study hypothesis of contribution of this source to plant nutrition, besides being one of the possible factors that lead to increased NH₄⁺ levels 91 DAF, especially in soils with ESP 21.2 and 32.7 % (Figure 1c,d).

The hypothesis of the contribution of non-exchangeable forms of NH₄⁺ to rice nutrition, although difficult to measure, cannot be ruled out, based on data available in literature. Zhang & Scherer (2002), for example, observed the release of non-exchangeable NH₄⁺ to the solution of rice soils, and the mobilization of this fraction was higher in the rhizosphere of plants and decreased with distance from the roots; this could somewhat explain the non-detection of NH₄⁺ by the method of soil solution collection used in this study. According to Mengel et al. (1990), the depletion of non-exchangeable NH₄⁺ sources occurs only in the rhizosphere, where the NH₄⁺ concentration in the soil solution is depleted to a level that allows the outward diffusion of NH₄⁺ ions from the interlayers of clay minerals. Moreover, Fe²⁺ oxidation in the rice rhizosphere, facilitated by the presence of aerenchyma, results in the release

Table 3. Ammonium concentration in the soil solution, ammonium uptake at flowering and difference between the ammonium concentration in the soil solution and ammonium uptake by rice, grown in soils with different salinity levels

ESP	Sol [7 DAF - 77 DAF] ⁽¹⁾	Uptake	Δ ⁽²⁾
%	mg L ⁻¹	mg dm ⁻³	mg L ⁻¹
		NH ₄ ⁺	
5.6	24.5	175	-150
9.0	18.7	116	-98
21.2	21.4	109	-88
32.7	31.0	24	7.0

⁽¹⁾ Ion balance in the soil solution based on the difference in ammonium concentration between 7 and 77 days after flooding.

⁽²⁾ Difference between the ammonium concentration in the soil solution and ammonium uptake by rice plants.

of protons, which penetrate the interlayer of clay minerals and displace adsorbed cations (Sparks & Liebhard, 1982).

In the present study, the damage caused by salinity on NH₄⁺ uptake by plants should be taken into account, especially in soil with ESP 32.7 %, where the plant density was only 10 plants m⁻² (Carmona et al., 2010). The smaller number of plants due to higher salinity, therefore, may be one of the factors associated with a higher concentrations of exchangeable NH₄⁺ in the soil solution (Figure 1d), since the root density was proportionally smaller, not only because of the lower presence of plants, but also due to the stress caused by high levels of salts, inhibiting root growth. Furthermore, at high salinity, the transport capacity and selectivity of ions requires metabolic energy produced by carbohydrates from the roots, which affects root growth (Welfare et al., 1996).

Moreover, the soil salinity can cause damages to its physical structure (Ayers & Westcot, 1999), which may have contributed to the lower NH₄⁺ uptake in the soil with ESP 32.7 % (Table 3). Clay dispersion, caused by the presence of sodium, clogs micropores, reducing the hydraulic conductivity of soils. This restricts the upward movement of NH₄⁺ to the oxidized layer, avoiding losses by denitrification. According to Reddy (1982), several factors control the diffusion of NH₄⁺ in the flooded soil profile, e.g., NH₄⁺ concentration in the soil solution, which was higher in the soil with highest salinity (Figure 1d); presence of other cations in the exchange complex, also higher in the soil with ESP 32.7 % (Table 1); and the relative volume of pore space, which is a function of soil density. Although this physical property was not evaluated, the high sodium concentration in this soil (Table 1) indicates a greater bulk density than of the others.

pH in soil solution and its relation to exchangeable NH₄⁺

The dynamics of pH in the soil solution was similar in soils with ESP 5.6 % (Figure 2a) and 9.0 % (Figure 2b), decreasing with the time of flooding at all depths. In the soil with ESP 21.2 %, a decrease was observed at 5 cm and an increase at the other depths (Figure 2c). In the ESP 32.7 %, at depths of 5 and 20 cm, an increase of pH was verified during the crop cycle; and at 10 cm, a pH decrease, followed by an increase to values close to those recorded at the beginning of the irrigation cycle 7 DAF (Figure 2d).

Apparently, the presence of plants influenced the pH of the soil solution, since at sites with lower salinity (Table 1), where plant establishment was better (Carmona et al., 2010), the dynamics of acidity contradicted previously established concepts. According to Camargo et al. (1999), the pH of flooded soils tends to neutrality after submergence. In this sense, the buffering action of waterlogged soils should be attributed to the reduction of Fe, Mn and carbonic acid, since their redox reactions involve the consumption or production of H⁺/OH⁻. Moreover, the changes must also be attributed to the accumulation of NH₄⁺, sulfate reduction to sulfide and reduction of CO₂ to CH₃, and the rate and extent of pH changes depend on soil properties and temperature. However, the accumulation of NH₄⁺, one of the requirements for a pH increase, did not occur in these soils, but conversely, dropped sharply (Figure 1a,b). In addition, another factor that may have contributed to the results is the fact that acid soils, with low contents of organic matter and active Fe, or high S contents, hardly reach pH above 6.0, even after months of flooding (Ponnamperuma, 1976). In addition to the low organic matter content observed (Table 1), in some soils very close to the studied areas, sulfate levels above 300 mg dm⁻³ (data not shown) were recorded.

The pH of the soil solution was positively correlated ($p \leq 0.01$) with the NH₄⁺ concentrations in soils with ESP 5.6 and 9.0 % at all depths evaluated, except at 20 cm with ESP 5.6 % (Table 4). It is noteworthy that the correlation under these conditions was highest at 5 cm (Table 4), which can be explained by the higher concentration of roots at this depth (Lopes et al., 1994). Accordingly, the pH decrease in the soil solution (Figure 2a,b) can be associated with the extrusion of H⁺ ions by rice roots, as a result of NH₄⁺ uptake. Ishizuka & Tanaka (1969), studying changes in the pH of soil solution caused by a selective uptake of several ionic species, observed a reduction between 0.38 and 3.26, comparing the original pH and pH on the fifth day of evaluation, after uptake of the species NH₄NO₃, NH₄Cl, (NH₄)₂SO₄ and NH₄H₂PO₄ by rice plants. It should be noted, however, that the decrease in

pH in the rhizosphere may be associated with other factors such as O₂ secretion, as verified by Zhang & Scherer (2002). Nevertheless, the decrease was relatively low (only 0.8).

In the soil with ESP 21.2 %, the pH and NH₄⁺ concentrations were negatively correlated at

the depths of 10 and 20 cm. In the soil with ESP 32.7 %, this correlation occurred at depths of 5 and 20 cm (Table 4). In these cases, the lower influence of root activity seems to have favored the increase in soil pH (Figure 2c,d), characteristic of waterlogged soils.

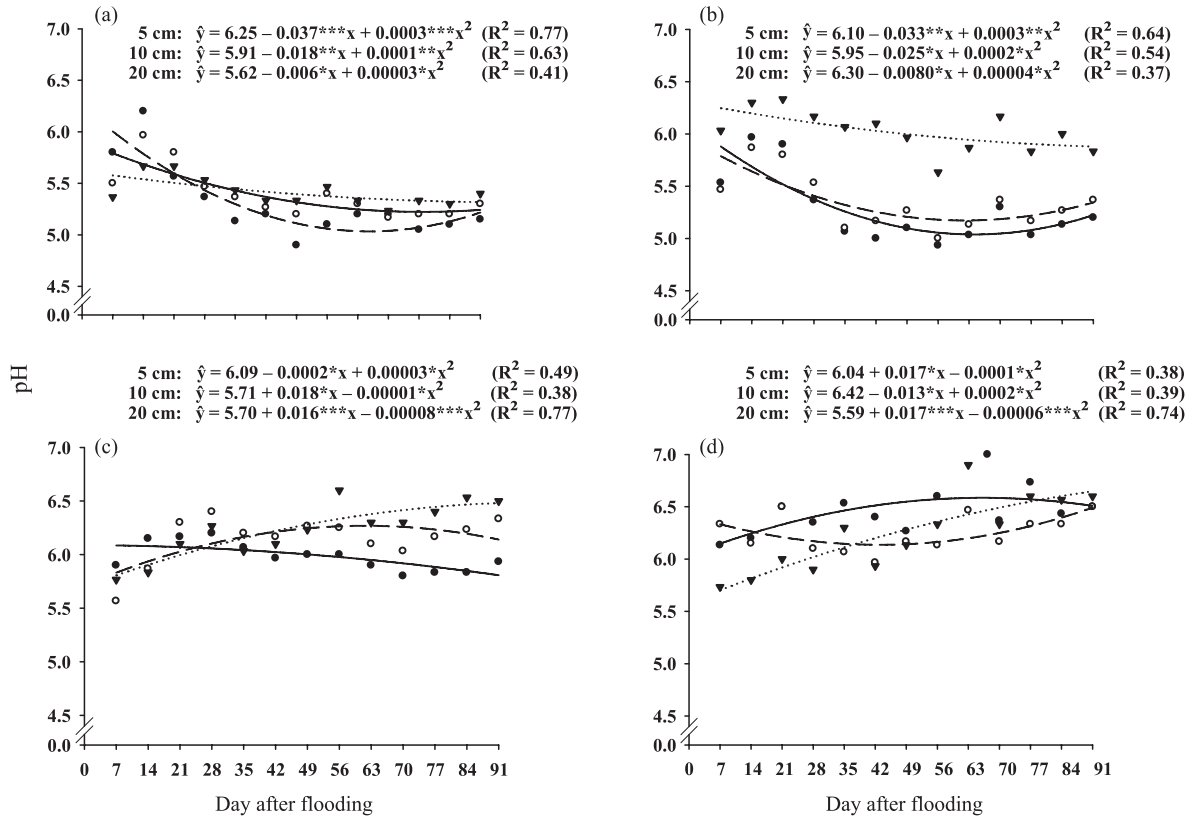


Figure 2. pH of the soil solution at different depths and salinity levels: ESP 5.6 % (a), ESP 9.0 % (b), ESP 21.2 % (c), ESP 32.7 % (d). *, **, ***: significant at 10, 1 and 0.1 %, respectively, by the F test.

Table 4. Relationship between pH and ammonium content in the soil solution at different depths at four salinity levels

ESP	Depth	Linear regression equation	Correlation coefficient (r)
%	cm		
5.6	5	$\hat{y} = 5.106 + 0.025x$	0.88**
	10	$\hat{y} = 5.299 + 0.015x$	0.66**
	20	$\hat{y} = 5.374 + 0.0162x$	0.45
9.0	5	$\hat{y} = 5.082 + 0.040x$	0.83**
	10	$\hat{y} = 5.188 + 0.030x$	0.67**
	20	$\hat{y} = 5.906 + 0.016x$	0.69**
21.2	5	$\hat{y} = 5.958 + 0.008x$	0.21
	10	$\hat{y} = 6.247 - 0.014 x$	-0.79**
	20	$\hat{y} = 6.382 - 0.038x$	-0.80**
32.7	5	$\hat{y} = 6.638 - 0.012x$	-0.57*
	10	$\hat{y} = 6.214 + 0.002x$	0.15
	20	$\hat{y} = 6.539 - 0.032x$	-0.75**

*, **: Significant at 5 and 1 %, respectively.

CONCLUSIONS

1. The levels of exchangeable NH_4^+ in the soil solution decreased with flooding and rice growth, and this depletion was more pronounced in soils with lower salinity levels.

2. The NH_4^+ uptake by plants was higher than the original capacity of supply from the soil solution, indicating a contribution from other sources to plant nutrition.

3. The soil solution pH decreased with time in soils with lower salinity content, being positively correlated to the decrease of NH_4^+ levels in these soils.

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