



Article

Relationship between Leaf Degradation and Pore Water Chemistry in Two Mangrove Forests of Southeastern Mexico

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Abstract: The productivity of mangrove ecosystems is associated with litterfall production, which continuously contributes large quantities of organic matter, in the form of detritus, to the food web via adjacent ecosystems. However, the degree of deterioration of mangrove ecosystems worldwide has been increasing due to anthropogenic activities, leading to the loss of vegetation cover and changes in hydrological patterns, the chemical conditions of interstitial water and soil, and the litterfall degradation rate and, thus, the integration of organic matter into the ecosystem. In this study, we investigate the relationship between leaf degradation and interstitial water chemistry in two mangrove forests located in Oaxaca, Mexico, that are characterized by differences in environmental conditions, species, and anthropogenic activity. Forty-two 10 cm × 20 cm nylon mesh bags were installed in the *Rhizophora mangle* forest along two flood-associated lines (21 per line), and twenty-one bags were installed centrally in the *Avicennia germinans* forest because of the flood conditions in this area. Three bags per line were collected each month. This material was then dried and calcined for determination of the decomposition rate (k). The in situ redox potential and interstitial water salinity of mangrove forests were measured using a HACH HQ40d multiparametric probe and A&O refractometer, and the sulfate concentration was determined by ion chromatography. The results show that daily average decomposition rates were higher in the Salina lagoon ($k = 0.01 \text{ g} \cdot \text{day}^{-1}$) than in the Chacahua lagoon ($k = 0.004 \text{ g} \cdot \text{day}^{-1}$). The degradation model was $Y = 66.054e^{-0.010t}$, $R^2 = 0.89$, $p \leq 0.05$, for the Salina lagoon and $Y = 67.75e^{-0.004t}$, $R^2 = 0.76$, $p \leq 0.05$, for the Chacahua lagoon. Leaf decomposition rates differed between the Salina and Chacahua lagoons ($F_{1,206} = 4.8$, $p < 0.03$). In the Salina lagoon, dominated by *A. germinans*, an inverse relationship was established between the percentage of degraded biomass with respect to salinity concentration ($R^2 = 0.82$, $p < 0.013$) and redox potential ($R^2 = 0.89$, $p < 0.015$), and for the Chacahua lagoon, dominated by *R. mangle*, the percentage of degraded litter biomass was found to be inversely correlated with redox potential ($R^2 = 0.94$, $p < 0.005$) and sulfate concentration ($R^2 = 0.88$, $p < 0.017$). Based on the results obtained in this study, we conclude that variations in the chemical conditions of interstitial water and hydrological patterns can affect the process of mangrove leaf degradation based on species and the integration of organic matter in the soil and in adjacent ecosystems. These findings are potentially useful for mangrove management because they advance understanding of the dynamics of organic matter in mangroves and the importance of maintaining the health of these ecosystems, which is necessary for the maintenance of coastal fishing production.

Keywords: degradation rate; hydrology; soil; mangroves; salinity



Citation: Chan-Keb, C.A.; Agraz-Hernández, C.M.; Pérez-Balan, R.A.; Expósito-Díaz, G.; Gutiérrez-Alcántara, E.J.; Muñoz-Salazar, R.; Osti-Sáenz, J.; Reyes-Castellano, J.E. Relationship between Leaf Degradation and Pore Water Chemistry in Two Mangrove Forests of Southeastern Mexico. *Diversity* **2023**, *15*, 432. <https://doi.org/10.3390/d15030432>

Academic Editors: Thomas Fickert and Michael Wink

Received: 8 November 2022

Revised: 8 March 2023

Accepted: 12 March 2023

Published: 15 March 2023



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1. Introduction

Mangroves present high rates of net primary productivity due to their environmental conditions, nutrient input from river runoff, tides, and soil type [1]. This high productivity is largely related to litterfall production, which continuously contributes significant amounts of organic matter to the food chain [2,3]. Various authors estimate that between 20% and 40% of mangrove forest primary productivity is generated as litterfall (leaves, flowers, seeds, branches, and stipules), with litterfall serving as the primary source of energy for trophic network consumers in the form of detritus [4,5]. Wolanski et al. [6] describe that a high percentage of the productivity created by mangroves is exported in the form of detritus to adjacent aquatic ecosystems, thus passing into the food webs responsible for sustaining the productivity of fishery resources. Authors such as Burbridge [7] mention that the use of mangroves as a habitat to support fisheries is more important than that of any other factor, including aquaculture, and it has even been estimated [8] that each hectare of mangrove habitat facilitates the production of approximately 767 kg of shrimp and commercially important fish. Granek et al. [9] estimated that 10% of litterfall production by mangrove forests is transformed into commercially important fish, mollusks, and crustaceans. Despite the above data, the degree of deterioration of mangrove ecosystems worldwide has been increasing over the last 25 years. This also applies to the Mexican states, with the largest mangrove cover in Mexico, where the highest rates of cover loss are reported [10,11] due to various anthropogenic activities (immoderate industrial and urban development, road construction, wastewater discharge, as well as unsustainable livestock and agricultural practices). This is a worrying situation because such activities are leading to plant cover loss, changes in hydrological patterns and the chemical conditions of interstitial water and soil, as well as changes in the rate of litter degradation and organic matter integration into aquatic systems. The degradation rate depends on microtopography; the level and frequency of tidal and freshwater flooding (hydroperiod patterns); climatic and edaphic factors; the physicochemical conditions of surface and interstitial water; and the presence or absence of fauna that consume and degrade leaf litter within wetlands, which is reflected by bacteria and fungi diversity, as well as the presence of crustaceans that play an important role in leaf size reduction, facilitating the decomposition process [12,13]. Several factors influence the rate of organic matter degradation in mangrove forests, including the oxidation-reduction conditions of interstitial water, which are determined by hydrological behavior, nutrient increases, and anthropogenic matter input [14]; as well as the composition of leaves (for example C:N ratio, tannin concentration) and the types of mangrove species [14] that, together with the soil physicochemical conditions, microbial consortium, and other consumers, also contribute to the rate of organic matter degradation [15]. On the other hand, Newell [16] and Odum [17] mention that the decomposition process of leaf litter, once it falls into the water or onto the forest floor, is initiated by bacteria, fungi, or physicochemical processes, increasing its nutritional quality compared with living plant tissue. For this study, the concentration of salinity and sulfates (SO_4^{2-}) were considered the chemical variables because these are present in high concentrations in seawater [11,18] and were considered as oxidizing agents, associated with redox variation, that influence the mangrove leaves' degradation. The objective of the present study is to relate leaf degradation with interstitial water chemistry in two mangrove forests located in the state of Oaxaca, Mexico, that differ in terms of species, forest structure, hydrological patterns, and anthropogenic activity. The overall aim is to enhance the protection and conservation of mangrove ecosystems and therefore the fishing resources that rely on them. This type of research has yet to be registered for the area under study and thus represents a highly relevant contribution.

2. Materials and Methods

2.1. Study Area

The Chacahua–Pastorías lagoon system is located in the state of Oaxaca, in the municipality of San Pedro Tututepec, at the geographical coordinates of 15°57'0" and 16°02'0"

north latitude and $97^{\circ}33'0''$ and $97^{\circ}47'0''$ west longitude [19]. This complex belongs to category III-A, defined by a flooded depression on the inner margin of the continental margin [20]. The lagoon system covers an area of 13,274 ha, of which 2902.7 ha are mainly represented by three major lagoons: Chacahua, Salina, and Pastoría [21]. The Chacahua and Pastoría lagoons are separated by a two-kilometer channel. This complex is also composed of smaller lagoons interconnected with narrow channels (Salina, Grande, Poza, El Mulato, Poza de los Corrales, and Palizada) [21]. The regional climate, according to the Köppen classification modified by García (1988) [22] is Aw1 (w) (i), which corresponds to a warm subhumid climate group with a mean annual temperature of 28°C , a mean minimum temperature of 23.2°C , and a mean maximum of 37°C . Annual precipitation is approximately 1000 mm, and there are two seasons, identified as rainy and dry [23]. Seven sites were analyzed in this study, with four sites in the Salina lagoon and three sites in the Chacahua lagoon, Oaxaca (Figure 1).

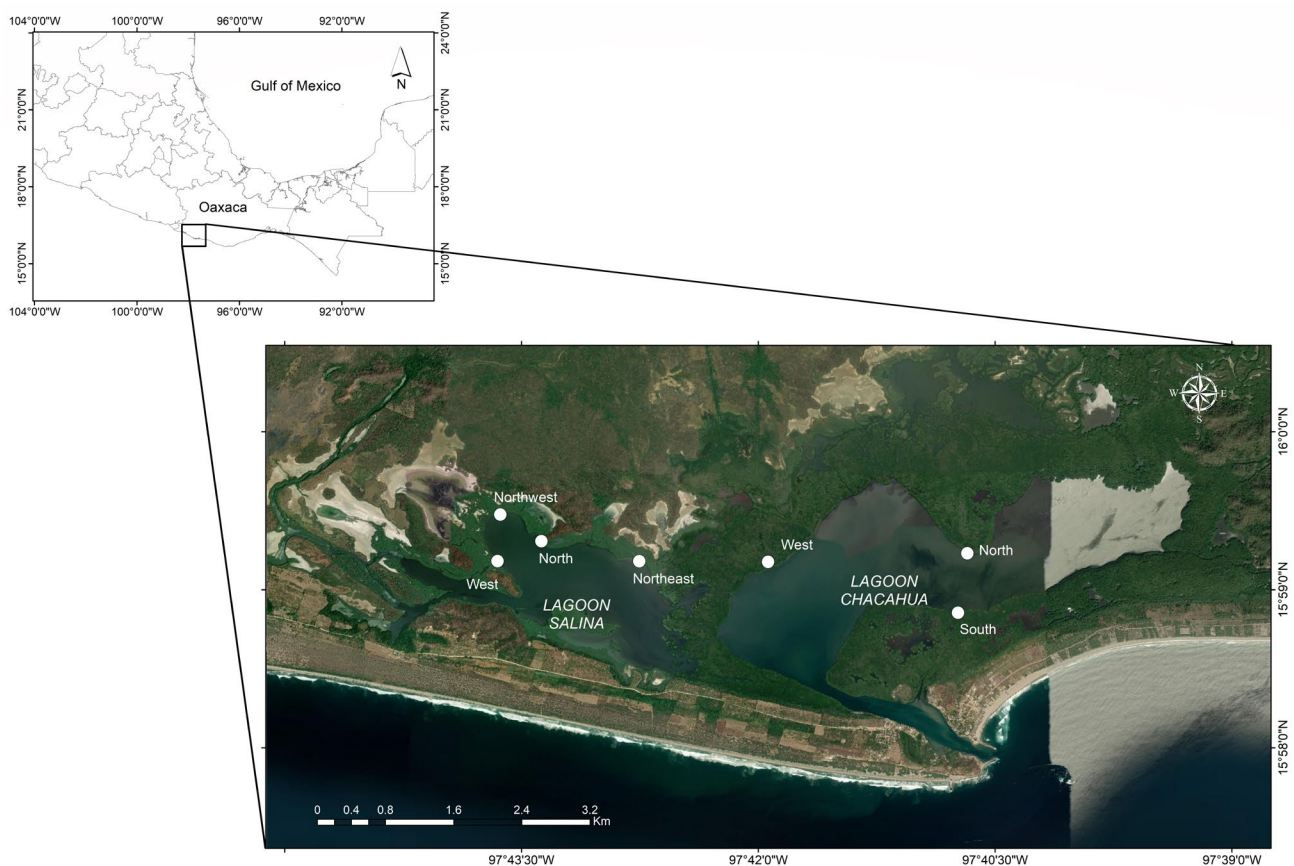


Figure 1. Study sites located in the Salina and Chacahua lagoons, Oaxaca, Mexico. Image prepared by the authors.

The state of Oaxaca, despite registering only 3.7% of the total mangrove cover on the Pacific coast of Mexico, provides important environmental services. For this reason, the Bajo Río Verde–Chacahua system, Oaxaca, Mexico, is considered one of the Priority Terrestrial Regions of Mexico in terms of conservation. This is due to its high productivity, and this system provides refuge to numerous wildlife species, a large number of which are important, such as in serving as fishing resources for fishing communities. However, between 1966 and 1991, the mangrove forests in the state of Oaxaca were severely impacted by various anthropogenic activities, such as livestock farming, poorly planned tourism, urban settlements, silt, pollution, deforestation, and misuse of natural resources, resulting in a loss of 13.6% of mangrove cover and a decrease in fishing production. Similarly, this deterioration is attributed to a lack of information (deficient and scattered), mainly on the ecology and magnitude of the deterioration of these mangrove forests.

2.2. Forest Attributes and Physiognomic Type

Forest structure was defined through the measurement of forest attributes (diameter, height, density, and basal area); these variables were measured in May 2008. The forest structure was evaluated using the quadrat method [24]. Two 10 m × 10 m quadrats were used in each study site and the number of trees and forest attributes were recorded in each quadrat. In forests where mangrove trees had a stem diameter ≤ 2.5 cm, 5 m × 5 m quadrats were used. Tree diameter for *Avicennia germinans* and *Laguncularia racemosa* species was determined at 130 cm above the ground, and for *Rhizophora mangle* it was determined at 30 cm above the last root. Tree densities and basal areas were calculated according to [25]. The physiognomic type of the forest was determined through density, basal area, and forest height following [26].

2.3. Interstitial Water Chemistry

Two piezometers (polyvinylchloride pipes) with a diameter of 10.16 cm and a length of 1.5 m were installed in each study site. Holes of 1 cm in diameter were drilled in the lower part of each 30 cm tube. Each tube was installed at 50 cm depth from soil surface (depth where the maximum root biomass was located). In the forests bordering the Chacahua and Salinas lagoon, the first tube was installed at the edge of the lagoon shore, and the second was installed in the central area [11]. In the internal forest, located after the forest bordering the Chacahua lagoon, two tubes were installed, 10 m from the edge of the forest and in the central area, separated for each site depending on the width of the forest [11]. A water sample was collected with the aid of manual pumps once the tube had been drained and the infiltration of water into the tube had stabilized. The collection was conducted each month during the year 2019. At the laboratory, water samples were put in cold storage (4 °C) until processing. Processing consisted of letting the water samples warm up to room temperature and filtering (47-mm GF/A micro-fiberglass filters) before being analyzed by ionic chromatography. In order to determine the availability of dissolved oxygen in interstitial water [27], the redox potential was measured based on the chemical activity of electrons in the soil using a multiparameter probe, model HACH HQ40d (Loveland, CO, USA). The HQd meter had an oxide reduction (redox) potential (ORP) probe that was not gel-filled. Salinity was determined with an A&O refractometer, with a measurement range from 0 to 100 PSU (Practical Salinity Units) [28] (ATAGO, Inc., Bellevue, WA, USA). To determine sulfate concentrations, interstitial water was collected in 50 mL bottles monthly, by means of a vacuum pump, and individual samples were analyzed using a piezometer. Sulfate determination was carried out according to the criteria of [29] by ion chromatography (IC advanced 861). This chromatography technique is a fast, sensitive, and precise method for analyzing soluble anions and cations in aqueous samples that involves the separation of ions from a solution via ion exchange between the mobile and stationary phases (column); because of their different charge properties, the ions are reversibly retained in the column. As ions separate in the column, they are detected by a conductivity detector and recorded on a chromatogram, which represents the eluted (extracted) ion's signal intensity versus time [30].

2.4. Experimental Design for Determination of Leaf Degradation Rate

A decomposition experiment using nylon mesh bags was carried out to estimate the rate of leaf breakdown [31].

Lines of nylon bags containing mangrove leaves were installed, determined by taking into account the periodicity of flooding (and exposure to air) of the coastal lagoon under study. Occurrence of a flood is determined by a combination of tides, fluvial inputs/land runoff, precipitation–evaporation, wind effect, depth and geomorphology of the adjacent body of water, sedimentation rate (and subsidence), and the extension of the topographic level (Flores Verdugo et al., 2007). If these factors are interrelated, they establish the structure, function, distribution, species dominance, zonation, and succession of the mangroves, and also establish the degradation and export of organic matter [32]. Thus, *R. mangle* grows

optimally under periodic flooding and mesohaline with a tendency to oligohaline, since this is the only species with an ultrafiltration mechanism, in contrast to *A. germinans*, which exhibits excretion, exclusion, and accumulation mechanisms, and is thus distributed where there is less frequent flooding and in mesohaline to hypersaline conditions [33,34].

The prevailing flood conditions in the Chacahua lagoon are derived from its interactions with an artificial channel, the sea at the mouth of the Chacahua, four tributaries, and the intertidal zones in addition to the geoform of the lagoon, tidal amplitude, and discharge from the San Francisco River, which cause it to be partially flooded. During the rainy season, the Chacahua mouth presents a maximum flow of $216 \text{ m}^3 \cdot \text{s}^{-1}$ during tidal flow and up to $126 \text{ m}^3 \cdot \text{s}^{-1}$ during ebb. In the dry season, the maximum flow is $219 \text{ m}^3 \cdot \text{s}^{-1}$ and $121 \text{ m}^3 \cdot \text{s}^{-1}$ in reflux. For both conditions, the reflux time is longer than the flow time. The average flood amplitude in the Chacahua lagoon is 24–40 cm from the edge of the lagoon toward the inner part of the mangrove swamp. These flow and flood amplitude data were obtained from [32].

For the Salina lagoon, the tidal exchange depends on two interconnected shallow channels in the western part of the Chacahua lagoon and the interstitial and subsurface freshwater runoff. The export of water (similarly to tidal flow) from the Chacahua to the Salina lagoon is a maximum of 11.41 and $10.85 \text{ m}^3 \cdot \text{s}^{-1}$ in dry and rainy seasons, respectively. The maximum values of reflux toward the Chacahua lagoon are 9.41 and $8.77 \text{ m}^3 \cdot \text{s}^{-1}$ for dry and rainy seasons, respectively. The tidal range in the Salina lagoon is very similar in the rainy and dry seasons, with an average value of $0.14 \pm 0.8 \text{ m}$. These flow and flood amplitude data were obtained from [32].

Based on the above data, leaves of *R. mangle* were collected because it is the dominant species in the Chacahua lagoon. Senescing and decayed leaves at the above stages were used. Leaves that had turned yellowish were hand-picked from trees because these are normally the majority of the leaves on the forest floor and have already begun decomposing [31]. The collection of these leaves was conducted at three sites in the maximum (shore) and minimum flooding zones. For the Salina lagoon, leaves of *A. germinans* were collected at 4 sites in the middle part of the forest, as it is the dominant species in this area. The dried leaves were collected from the middle and lower parts of canopy trees, then dried at 65°C in a convection oven until a constant weight was obtained (approximately 3 days). Once the leaves were dried, they were weighed to the nearest 10 g (t_0) and placed in a nylon bag of 1 mm^2 mesh with dimensions of $10 \text{ cm} \times 20 \text{ cm}$.

In the Chacahua lagoon, at each of the three sampling sites, a string was installed to which 21 nylon bags were attached. The string lines were tied to the trees and placed at ground level. One more line with 21 bags was also placed in the inner part of the forest at approximately $70 \pm 5 \text{ m}$ from shore, with each line being 5 m long. In each of the four selected sampling sites of the Salina lagoon, a line of 21 nylon bags was placed $25 \pm 6 \text{ m}$ in the middle of the forest.

Each month, 3 bags from each line for each sampling site in both lagoons were collected; thus, of the 7 months of collection, 3 correspond to the dry season (November–January) and the other 4 to the rainy season (June–September). The collected bags were taken to the laboratory, where they were carefully washed to remove residual sediment and organic matter outside the bag, and residual leaf matter was dried at 65°C in a convection oven until a constant weight was obtained, and the samples were then calcined at 500°C for 4 h in a furnace [35]. The samples were weighed using a digital scale with 0.001 g precision.

The biomass degradation percentage was calculated by applying the formula $t_x - t_i$, where t_x refers to the initial or previous collection time and t_i corresponds to the collection time. To determine a constant rate of decomposition (k), a negative exponential function was applied based on the loss of organic matter (mass remaining at time t) following the model proposed by [36,37] using the equation $Y = X_0 e^{-kt}$, where Y is the amount of leaf matter remaining at time t (days), X_0 is the amount of initial leaf matter, and k is the constant rate of decomposition. Likewise, the average time (t_{50}) in which 50% of the litter decomposes was calculated for the Salina and Chacahua lagoons using the adjustment

equation presented in Figure 2. For this study, the leaf degradation data (independent variable) with respect to time (independent variable) were fitted in a regression analysis to a negative exponential equation similar to the one described by the cited authors.

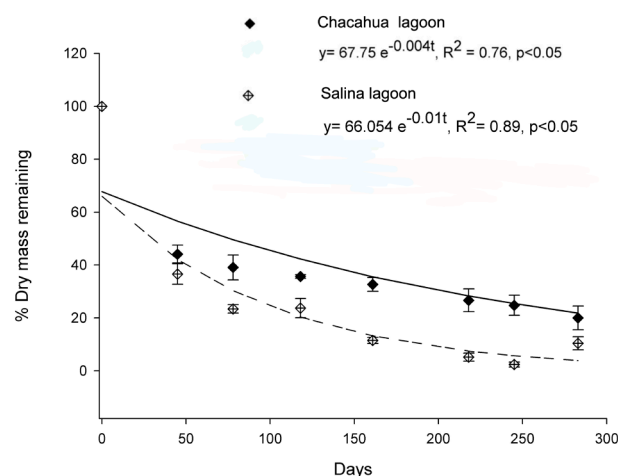


Figure 2. Leaf degradation rate in the Chacahua and Salina lagoons, Mexico (\pm SE = standard error).

2.5. Statistical Analysis

A database was generated with the chemical parameters of interstitial water (salinity, redox potential, and sulfate concentration) and leaf degradation rate by site and lagoon. The variation in the amount of mangrove leaf degradation and the chemical parameters of the interstitial water between the two lagoons (Salina and Chacahua) and according to the season (dry or rainy) were determined on the basis of comparison using 2×2 factorial (lagoon and season) analysis of variance (ANOVA).

Prior to this comparison analysis, the normality of the variables was validated using the Shapiro–Wilk test [38] with a significance level of $\alpha = 0.05$. When the assumption of normal distribution was not met, the data were transformed using the Box–Cox method such that the variables would present the assumptions of normal distribution [39]. Additionally, Pearson correlations were used to establish relationships between the biological variables of the mangrove forest and the chemical parameters of the interstitial water. Finally, simple linear regression analysis was applied to evaluate the effect of interstitial water chemical parameters (independent variables) on the percentage of degraded leaf biomass (dependent variable) in each of the study ponds. The assumption of normality in the data was tested using the Shapiro–Wilk method, which uses residuals to determine whether a data set follows a normal distribution or not. To obtain normality in the data for this study, the variable transformation method known as Box–Cox was used, as it is one of the best transformation methods that allows selecting the exponent (λ) that gives the best fit to be used in the data transformation ($Y_i^l = Y_i^\lambda$). In this way, parametric and robust statistical analyses can be performed. Pearson’s parametric correlation method was used to provide a better description of the association behavior of the forest and the environmental variables of water and soil. This test allows for the best bivariate adjustment. All statistical analyses were performed at a significance level of $\alpha = 0.05$ using STATISTICA V.12 software (StatSoft, Inc., Palo Alto, CA, USA, 1984–2014).

3. Results

3.1. Forest Structure

Physiognomically the mangrove forests bordering the Salinas lagoon system are scrub type, dominated by *Avicennia germinans* (99%) and some individuals of *Laguncularia racemosa* (1.0 %), with a density of 7623 ± 3390 trees/ha, a basal area of 5 ± 1.7 m²/ha, and heights 2.0 ± 1 m. They show a close inverse relationship between salinity and total tree

height ($r = -0.81$, $p < 0.001$), and a direct correlation between salinity and forest density ($r = 0.89$; $p < 0.001$).

The mangrove forest bordering the Chacahua lagoon is characterized as a riparian physiognomic type with a tendency to fringe type and a dominance of *Rhizophora mangle* with a density of 800 ± 200 trees/ha, a basal area of 15 ± 3 m²/ha, and heights of 14 ± 2 m.

The physiognomy of the mangrove in the Chacahua lagoon is closely related to interstitial salinity, since it presents an inverse relationship of basal area with salinity ($r = -0.95$; $p < 0.047$), as well as with density, but in a direct way ($r = 0.99$; $p < 0.001$).

3.2. Physicochemical Parameters

The salinity concentration of interstitial water is higher in the Salina lagoon than in the Chacahua lagoon (Table 1), generating euhaline-hyperhaline conditions (65 ± 2 UPS), in the rainy season, when the salinity was higher (70 ± 2 UPS), and decreasing in the dry season (60 ± 3 UPS) (Taking into account the average concentration of seawater salinity, 35 psu (Practical Salinity Units) can be expressed dimensionlessly as 35 g of salt per liter of solution (or 35 percent). In spite of hypersalinity, the oxygenation degree was oxic, with a redox potential of 13 ± 11 mV, and the redox potential values were 53 ± 14 mV in the rainy season and -26 ± 16 mV in the dry season. The sulfate concentrations presented an average of 2142 ± 142 mg·L⁻¹, with a higher concentration of 3000 ± 188 mg·L⁻¹ observed in the rainy season, decreasing to 1283 ± 212 mg·L⁻¹ in the dry season. In the Chacahua lagoon, the salinity of the interstitial water (36 ± 2 UPS) corresponded to mesohaline conditions, with a lower salinity (35 ± 3 UPS) in the rainy season, increasing in the dry season (39 ± 3 UPS). Oxic-hypoxic conditions were present, showing an average redox potential value of -192 ± 14 mV, with oxic conditions observed in the rainy season (-111 ± 18 mV) and hypoxic conditions observed in the dry season (-272 ± 21 mV). Sulfate concentrations were at an average of 1169 ± 185 mg·L⁻¹, with a higher concentration of 1519 ± 245 mg·L⁻¹ observed in the rainy season, decreasing to 819 ± 278 mg·L⁻¹ in the dry season. Significant differences ($p < 0.05$) in the salinity and sulfate concentrations and redox potential values were observed between the two lagoons and between their seasons, as well as in the lagoon–season interaction (Table 1), thus validating the environmental conditions of interstitial water chemistry in the mangrove forests bordering the Salina and Chacahua lagoons.

Table 1. Two-way ANOVA of leaf degradation rate (%), chemical parameters in two mangrove forests bordering the Chacahua and Salina lagoons, Oaxaca, at two times of the year with significance level (NS, not significant; * $p < 0.05$, ** $p < 0.0001$).

Factor	gl	Leaf Degradation Rate (%)		Salinity (UPS)		Redox Potential (mV)		SO ₄ ²⁻ (mg/L)	
		F	p	F	p	F	p	F	p
A: Lagoon	1	98.2	0.0001 **	95.91	0.0001 **	134.36	0.0001 **	17.31	0.0001 **
B: Season	1	103.3	0.0001 **	1.21	0.2725 NS	45.88	0.0001 **	26.69	0.0001 **
AXB	1	4.8	0.030 *	6.94	0.0095 *	5.26	0.0235 *	4.73	0.0315 *
Error	206								

3.3. Leaf Degradation Rate

When applying negative exponential regression analysis of organic matter loss, a higher decomposition rate was observed for the Salina lagoon than for the Chacahua lagoon ($k = 0.01$ vs. 0.004 , respectively), and the model fit was $Y = 66.054e^{-0.01t}$, $R^2 = 0.89$, $p \leq 0.05$ for the Salina lagoon and $Y = 67.75e^{-0.004t}$, $R^2 = 0.76$, $p \leq 0.05$ for the Chacahua lagoon (Figure 2).

For the Salina lagoon, no significant differences were observed in degraded biomass percentage between the sites ($F_{3,80} = 0.69$, $p < 0.561$) (Table 1), whereas for the Chacahua lagoon, significant differences were observed between the sites ($F_{2,120} = 11.64$, $p < 0.001$),

but not for degraded biomass between the lines placed on the shore and the inner part of the forest ($F_{1,120} = 2.14$, $p > 0.146$). The leaf decomposition dynamics varied significantly between the Salina and Chacahua lagoons ($F_{1,206} = 98.2$, $p \leq 0.0001$, Table 1) and it is confirmed that the degradation rate was rapid for the Salina lagoon, with 3.8% of the original leaf biomass material remaining at the end of the study vs. 21.8% for the Chacahua lagoon (Figure 2). Likewise, it was determined that 50% of leaves are decomposed in 28 days for the Salina lagoon and 76 days for the Chacahua lagoon.

3.4. Predictive Models of Leaf Biomass Degradation in Relation to Interstitial Water Chemistry

Regarding the percentage of leaf biomass degraded in the Salina lagoon, dominated by *A. germinans*, an inverse relationship with respect to salinity concentration and redox potential was established through simple linear regression analysis. The percentage of degraded leaf biomass was inversely correlated with redox potential and sulfate concentration in the Chacahua lagoon, which also showed a direct relationship between the redox potential and sulfate concentration for this lagoon: relationships that are significant ($p \leq 0.05$) (Table 2).

Table 2. Simple linear regression analysis of leaf degradation rate (%) with chemical parameters in mangrove forests bordering the Chacahua and Salina lagoons, Oaxaca, where X_1 (salinity in UPS), X_2 (redox potential in mV), and X_3 (sulfates in mg/L) with a significance level of $p < 0.05$.

Lagoon/Dependent Variable (Y)	Equation	R ²	p
Salina lagoon			
Degraded biomass (%)	$Y = 157.2 - 1.1 X_1$	0.82	0.013
Degraded biomass (%)	$Y = 86.18 - 0.17 X_2$	0.89	0.015
Degraded biomass (%)	$Y = 91.77 - 0.0033 X_3$	0.23	0.523
Chacahua lagoon			
Degraded biomass (%)	$Y = -54.65 + 3.34 X_1$	0.62	0.072
Degraded biomass (%)	$Y = 48.43 - 0.099 X_2$	0.94	0.005
Degraded biomass (%)	$Y = 84.83 - 0.012 X_3$	0.88	0.017
Redox potential (mV)	$Y = -352.9 + 0.109 X_3$	0.75	0.05

4. Discussion

The Salina lagoon's hypersalinity is attributed to its having an evaporation rate higher than the volume of fresh water that the system receives from the artificial irrigation canal of the district adjacent to the lagoon, and the contributions from rain and interstitial runoff, together with its shallow depth and the seawater that reaches the Salina lagoon through tidal exchange. This exchange is dependent on two interconnected shallow channels in the western part of the Chacahua lagoon taking a balanced mass between the two lagoons resulting in a low level of water export from the Chacahua to the Salina, with a maximum flow of 11.41 and 10.85 m³·s^{−1} in the dry and rainy seasons, respectively, which contributes to the high concentrations observed for sulfates that are favorable for oxidation conditions. Because of these factors, the salinity of the Salina lagoon rises during the rainy season. The soil level, the scarce supply of fresh water, and evaporation cause the interstitial water to have higher salinity concentrations and temperatures.

The results of Pearson correlation analysis show a direct relationship between salinity and sulfates ($r = 0.27$; $p < 0.001$). As a result, the forests bordering the Salina lagoon system are scrub type. In this regard, authors such as those of [40] recorded hypersalinity conditions and high levels of oxidized nutrients of anthropogenic origin in the Salina water column lagoon. Likewise, a very low water level during the low water season, which is responsible for hypersalinity in the Salina lagoon, is described in [41]. On the other hand, the authors of [42] indicate that mangrove soils suffer strong variations in salt concentration, which is regulated by evapotranspiration, seawater, and freshwater supply. Interstitial water salinity is the environmental factor with the greatest influence on wetland forest attributes (salinity vs. height $r = -0.81$; $p < 0.001$ and salinity vs. density $r = 0.89$; $p < 0.001$). This effect has been reported by the authors of [26,28,43], who found that tree height

decreases toward the forest interior due to the increase in interstitial water salinity and soil level. Soil hypersalinity causes a reduction in growth (basal area and height) because tree vigor decreases due to the excessive energy expenditure required for the mechanisms of regulation, excretion, and filtration of salts. According to the data presented in [43], high salinity concentration is a stressor that can cause the mortality of *A. germinans* at salinities higher than 70 UPS.

The mesohaline and oxic environmental conditions with the hypoxic tendency of interstitial water that characterize the mangroves of the Chacahua lagoon system are caused by the entrance of water from the San Francisco River, the indirect discharge of the Verde River, and the entrance of seawater through the mouth of the Chacahua. The results of studies conducted in the area by [44] are in accordance with the conditions recorded in this study. It was mentioned by the authors of [45] that the variation in the redox potential values of the interstitial water are generated by the frequency and duration of tidal flooding, organic matter content, and availability of electron acceptors such as NO_3^- , Fe^{3+} , Mn^{4+} , and SO_4^{2-} . In the Chacahua lagoon, mesohaline conditions are optimal for the development of riparian mangroves dominated by *Rhizophora mangle*, which is the dominant phynomic and species in this lagoon, and this is consistent with the findings of others [46,47]. In Mexico, the presence of this physiognomic type has been reported in the states of Campeche and Nayarit [26,41], and in La Mancha Veracruz lagoon [28] (Table 1), as well as in other countries such as Costa Rica [48] and Brazil [49]. In this regard, Rico Gray and Palacios (1996) point out that the tide, river input, and terrigenous nutrient runoff from the region, as well as fluctuations in the water table, generate optimal conditions for the development of the forest structure of riparian mangroves.

The chemical quality of the interstitial water, the hydrological patterns, and the species of the mangrove determined variation in the degradation of leaves in this study, with a higher rate of degradation for the Salina lagoon than the Chacahua lagoon. This is because the degree of oxygenation is classified as oxic, so we assume that the oxygen concentration is mainly due to the sulfate concentration in the interstitial water resulting from marine influence and the shorter residence time of the water in the Salina lagoon (2.2 ± 1.3 days in the dry season and 2.6 ± 1.8 days in the rainy season) compared with the Chacahua lagoon (7.0 ± 6.0 days in the dry season and 2.9 ± 3.1 days in the rainy season) [32], which allows more oxygen into the pore water together with the contributions of the San Francisco River and freshwater discharge from the artificial channel in the northwest area of the Salina lagoon, despite this lagoon receiving low volumes and flows of water and the hypersalinity of the interstitial water.

On the other hand, the decomposition rates vary significantly between plant species [50] depending on the anatomy and chemical composition of the leaves (particularly regarding lignin and nutrient concentrations) and environmental conditions. Therefore, the higher rates of leaf degradation in the Salina lagoon can also be attributed to the fact that *A. germinans* registers a lower amount of soluble tannins, a higher concentration of nitrogen, and a lower C:N ratio compared with *R. mangle*, which exhibits high concentrations of tannins and C:N ratio but lower nitrogen [13,15,51]. Likewise, *A. germinans* has a thin leaf cuticle, which allows greater leaf washing, in contrast to *R. mangle*, which has a thicker cuticle [49,52].

The results of simple linear regression analysis demonstrate an inverse relationship between leaf biomass degradation and both the salinity concentration and redox potential (Table 2). The decrease in salinity and increase in the degree of oxygenation in the Salina lagoon result in a higher degradation of *Avicennia germinans* leaves. In this regard, it is mentioned in [53] that the process of mangrove leaf degradation is influenced by physicochemical factors of the water and soil, such as humidity, temperature, pH, dissolved oxygen, texture, and salinity, and in [54], it is also mentioned that electrical conductivity and dissolved oxygen are factors that contribute to the decomposition of mangrove leaves.

For the Chacahua lagoon, the low rate of degradation is attributed to the longer residence time of water in the lagoon and the hypoxic conditions, mainly in the dry

season, because the amplitude of flooding is greater at this time (from November to May), with greater marine influence and residual water contributions of agricultural origin, which generates scenarios of less availability of and thus greater demand for oxygen (e.g., for the degradation of organic matter and oxygen consumption by organisms). This is validated by the significant association observed between redox potential and sulfate concentration, the inverse association between degraded leaf biomass percentage and both redox potential and sulfate concentration, as well as the direct correlation of redox potential with sulfate concentration.

In response to the reduction in freshwater input into the wetland, the dissolved oxygen in the pore water decreases, increasing bacterial respiration demand and organic matter degradation, among other biogeochemical processes, and differences in the degradation rates can also be attributed to moisture content and other physicochemical characteristics of the soil [55,56].

The k values registered in the Salina lagoon ($k = 0.01$), with dominance of *A. germinans*, are similar to those reported by the authors of [45] for *Avicennia schaueriana* ($k = 0.019$) and those of [5,13], with the highest rates of degradation being found for the genus *Avicennia* in this last study. The value of the degradation rate ($k = 0.004$) registered for the species *R. mangle* in the Chacahua lagoon is similar to that reported in [4], with values ranging from $k = 0.003$ to 0.005 in mangroves located in South Florida, USA. On the other hand, k values ranging from $k = 0.0048$ to 0.0057 have been reported for *R. mangle* species in Sontecomapan lagoon, Veracruz, Mexico [37]. Finally, in general, the results are similar to those obtained by [57] for Mecocan Tabasco lagoon, Mexico, with values of $k = 0.0057$ for *R. mangle* and $k = 0.01$ for *A. germinans*. We attribute the variation in degradation rates to the chemical composition of the leaves of species associated with the mangrove, and to the physicochemical composition of soil, regarding factors such as texture, hydrodynamics of interstitial water (hydroperiod), and the soil contents of nutrients of native and anthropogenic origin.

5. Conclusions

In this study, we demonstrate that the degradation process dynamics of mangrove leaves depend on the species, hydrological patterns, and physicochemical conditions of the forest to which they are exposed. In the Salina lagoon, with oxic and hypersaline conditions and dominated by *A. germinans* of physiognomic scrub type, the degradation rate of *A. germinans* leaves was higher than for *R. mangle* leaves in the Chacahua lagoon. There was also an inverse relationship between the degraded biomass percentage and both salinity and redox potential, where the lower the values of redox potential and salinity, the higher the amount of degraded biomass, and the opposite occurs when salinity is higher. In the case of the Chacahua lagoon, a lower rate of biomass degradation, namely of *R. mangle* leaves, was determined in comparison with the Salina lagoon, characterized by hypoxic and oxic conditions, longer residence time, and higher water amplitude in the dry season, and an inverse relationship was found between degraded biomass and both sulfate concentration and redox potential. Based on the results obtained in this study, we conclude that the contamination resulting from the wastewater discharge of anthropogenic and agricultural origin contributed by the artificial channel can generate variations in the oxidation-reduction conditions and variations in the salinity and sulfate concentrations of interstitial waters and soils in mangrove forests, thereby affecting the degradation of mangrove leaves in addition to the integration of organic matter into soil. Furthermore, there are alterations in the dynamics of the biogeochemical cycles of nutrients in adjacent ecosystems, since in conditions of reduced potential and hypersalinity, the percentage of degradation of leaf biomass decreases, as observed in this study. The results of this research provide a baseline of information that improve our understanding of ecological functioning and could be used in the management of mangrove communities and species, as well as implemented in conservation and protection strategies. Such strategies include sustainable agricultural and livestock practices and adequate management and treatment of wastewater. Therefore, we can recommend that further field studies be conducted regarding

associations of leaf biomass degradation with other environmental conditions, hydrological patterns, forest type and species, as well as the relationship with other physicochemical variables of interstitial water and soil.

Author Contributions: C.M.A.-H. and C.A.C.-K. conceived the study, participated in its design and coordination, and helped to draft the manuscript. G.E.-D., J.O.-S. and R.M.-S. provided advice during the study and analyzed and interpreted data. C.M.A.-H., R.M.-S., J.O.-S., G.E.-D., R.A.P.-B., J.E.R.-C., E.J.G.-A. and C.A.C.-K. collected, analyzed, and interpreted the data. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Electricity Federal Agency (CFE; Comisión Federal de Electricidad en México), grant number CFE-UAC: SC-CPH-02.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors acknowledge the EPOMEX Institute of the Autonomous University of Campeche. We also thank Gerardo Martinez and community of Chacahua for help during the monitoring period.

Conflicts of Interest: The authors declare no competing interests.

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