ORIGINAL RESEARCH

Clay soils and the importance of base saturation in limestone action and water quality maintenance: an evaluation for freshwater aquaculture setup

Vanessa Lewandowski ⬤ **. Ademar Alves Ferreira Neto . Francis Henrique Tenório Firmino** ⬤ **.
Dacley Hertes Neu**

Abstract This study investigates the influence of two clay soils on water quality, the action of limestone, and determines which chemical attributes of the soil have the greatest influence on water. A mesocosm system was set up in aquariums, where a 5 cm layer of soil was placed, and subsequently, 21 liters of water were added. Five treatments were evaluated: water + limestone; soil A + water; soil A + water + limestone; soil B + water; soil B + water + limestone. Soils A and B contained 456.00 g kg-1 and 642.00 g kg-1 of clay, 18.37 and 7.23 cmolc dm-3 of cation exchange capacity, 89.39% and 65.45% base saturation, respectively. After 28 days, the water in contact with soil A, without limestone addition, presented pH (7.60±0.14), alkalinity (69.21±4.50 mg L-1), and hardness (55.55±9.61 mg L-1) at levels suitable for freshwater aquaculture. The same effect was not observed for the water in contact with only soil B. When limestone was added, there was no statistical difference ($p>0.05$) in the water quality parameters in contact with both soils. The interaction between soil and water became evident by the decrease in acidity and increase in base saturation of soil B, without limestone addition. Base saturation showed a positive correlation with all evaluated water quality parameters, with coefficients ranging between 0.63 (alkalinity) and 0.72 (pH). It is concluded that, among the soil chemical parameters, the assessment of base saturation provides more relevant information on how the water in the aquaculture ponds will maintain alkalinity, pH, and hardness. In clay soils, when this index is at 89%, liming is unnecessary because the soil-water interaction maintains pH, alkalinity, and hardness at levels suitable for freshwater aquaculture.

Introduction

An aquaculture pond is an earthen dam that confines a space with water storage, where the production of aquatic organisms occurs. Ponds are the primary production units in aquaculture (FAO 2022) and hydraulic residence time is a fundamental characteristic of the system (Tidwell 2012). The water's residence time within the pond creates a natural ecosystem with interactions among biotic and abiotic components of the environment.

Soil is an abiotic factor that must be studied in aquaculture. Its physical characteristics are important for the construction and maintenance of pond dikes and slopes (Magalhães et al. 2019), while its chemical characteristics are intrinsically related to reactions occurring in the aquatic ecosystem (Hasibuan et al. 2023; Saraswathy et al. 2019). The influence of soil chemical attributes occurs through the exchange of ions

Vanessa Lewandowski (✉) . Ademar Alves Ferreira Neto . Dacley Hertes Neu
Faculdade de Ciências Agrárias, Universidade Federal da Grande Dourados, Rodovia Dourados-Itahum, km12, CEP 79804-970 Dourados, MS, Brazil
e-mail: vanessalewandowski@ufgd.edu.br

Francis Henrique Tenório Firmino
Centro de Ciências Agrárias, Universidade Federal de Viçosa, Avenida Peter Henry Rolfs, s/n, CEP 36570-900, Viçosa, MG, Brazil

between the soil and water, facilitated by the presence of colloids, which consist of small fragments of clay and organic matter (< 1μm in diameter). Colloids have electrically charged surfaces, generally negative, and are highly reactive, attracting ions with positive electric charges (cations), such as Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and H^+ (Pan et al. 2023). These cations are retained in the colloids through electrostatic attraction and can be easily replaced and made available to the environment.

The total number of cations that can be retained and made available to the environment is known as the soil's cation exchange capacity (CEC) (Pine et al. 2018). Another important parameter is base saturation, which consists of the percentage of Ca^{2+}, Mg^{2+}, and K^+ adsorbed on the surfaces of colloids when the soil has a pH of 7.0 (Tiecher et al. 2022) . Since the soil is a site of intense activity in the aquatic ecosystem of ponds, it is observed that both the cation exchange and the type of predominant cations will determine the soil's influence on water quality, which in turn is related to the development of phytoplankton and culti- vated animals, such as fish and shrimp (Hasibuan et al. 2023; Kamal et al. 2018). Among the water quality parameters influenced by the soil are pH, electrical conductivity, and alkalinity (Li et al. 2013). Alkalinity stands out as a fundamental parameter in aquaculture, as it neutralizes the acidity of the medium and pro- motes the water's buffering capacity, preventing abrupt pH changes within a 24-hour period (Boyd 2020).

When alkalinity is below the recommended level, less than 40mg/L (Boyd et al. 2016), liming is per- formed, which involves applying lime or limestone to the water. This process incorporates cations, such as Ca^{2+} and Mg^{2+}, as well as bicarbonates, which can be directed to reactions in the environment, serving as a carbon source for photosynthesis and in the composition of microbial biomass (Han and Boyd 2018; Sá and Boyd 2017). Therefore, liming is a common practice in aquaculture, and the required dose is generally determined by alkalinity (Boyd 2020), with the application occurring directly in the water (Queiroz et al. 2004). In aquaculture ponds, a unique ecosystem is formed where the exchange of elements between water and soil occurs, directly interfering with the chemical parameters of the aquatic environment (Hasibuan et al. 2023). Thus, it is crucial to consider the effect of the soil on water quality and the application of lime- stone.

Due to the cation exchange capacity, clay soils can act as sources or sinks of nutrients, influencing their availability through physical, chemical, and biological processes involved in the release and cycling of nutrients (Kome et al. 2019). In agriculture, liming takes into account the physical and chemical character- istics of the soil (Holland et al. 2018). This practice is indicated by the soil pH, and the dosage is determined by base saturation and the chemical characteristics of the limestone material (Holland et al. 2018; Kome et al. 2019; Chaganti et al. 2021). In aquaculture, the influence of soil on water quality and the action of limestone are less studied.

In this context, the literature provides information on the effect of organic matter, water characteristics, and the limestone material itself on its dissolution, as well as its influence on water quality (Fitrani et al. 2020; Han and Boyd 2018; Sá and Boyd 2017; Sá et al. 2019). Information obtained through studies of the water-soil relationship enables the understanding of water quality dynamics in ponds, and such data can serve as a basis for improving the efficiency of aquaculture management practices, such as liming. There- fore, the objective of the present study was to evaluate the influence of two clays soils on water quality and the action of limestone, as well as to determine which chemical attributes of the soil have the greatest influence on water.

Material and methods

Study site and soil collection

The study was conducted at the Aquaculture Production Laboratory of the Faculty of Agricultural Sciences at the Federal University of Grande Dourados. The experimental period lasted for 28 days.

Soil A was obtained from the Experimental Farm of the Faculty of Agricultural Sciences (UTM Coor- dinates: 706841.96 E; 7538797.32 S, zone 21S), and soil B was collected from the Aquaculture Production Area of Federal University of Grande Dourados (UTM Coordinates: 712943.46 E; 7543777.87 S, zona 21S). Both sites were situated in a dry environment. The collection was conducted in an area of 10 m² at each site, traversing the space in a "zigzag" pattern. Initially, the upper layer of soil was cleaned with a hoe, followed by the collection of material from a depth of 30 cm at 20 points at each site, using a cutting spade.

The 20 subsamples were homogenized and passed through a 2 mm mesh sieve. The collection and sieving process was carried out according to the methodology described by Filizola et al. (2006).

Subsequently, 100g of each soil type was sent for granulometric analysis, chemical parameters, and organic matter (Table 1). Granulometric variables (sand, silt, and clay) were determined using the pipette method, based on the sedimentation of particles. The chemical parameters analyzed included pH (CaCl2), exchangeable acidity, and verification of cation concentration (Al3+, Ca2+, Mg2+, and K+). Soil pH was determined using a 0.01 mol CaCl2 solution. Exchangeable Al3+, Ca2+, and Mg2+ were extracted with 1.0 mol L-1 neutral KCl and K+ with Mehlich-1. Based on the obtained values, the sums of exchangeable bases (SB = Ca2+ + Mg2+ + K+), effective cation exchange capacity (t = Ca2+ + Mg2+ + K+ + Al3+), potential cation exchange capacity (T = Ca2+ + Mg2+ + K+ + H+ + Al3+), base saturation (V% = (100 x (Ca2+ + Mg2+ + K+)/T)), and aluminum saturation (m% = (100 x Al3+)/t) were calculated. Organic matter was determined by the colorimetric method. Soil analyses were performed according to the methodologies described by Teixeira et al. (2017).

The main characteristics of the soils refer to the clay content, cation exchange capacity, and base saturation. Soil A contained 456.00 g kg-1 of clay, effective cation exchange capacity of 18.37 cmolc dm-3 and a base saturation of 89.39%. Soil B contained 642.00 g kg-1 of clay, effective cation exchange capacity of 7.23 cmolc dm-3 and a base saturation of 65.45%.

Experimental design

Fifteen experimental units were utilized. consisting of black aquariums with dimensions of 44.0 x 27.0 x 35.0 cm (length x width x height). The experimental units were divided into five treatments with three replications each. The treatments were: Water + limestone (W+L); Soil A + water (SA); Soil A + water + limestone (SA+L); Soil B + water (SB); Soil B + water + limestone (SB+L).

For treatments involving soil testing, a soil-water mesocosm was set up, with a 5 cm layer of soil placed at the bottom of the aquariums, followed by the addition of 21 L of water. In the treatment without soul inclusion (W+L), only 21 L of water and limestone were added. All experimental units were filled with water supply from the Aquaculture Production Laboratory, sourced from a well located at the University (Table 1). The experimental unit consisted of isolated structures, without water circulation and exchange, as well as

Table 1 Initial characteristics of the soils and water used in the study

Parameters	Soil A	Soil B
pH	6.20	5.40
K^+ (cmol$_c$ dm^{-3})	0.31	0.17
Ca^{2+} (cmol$_c$ dm^{-3})	11.36	4.91
Mg^{2+} (cmol$_c$ dm^{-3})	6.70	2.15
$H^+ + Al^{3+}$ (cmol$_c$ dm^{-3})	2.18	3.82
Al^{3+} (cmol$_c$ dm^{-3})	0.00	0.00
Effective Cation Exchange Capacity – t (cmol$_c$ dm^{-3})	18.37	7.23
Potential Cation Exchange Capacity – T (cmol$_c$ dm^{-3})	20.55	11.05
Base Saturation – V (%)	89.39	65.45
Aluminum Saturation – m (%)	0.00	0.00
Organic Matter (g dm^{-3})	32.45	18.83
Organic Carbon (g dm^{-3})	22.67	13.15
Sand (g kg^{-1})	221.00	150.00
Clay (g kg^{-1})	456.00	642.00
Silt (g kg^{-1})	323.00	208.00
	Water	
Temperature (ºC)	18,60	
pH	6.78	
Electrical conductivity (µS cm^{-1})	267.00	
Total dissolved solids (mg L^{-1})	150.00	
Alkalinity (mg L^{-1})	28.64	
Hardness (mg L^{-1})	33.33	

aeration. Therefore, the water remained static during the experimental period. The methodology used for the assembly and design of the experimental units followed as described in the literature (Li et al. 2013; Han and Boyd 2018).

The amount of limestone applied was equal (12 g) in all experimental units where it was tested, and the dosage was determined based on the water alkalinity, as described by Senar (2019). This amount represents 100 g m-2, which is the recommended dosage for water with alkalinity between 20-30 mg L-1. Dolomitic limestone was used, which was purchased from a commercial establishment in Dourados – MS. The product contained 19% magnesium oxide (MgO) and 29% calcium oxide (CaO), with a Relative Power of Total Neutralization (PRNT) of 90.1%. The application of limestone was carried out only once, on the first day of studying. To do so, the determined amount was applied to the water of the experimental unit.

Water and soil analysis

Weekly, the temperature (ºC), pH, total dissolved solids (TDS) (mg L^{-1}), and electrical conductivity (EC) (µS cm^{-1}) of the water were checked with an Akso AK88 multiparameter. In addition, two 50 mL samples of water were collected from each experimental unit, which were designated for alkalinity (mg L^{-1}) and water hardness (mg L^{-1}) analysis. The first parameter was evaluated by the titration method using phenolphthalein indicator, and the second by the EDTA titration method. For this purpose, reagent kits from Alfakit LTDA were used, and the analysis process was carried out according to the manufacturer's recommendations.
At the end of the experimental period, soil samples from the units were sent for analysis of pH, cation concentration (cmol$_c$ dm^{-3}), effective (t) and potential (T) cation exchange capacity (CEC) (cmol$_c$ dm^{-3}), base saturation (V) (%) and aluminum saturation (m) (%). In addition to the chemical parameters, the amount of organic matter (g dm^{-3}) and organic carbon (g dm^{-3}) were also determined. Soil analyses were performed following the procedures established by Teixeira et al. (2017).

Data analysis

Statistical analyses were conducted with the data obtained at the end of the study. Initially, they underwent tests for normality and homogeneity of variances. Subsequently, analysis of variance (ANOVA) was performed, and upon detecting statistical differences, means were compared using the Tukey test at a 5% probability level. Additionally, water quality parameters and soil parameters such as pH, cation concentration, organic matter, effective cation exchange capacity (CEC), and base saturation were subjected to Pearson correlation analysis. Principal Component Analysis (PCA) was also conducted, considering alkalinity, hardness, water and soil pH, base saturation, effective and potential CEC, and soil organic matter. Correlation and PCA analyses were carried out to assess the relationship between soil and water variables. The statistical procedures were executed using Statistica 7.0 software.

Results

The study revealed that soils influenced water quality in distinct ways, depending on their composition. In this regard, considering treatments without the addition of lime, it was observed that all evaluated parameters were statistically lower (p<0.05) for the water in contact with soil B (Table 2). The values of alkalinity demonstrate an important result, where the water in contact with soil A was 2.4 times higher than the water in contact with soil B (p<0.05), with values of 69.21 and 28.64 mg L^{-1}, respectively.

The limestone resulted in an increase in the evaluated water parameters across all treatments where it was incorporated. However, it was observed that electrical conductivity, TDS, alkalinity, and hardness were statistically higher (p<0.05) when the water was in contact with some type of soil compared to the treatment where only water and limestone were evaluated. For instance, the alkalinity of the water in contact with soil A or B remained above 100 mg L^{-1}, representing more than double the value observed in water without soil contact (47.73 mg L^{-1}). The same effect was noted for electrical conductivity, TDS, and hardness.

During the study, the main change in pH was due to the treatment rather than temporal variation, with higher values observed when limestone was added to the water and lower values when the water was in contact with soil B (Figure 1).

Conversely, a progressive increase in the alkalinity of the water was observed when in contact with both evaluated soils and with the addition of limestone, as well as in the water only in contact with soil A (Figure 2).

At the end of the experimental period, the chemical properties of the soils were assessed, with only pH, aluminum concentration and aluminum saturation showing no statistically significant difference among the treatments ($p < 0.05$) (Table 3). Values for Ca^{2+}, effective cation exchange capacity, potential cation exchange capacity, organic matter, and organic carbon only differed based on the type of soil ($p < 0.05$), irrespective of the addition of limestone.

The addition of limestone to the water resulted in a decrease in the concentration of $H^+ + Al^{3+}$, an in-

Table 2 Chemical parameters of water quality after 28 days

Parameters	Treatments				
	W+L	SA	SA+L	SB	SB+L
Temperature (ºC)	21.80±0.00	21.80±0.00	21.80±0.00	21.80±0.00	21.80±0.00
pH	8.02±0.03a	7.60±0.14ab	7.66±0.07ab	7.14±0.25c	7.53±0.18ab
EC* (µS cm^{-1})	107.33±2.89c	162.33±13.80b	225.67±2.31a	66.00±12.12d	231.00±10.44a
TDS* (mg L^{-1})	54.00±0.00c	81.33±6.66b	114.00±2.65a	33.00±6.08d	115.00±6.24a
Alkalinity (mg L^{-1})	47.73±1.03c	69.21±4.50d	100.24±4.74a	28.64±4.74b	102.95±4.48a
Hardness (mg L^{-1})	33.32±0.00c	55.55±9.61b	83.30±0.00a	22.17±9.65c	83.30±0.00a

Data are expressed as the mean ± SD. Values with different letter on the same row indicates statistical difference by Tukey's test ($p < 0.05$). EC: electrical conductivity; TDS: total dissolved solids.
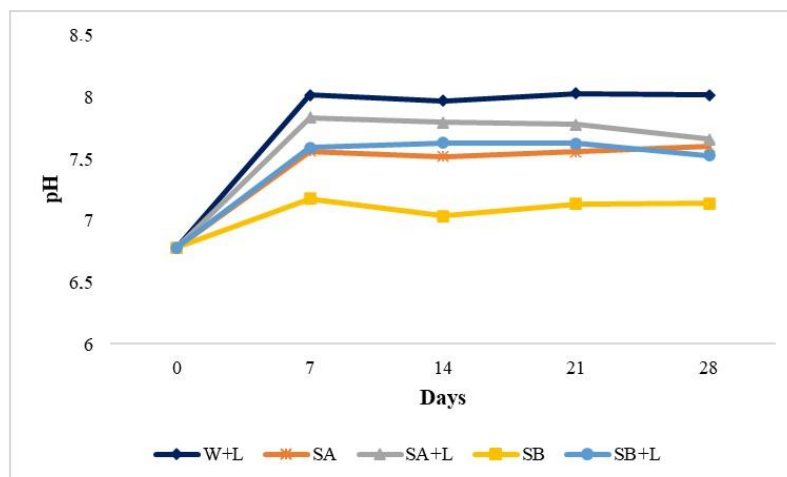

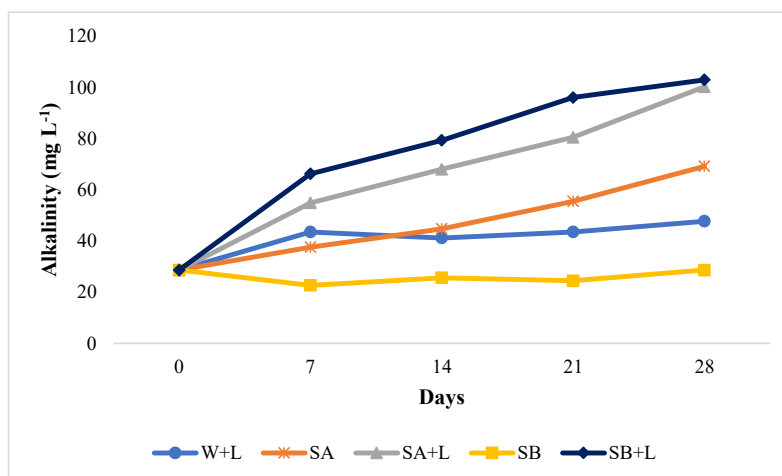**Fig. 1** pH fluctuations in relation to treatments over the 28-day study period

Fig. 2 Alkalinity fluctuations in relation to treatments over the 28-day study period

crease in the concentration of Mg^{2+}, and a higher percentage of base saturation in soil B. Compared with the initial data, soil B without the addition of limestone also showed an increase in base saturation and a decrease in acidity ($H^+ + Al^{3+}$), from 65.45% to 71.09% and from 3.82 $cmol_c$ dm^{-3} to 2.75 $cmol_c$ dm^{-3}, respectively. In contrast, the characteristics of soil A did not significantly alter with and without addition of limestone ($p > 0.05$).

To verify the influence of soil characteristics on water quality parameters, a correlation analysis was conducted for the variables of the treatments containing soil + water (SA and SB), as well as soil + water + limestone (SA+L and SB+L) (Table 4). The pH of the water showed a positive correlation with the pH of the soil (0.58), and the same effect was observed for Ca^{2+} (0.63), Mg^{2+} (0.69), t (0.65), and V% (0.72), which had the highest value. Base saturation (V%) also showed a positive correlation with EC (0.66), TDS (0.64), alkalinity (0.63), and water hardness (0.64). Thus, base saturation was the soil parameter most correlated with water quality, showing significant results for all evaluated aquatic parameters.

Discussion

In the present study, the interaction between soil and water was observed, revealing that soils influence water quality differently depending on their chemical attributes. Soil A has initial values of pH, cation exchange capacity (CEC), and base saturation of 6.2, 18.37 cmolc dm-3, and 89.39%, respectively, compared to soil B, which has values of 5.4, 7.23 cmolc dm-3, and 65.45%, respectively. Base saturation indicates the percentage of Ca2+, Mg2+, and K+ retained in soil colloids. When combined with high CEC, this enhances the availability of these cations to the aquatic environment (Hasibuan et al. 2023; Li et al. 2013; Pine et al.

Table 3 Chemical parameters, organic matter, and organic carbon of the soils at the end of the experimental period

Parameters	Treatments			
	SA	SA+L	SB	SB+L
pH	6.10±0.26	6.33±0.21	5.97±0.21	6.03±0.23
K^+ ($cmol_c$ dm^{-3})	0.30±0.01a	0.28±0.00ab	0.24±0.05ab	0.21±0.01b
Ca^{2+} ($cmol_c$ dm^{-3})	10.85±0.77a	10.28±0.00a	4.59±0.17b	5.20±0.29b
Mg^{2+} ($cmol_c$ dm^{-3})	5.96±0.29a	6.14±0.16a	1.94±0.11c	2.87±0.14b
$H^+ + Al^{3+}$ ($cmol_c$ dm^{-3})	2.04±0.06ab	1.84±0.06a	2.75±0.13c	2.11±0.09b
Al^{3+} ($cmol_c$ dm^{-3})	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
CEC – t* ($cmol_c$ dm^{-3})	17.10±0.97a	16.83±0.62a	6.77±0.29b	8.28±0.29b
CEC – T* ($cmol_c$ dm^{-3})	19.15±1.02a	18.67±0.56a	9.53±0.31b	10.40±0.35b
Base saturation (%)	89.32±0.29a	90.03±0.66a	71.09±1.38c	79.61±1.44b
Aluminum saturation (%)	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
Organic matter (g dm^{-3})	33.83±1.65a	32.24±3.50a	22.82±1.74b	20.72±0.76b
Organic carbon (g dm^{-3})	19.63±0.96a	18.70±2.03a	13.24±1.01b	12.01±0.44b

Data are expressed as the mean ± SD. Values with different letter on the same row indicates statistical difference by Tukey's test ($p < 0.05$). CEC – t: effective cation exchange capacity; CEC – T: potential cation exchange capacity.

Table 4 Correlation indices among water and soil quality parameters

	pH_W	EC	TDS	Alk	Hard	pH_S	K^+	Ca^{2+}	Mg^{2+}	OM	t	V
pH_W*	1.00											
EC*	0.68	1.00										
TDS*	0.69	1.00	1.00									
Alk*	0.71	0.99	0.99	1.00								
Hard*	0.63	0.99	0.99	0.98	1.00							
pH_S*	0.58	0.33	0.34	0.39	0.38	1.00						
K^+	0.12	0.02	0.03	-0.02	0.06	0.26	1.00					
Ca^{2+}	0.63	0.37	0.38	0.35	0.34	0.46	0.76	1.00				
Mg^{2+}	0.69	0.50	0.51	0.47	0.48	0.51	0.72	0.99	1.00			
OM*	0.47	0.18	0.20	0.14	0.18	0.34	0.85	0.93	0.91	1.00		
t*	0.65	0.42	0.43	0.39	0.40	0.48	0.75	1.00	0.99	0.93	1.00	
V*	0.72	0.66	0.66	0.63	0.64	0.46	0.64	0.94	0.97	0.82	0.95	1,00

Bold numbers indicate significant correlation at $p < 0.05$.
pH_W: Water pH; EC: Eletric conductivity; TDS: Total dissolved solids; Alk: Alkalinity; Hard: Harness; pH_S: Soil pH; OM: Organic matter; t: Effective CEC; V: Base saturation

2018). Since soil A has more than double the CEC of soil B and high base saturation, it indicates that these cations were made available to the aquatic environment and are directly related to electrical conductivity, TDS, and water hardness (Fitrani et al. 2020), which explains the differences found in these parameters for the waters in contact with the two types of soil, without the addition of limestone.

Alkalinity was one of the parameters that showed the greatest distinction between the two soils, without the addition of limestone. The influence of soil on alkalinity is due to the need to neutralize the acidity caused by the interaction between these two abiotic factors (Sá 2023). Soil B exhibited a higher acidity concentration ($H^+ + Al^{3+}$). Under these conditions, the increased dissociation of protons from the soil into the water led to the consumption of alkalinity, represented by bicarbonate (HCO_3^-), which acted to neutralize water acidity, following the reaction: $HCO_3^- + H^+ \leftrightarrow H_2O + CO_2$ (Boyd et al. 2016).

When limestone materials are applied to water, there is an increase in pH, alkalinity, and hardness due to the incorporation of calcium and magnesium carbonates, which react with CO2 and water, resulting in the release of cations and bicarbonates: $CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$ (Boyd 2020). Carbon dioxide is the main agent responsible for the dissolution of limestone, and in this study, the presence of this compound in the medium was due to the exchange between the atmosphere and water, as there were no aquatic organisms performing respiration and releasing CO2 in the experimental environment. Thus, the differences in alkalinity and hardness observed between the treatments where limestone was included are due to the abiotic interaction of the medium, demonstrating that the kinetics occurring in the retention and availability of cations between soil colloids and water play an important role in the efficiency of limestone action. These results are significant as they indicate that the application of limestone in tanks lined with geomembrane, for example, will yield different water quality results compared to ponds.

The progressive increase in alkalinity in these treatments is due to the slow dissolution of limestone, dependent on the reaction with CO2, as previously discussed, and the absence of bicarbonate (HCO3-) consumption over time. In a production environment, bicarbonate neutralizes the acidity of the medium and acts as a source of CO2 for photosynthesis: $HCO_3^- + H \leftrightarrow CO_2 + H_2O$ (Cavalcante and Sá 2010; Sá and Boyd 2017). In the experimental units, there was no photosynthetic process, and after the initial neutralization of the water's acidity, it can be considered that there was no bicarbonate consumption, which contributed to the progressive increase in alkalinity after the inclusion of limestone in the water in contact with the soil. Photosynthesis, and consequently the consumption of CO2, modulates pH oscillation in the aquatic environment, and therefore, the absence of this process also explains the constant maintenance of pH throughout the experimental period, where the main differences were observed in relation to the treatments analyzed.

When considering only the two types of soil and water, the results corroborate with Li et al. (2013), who evaluated the interaction between soil and water from different sources and found that soils with higher cation exchange capacity and concentrations of Ca2+ and Mg2+ led to an increase in pH, electrical conductivity, cation concentration, and water alkalinity. Pine et al. (2018) evaluated soils from four aquaculture farms with different granulometric compositions and nutrient concentrations. After 42 days, they observed notable differences in ion concentrations in the water. However, more in-depth evaluations and discussions on the parameters involved in soil-water interaction and its influence on aquaculture productivity are necessary.

Generally, studies evaluating the soil and sediment of aquaculture ponds aim to characterize and demonstrate the transformations that occur in the soil and sediment over time (Fitrani et al. 2019; Kamal et al. 2018; Shafi et al. 2021; Siddique et al. 2012; Thunjai et al. 2004). Just as the pond water acquires distinct characteristics from the source, the sediment is modified acquiring different chemical characteristics from the base soil. The pH, for example, tends to increase due to routine limestone application practices (Sá 2023; Shafi et al. 2021). Therefore, the results found in this study can be compared to newly constructed ponds that still maintain the chemical characteristics of the base soil. However, the observed relationship and effect between soil and water parameters are independent of the pond's age.

With respect to the soils, at the end of the study it was observed that the differences found were due to their chemical characteristics and not the addition of limestone. The main effects were observed in soil B, where a decrease in acidity concentration (H+ + Al3+) and an increase in Mg2+ and base saturation were noted. This indicates that cation exchange occurred in the colloids, with H+ being displaced and Mg2+ retained, contributing to an increase in base saturation. Even with lower cation exchange capacity, soil B

retained cations (Ca2+ and Mg2+) that were dissolved in the water and released H+, explaining the distinction mainly in hardness, electrical conductivity, and TDS in relation to the water in contact with soil A.

Soils with high clay content can distinctly influence water quality. Clays and organic matter have surface charges that enable cation exchange between soil and water. However, for clays, mineralogy determines their representativeness in this soil parameter, with clays of high and low activity being found (Kome et al. 2019; Pan et al. 2023). Soil B, despite having a higher clay concentration, did not result in a higher cation exchange capacity, indicating that the clays present in its composition have lower activity compared to soil A. For soil A, a higher concentration of organic matter was verified, which can be considered the main factor responsible for its higher cation exchange capacity. These results indicate that granulometric composition alone does not provide sufficient information on how the soil might influence water quality, necessitating a chemical composition analysis.

Cation exchange capacity reflects the soil's ability to retain and exchange positively charged elements, such as Al3+, Ca2+, Mg2+, K+, and H+ (Kome et al. 2019; Pine et al. 2018). Along with these parameters, base saturation should be assessed, which will indicate which cations are adsorbed into the colloids (Tiecher et al. 2022), resulting in distinct effects on water quality. The base saturation of soil A at the end of the study ($89.32 \pm 0.29\%$) remained similar to the initial value (89.39%) and when limestone was added ($90.03 \pm 0.66\%$). This suggests that after reaching a certain level of base saturation, even with the addition of cations, they are not incorporated into the exchange sites of the soil colloids. Furthermore, the results showed that with a base saturation of 89%, the application of limestone in the water would not be necessary, considering that the pH, alkalinity, and hardness parameters of the water in contact with soil A were within the ideal range for freshwater aquatic production (Sá 2023).

In the present study, the determination of the amount of limestone was based on the alkalinity of the water, which is the most common procedure in aquaculture (Han and Boyd 2018). Other methods are described in the literature, such as determining the amount of limestone materials based on soil pH and the soil acidity to be neutralized (Boyd et al. 2002; Han et al. 2014). In this study, a significant positive correlation was observed between soil pH and water pH (0.58). However, the same effect was not observed for alkalinity and hardness, which also composes the water buffering system, corroborating the results found by Fitrani et al. (2019). In contrast, the results differ from those of Silapajarn et al. (2005), who observed a positive correlation between soil pH and water pH (0.307), as well as for alkalinity (0.566) and hardness (0.389).

In agriculture, pH is not considered a reliable predictor for determine lime dosage, serving merely as an indicator of need for liming (Teixeira et al. 2020). One of the most widely used methos for determining lime dosage is considering the initial base saturation value, the soil's exchange capacity and, the desired value to be achieved for the production of different cultivars, which generally does not exceed 80% (SBCS 2004; Teixeira et al. 2020; Villar 2007). According to our results, the base saturation proved more relevant, showing a significant correlation with all evaluated water quality parameters, with coefficients between 0.63 and 0.72, indicating that this parameter should be evaluated in the characterization of soils and sediments for aquaculture and can also be used to determine the lime dosage to be added to the water for freshwater aquaculture production, aiming to increase this index by up to 89%.

The present study demonstrated that, depending on soil characteristics, there is a distinction in water quality due to the application of lime. In agriculture, for different regions of the country, various soil parameters are categorized, including cation exchange capacity and base saturation, aiming to optimize fertility management processes for different cultivars (SBCS 2004; Sousa and Lobato 2004). However, in aquaculture, soil characteristics and their influence on the dynamics of the aquatic ecosystem in ponds are little explored. The results found in this research provide a basis for new studies on the subject and highlight the importance of considering soil to thoroughly verify the action of lime on water quality.

Conclusions

This study demonstrated that the chemical attributes of clay soils play a crucial role in maintaining water quality in aquaculture ponds. Among these attributes, the initial base saturation of the soil emerged as a key factor in subsequent management. In soils with approximately 89% base saturation, after at least seven days of contact and in the absence of fish, the application of limestone becomes unnecessary to ensure appropri-

ate pH and alkalinity for aquaculture.

Incorporating the evaluation of soil chemical attributes, such as potential acidity, base saturation, and cation exchange capacity, into aquaculture management practices can enable more efficient water quality control, reducing the need for frequent chemical corrections. This approach contributes to optimizing the use of alkaline amendments, resulting in lower operational costs and reduced environmental impact.

Furthermore, the findings of this study highlight the need for additional research on clay mineralogy and its role in cation exchange, as well as studies that consider the influence of aquatic organisms on water dynamics under different farming conditions. A deeper understanding of these aspects will allow for the development of more effective water management strategies, promoting more sustainable and productive aquaculture.

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