HOW DO SALINITY AND WATER DEFICIT INFLUENCE THE INITIAL DEVELOPMENT OF CAATINGA SEEDLINGS?

COMO A SALINIDADE E O DÉFICIT HÍDRICO INFLUENCIA O DESENVOLVIMENTO INICIAL DE MUDAS DA CAATINGA?

¿CÓMO INFLUYEN LA SALINIDAD Y EL DÉFICIT HÍDRICO EN EL DESARROLLO INICIAL DE PLÁNTULAS DE LA CAATINGA?

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ABSTRACT

The Caatinga presents high climatic variability, marked by long periods of drought, irregular rainfall, and high evapotranspiration rates, factors that shape vegetation dynamics. The intensification of anthropogenic activities, especially deforestation and irrigated agriculture with inadequate management, has expanded processes of salinization and environmental degradation, compromising the establishment and regeneration of native vegetation. In this context, understanding the effects of salinity and water scarcity on the early stages of plant development is essential to support conservation and ecological restoration strategies.

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Salinization, whether of natural or anthropogenic origin, reduces the soil's osmotic potential, hinders water and nutrient uptake, and causes ionic toxicity, affecting germination, growth, and physiology. In Caatinga species, these effects include decreased germination speed and percentage, accumulation of reactive oxygen species, plasmolysis, nutritional disorders, and severe reductions in early growth, with losses exceeding 90% in some sensitive species. At the same time, recurrent water deficit intensifies developmental limitations by promoting stomatal closure, reducing CO_2 assimilation and compromising gas exchange, biomass accumulation, and leaf expansion. Evidence shows wide interspecific variation in responses to these stresses, involving osmotic adjustments, morphological changes, antioxidant mechanisms, and biomass allocation strategies. This functional diversity highlights both the vulnerability and the adaptive potential of Caatinga species in the face of environmental changes. The evidence found showed that salinity and water deficit act as the main limiting factors for the establishment of Caatinga species, directly affecting germination processes, initial growth, and physiological functioning. Although many species exhibit adaptive mechanisms capable of mitigating part of these effects, the intensity and combination of stresses often result in significant reductions in plant performance.

Keywords: Salts. Germination. Photosynthesis. Semi-arid.

RESUMO

A Caatinga, apresenta elevada variabilidade climática, marcada por longos períodos de seca, chuvas irregulares e altas taxas de evapotranspiração, fatores que moldam a dinâmica vegetal. A intensificação das atividades antrópicas, especialmente o desmatamento e a agricultura irrigada com manejo inadequado, tem ampliado processos de salinização e degradação ambiental, comprometendo o estabelecimento e a regeneração da vegetação nativa. Nesse contexto, compreender os efeitos da salinidade e da escassez hídrica sobre as fases iniciais das plantas é essencial para subsidiar estratégias de conservação e restauração ecológica. A salinização, seja de origem natural ou antrópica, reduz o potencial osmótico do solo, dificulta a absorção de água e nutrientes e provoca toxicidade iônica, afetando germinação, crescimento e fisiologia. Nas espécies da Caatinga, esses efeitos incluem diminuição da velocidade e porcentagem de germinação, acúmulo de espécies reativas de oxigênio, plasmólise, distúrbios nutricionais e reduções severas no crescimento inicial, com destaque para perdas superiores a 90% em algumas espécies sensíveis. Paralelamente, o déficit hídrico recorrente intensifica limitações ao desenvolvimento ao promover fechamento estomático, reduzindo a assimilação de CO_2 e comprometendo as trocas gasosas, o acúmulo de biomassa e a expansão foliar. Evidências mostram ampla variação interespecífica nas respostas a esses estresses, envolvendo desde ajustes osmóticos e alterações morfológicas até mecanismos antioxidantes e estratégias de alocação de biomassa. Essa diversidade funcional destaca tanto a vulnerabilidade quanto o potencial adaptativo das espécies da Caatinga frente às mudanças ambientais. As evidências encontradas mostraram que a salinidade e o déficit hídrico atuam como os principais fatores limitantes ao estabelecimento das espécies da Caatinga, afetando de forma direta os processos de germinação, crescimento inicial e funcionamento fisiológico. Apesar de muitas espécies apresentarem mecanismos adaptativos capazes de mitigar parte desses efeitos, a intensidade e a combinação dos estresses frequentemente resultam em reduções expressivas no desempenho das plantas.

Palavras-chave: Sais. Germinação. Fotossíntese. Semiárido.

RESUMEN

La Caatinga presenta una elevada variabilidad climática, marcada por largos períodos de sequía, lluvias irregulares y altas tasas de evapotranspiración, factores que moldean la dinámica vegetal. La intensificación de las actividades antrópicas, especialmente la deforestación y la agricultura de riego con manejo inadecuado, ha ampliado los procesos de salinización y degradación ambiental, comprometiendo el establecimiento y la regeneración de la vegetación nativa. En este contexto, comprender los efectos de la salinidad y la escasez hídrica sobre las fases iniciales de las plantas es esencial para respaldar estrategias de conservación y restauración ecológica. La salinización, ya sea de origen natural o antrópico, reduce el potencial osmótico del suelo, dificulta la absorción de agua y nutrientes y provoca toxicidad iónica, afectando la germinación, el crecimiento y la fisiología. En las especies de la Caatinga, estos efectos incluyen disminución de la velocidad y el porcentaje de germinación, acumulación de especies reactivas de oxígeno, plasmólisis, trastornos nutricionales y reducciones severas en el crecimiento inicial, con pérdidas superiores al 90% en algunas especies sensibles. Paralelamente, el déficit hídrico recurrente intensifica las limitaciones al desarrollo al promover el cierre estomático, reduciendo la asimilación de CO_2 y comprometiendo el intercambio gaseoso, la acumulación de biomasa y la expansión foliar. La evidencia muestra una amplia variación interespecífica en las respuestas a estos estreses, involucrando ajustes osmóticos, cambios morfológicos, mecanismos antioxidantes y estrategias de asignación de biomasa. Esta diversidad funcional destaca tanto la vulnerabilidad como el potencial adaptativo de las especies de la Caatinga frente a los cambios ambientales. La evidencia encontrada mostró que la salinidad y el déficit hídrico actúan como los principales factores limitantes para el establecimiento de las especies de la Caatinga, afectando directamente los procesos de germinación, el crecimiento inicial y el funcionamiento fisiológico. Aunque muchas especies presentan mecanismos adaptativos capaces de mitigar parte de estos efectos, la intensidad y la combinación de los estreses con frecuencia resultan en reducciones significativas en el desempeño de las plantas.

Palabras clave: Sales. Germinación. Fotosíntesis. Semiárido.

1 INTRODUCTION

The Caatinga, the largest seasonally dry forest in the world, is characterized by high climatic variability, marked by long dry periods, irregular rainfall and high evapotranspiration rates, conditions that exert a strong influence on ecological processes and vegetation dynamics (Marengo et al., 2018). The Caatinga performs essential ecological functions, including maintaining primary production, nutrient cycling, and climate regulation (Silva et al., 2019; Szyja et al., 2019). However, the intensification of anthropogenic activities has accelerated the degradation of native vegetation and contributed to soil salinization, requiring urgent interventions.

The removal of native vegetation for the implementation of irrigated agriculture, added to the inefficient drainage and climatic conditions of the semi-arid region, intensify the accumulation of salts in the soil and water, making salinity a critical factor for plant establishment (Silva et al., 2019). Excess salts reduce the water potential of the soil, limit the absorption of water and nutrients, and trigger osmotic and ionic imbalances that compromise photosynthesis and initial growth (Avrella et al., 2019; Có et al., 2023; Gonçalves et al., 2020; Lopes et al., 2019). Among the most common effects are plasmolysis and nutritional disorders caused by the excess of solutes inside the tissues, which affect the cellular integrity and metabolic efficiency of plants, limiting plant development (Alvarenga et al., 2019; Days et al., 2016).

At the same time, the recurrent water stress in the semiarid region due to irregular rainfall and high evapotranspiration, aggravates these limitations by promoting stomatal closure, reducing CO_2 assimilation and compromising nutrient transport, resulting in lower photosynthetic efficiency and restrictions to development (Campos; Santos; Nacarath, 2021; Cross et al., 2023; Mendes et al., 2020; Ramos; Freire; France, 2021). Studies conducted with Caatinga species have shown that these stresses act differently among species, evidencing wide variation in their morphophysiological responses (Barros et al., 2019; Bessa et al., 2017; Dantas et al., 2019; Moura et al., 2025; Sabino et al., 2021).

That said, in view of the continuous loss of native vegetation in the Caatinga and the growing need to recover degraded areas, it is essential to understand how environmental stresses influence the establishment of species. In this context, this work aims to gather and analyze evidence on the effects of salinity and water deficit in the early stages of development of Caatinga seedlings, highlighting how these factors condition the growth, survival and restoration potential of native species.

1.1 SALINITY IN SEMI-ARID ENVIRONMENTS

Water and soil salinization is more prone in arid and semi-arid regions, and can occur naturally or anthropogenicly, affecting water bodies, soils and all biodiversity (Balakrishnan et al., 2024). Primary, or natural, salinization occurs due to environmental characteristics, such as climate, soil drainage, topography, and relief. The process consists of the transport of salts by brackish water capillaries to non-salinized layers of the soil, deposited mainly near the surface due to high evapotranspiration (Akça et al., 2020). Secondary salinization, or anthropogenic, is caused by inadequate irrigation practices, usually with an inefficient drainage system, or by the use of agricultural fertilizers with high levels of salts (Person et al., 2016; Zhou et al., 2013).

In the semi-arid regions, low rainfall and high evapotranspiration intensify the salinization process, since salts are leached and accumulated in the soil, making it difficult for plants to absorb water and nutrients and develop (Vasconcelos et al., 2013). The increase in population and demand for food production, associated with climatic conditions of low rainfall and high evapotranspiration rates, and inadequate water management for irrigation, leads to an increase in the number of areas with salinized soils in the Brazilian semi-arid region (Bezerra et al., 2020; Son et al., 2020). Salinization causes imbalance in soil biodiversity and nutritional losses, as it influences the survival of organisms in the microbiota responsible for maintaining biogeochemical cycles, being considered a precursor of desertification (Castro; Santos, 2020; Sá et al., 2021).

1.2 WATER SCARCITY IN SEMI-ARID ENVIRONMENTS

The Brazilian semi-arid region faces historical challenges related to water scarcity. The region has high evapotranspiration rates and low precipitation rates throughout the year, which results in a negative water balance and the recurrence of prolonged droughts. To meet the demand for water, local populations resort to alternatives such as dams and tubular wells; However, the quality of groundwater is not always suitable for consumption, due to the high concentrations of salts (Rodriguez et al., 2016).

In addition, anthropic action intensifies environmental problems. The removal of vegetation cover for agricultural purposes, added to the natural climatic vulnerabilities of the region, contributes to soil degradation Marengo et al. (2018) and alters essential processes, such as the dynamics of water and carbon in the environment (Mendes et al., 2020). Projections indicate that, in the coming years, the semi-arid region of Brazil may face even greater water scarcity and intensification of aridity, due to reduced rainfall (about 22%), decreased soil moisture and increased temperatures (Marengo; Bernasconi, 2015). Given this scenario, it is essential to seek mitigation actions and strategies capable of reducing the impacts of these increasingly severe environmental conditions (Ledru et al., 2020).

1.3 GERMINATION

Germination is considered one of the most critical phases of plant development, as it depends on several factors, such as water availability, presence of salts, temperature, physiological quality of the seed, and storage time. Salt stress, in particular, directly affects essential processes of this phase, altering primary root growth, speed, and average germination time (Santos et al., 2016).

These effects occur mainly due to the reduction of the osmotic potential of the soil or substrate, which hinders the absorption of water by the seed (Chaves; Arrows; Pinheiro, 2009). Excess salts also cause physiological disturbances, such as changes in the proton pump, membrane permeability, and solute transport between cells (Aragon et al., 2009). Such changes compromise the biochemical reactions necessary for germination and can reduce or even completely inhibit the process, resulting in seed loss (Anaya et al., 2018).

Several studies have evaluated the effect of salinity on the germination of forest species in the Caatinga (Santos et al., 2021a). For Cenostigma pyramidale (Tul.) Gagnon & G.P. Lewis, a reduction in the speed and percentage of germination was observed, results similar to those reported for Anadenanthera colubrina (Vell.) Brenan (Gomes; Gomes; Dantas, 2023; Pereira et al., 2015). The decrease in osmotic potential, caused by the excess of salts in the soil, in addition to restricting water uptake, leads to the formation of reactive oxygen species, which can denature proteins and compromise seed vigor. This behavior has been identified in species such as Erythrina velutina, Anadenanthera macrocarpa (Benth.) Brenan, Aspidosperma pyrifolium (Mart.) and Myracrodruon urundeuva (Fr. All.), all of them showing a drop in germination and protein alterations (Nóbrega et al., 2021; Sena et al., 2023).

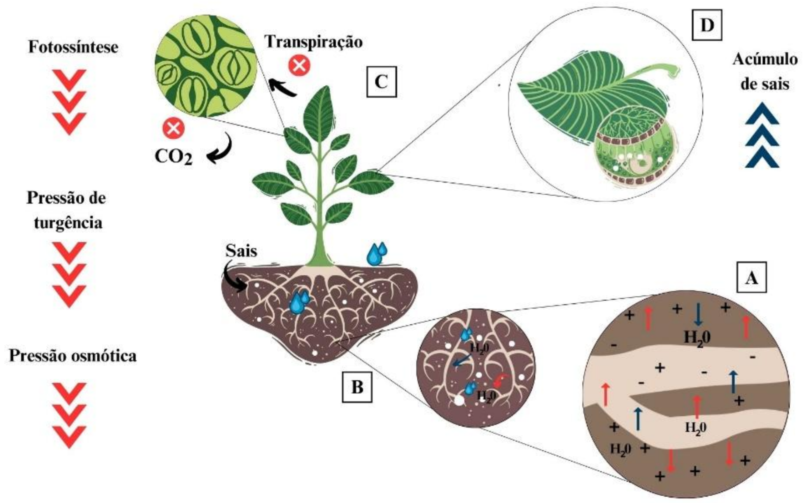
In the Brazilian semi-arid region, where the water regime is marked by irregularity and long dry periods, seeds can go through repeated cycles of hydration and dehydration, which reduces the percentage of germination, as observed in Mimosa caesalpiniifolia Benth. e Pityrocarpa moniliformis (Benth.) Luckow & R.W. Jobson (Nicolau et al., 2020). Factors intrinsic to seeds, such as size and weight, also influence germination success. In Amburana cearensis (Allemão) A.C. Smith, for example, lighter seeds showed greater water absorption under water stress, while heavier seeds showed different behavior (Almeida et al., 2014). The association of water and saline stresses can potentiate the harmful effects on the germination of species.

1.4 EARLY GROWTH

The establishment stage occurs right after germination and, like it, is a phase that is highly sensitive to abiotic stresses, especially salinity and water deficit. During this period, the excess of salts limits the development of seedlings both by the water restriction caused by the reduction of the osmotic potential and by the toxicity generated by the accumulation of ions in the tissues (Figure 1). In Pityrocarpa moniliformis (Benth.) Luckow & R.W. Jobson, for example, salt stress reduced the growth of cotyledons, hypocotyl and root, in addition to delaying the emission of the first leaves, compromising the quality of seedlings and altering the accumulation of photosynthetic compounds and soluble proteins (Silva et al., 2019; Ferreira et al., 2021). Similar results were observed by Moura et al. (2025), which reported reductions of up to 97% in height growth of Handroanthus impetiginosus e Handroanthus spongiosus, mainly attributed to toxicity resulting from the accumulation of salts in seedling tissues.

Figure 1

Dynamics of salt stress in the soil-plant system, highlighting barriers to water uptake and reduction of photosynthesis



The increase in salinity also causes water loss in the tissues and a reduction in turgidity pressure, which compromises the growth of species such as Anadenanthera colubrina (Vell.) Brenan, Erythrina velutina Willd. e Aspidosperma pyrifolium Mart. & Zucc. when irrigated with brackish water (DANTAS et al., 2019). In addition to affecting the root system, salt stress interferes with the development of the aerial part. In Mimosa ophthalmocentra Mart. ex Benth, for example, the reduction of root growth acts as an adaptive mechanism to limit the entry of salts into plants (Walnut et al., 2018).

Water deficit, in turn, is one of the main causes of delayed development and poor plant formation (Shane et al., 2010). The decrease in water availability reduces the osmotic potential of the soil, hindering its absorption by the roots and causing metabolic disorders and loss of turgor (Lum et al., 2014). In Senegalia polyphylla (DC.) Britton & Rose, it was observed that the combination of plant density and water stress directly influenced the transpiration of seedlings (Honda; Pilon; Durigan, 2019). For Erythrina velutina Willd. e Enterolobium contortisiliquum (Vell.) Morong, severe water stress caused a reduction in the number of leaves and leaflets, in addition to a decrease in leaf area (Lucius et al., 2017).

In Pityrocarpa moniliformis, it was found that, in order to maintain development under water stress, plants perform osmotic adjustment by accumulating sugars, proline and amino acids (Guirra et al., 2022). Similar results were observed in Poincianella bracteosa (Tul.) L.P. Queiroz and Iron-tendered libidibia (Mart. ex Tul.) L.P. Queiroz, which showed reductions in stem diameter, number of leaves, leaf area, total dry mass and gas exchange, showing important morphological and physiological changes (Ferreira et al., 2015).

Dry biomass accumulation is also often affected by water restriction (Magalhães Filho et al., 2008). Studies with Piptadenia stipulacea (Benth.) Ducke, Anadenanthera colubrina e Aspidosperma pyrifolium showed that low water availability significantly compromises biomass accumulation, although the intensity of the effects varies between species (Barros et al., 2019). Sabino et al. (2021) They also point out that these changes can occur differently between plant partitions, some species start to invest proportionally more in root biomass as a strategy to increase water uptake, reducing investment in the aerial part.

1.5 PHYSIOLOGY

Salinity poses a significant risk to plant development, as it causes excessive accumulation of ions in tissues, triggers water stress, and favors the imbalance of the redox system (Morais et al., 2019). Given these conditions, plants have developed, over time, different adaptive strategies to ensure their survival, including stomatal closure, which reduces water loss through transpiration (Silveira et al., 2016).

Studies carried out by Bessa et al. (2017) with Myracrodruon urundeuva M. Allemão, Handroanthus impetiginosus (Mart. ex DC.) Mattos, Bauhinia ungulata L., Erythrina velutina Willd., Mimosa caesalpiniifolia Benth. e Luetzelburgia auriculata (German) Ducke revealed that salinity significantly reduced gas exchange in these species. Salt stress decreased water absorption and promoted the accumulation of toxic ions in the cytoplasm. Even after pre-treatments, Myracrodruon urundeuva failed to perform ionic adjustment, an essential physiological strategy to deal with excess salts (Souza et al., 2022). In these cases, plants start to depend more heavily on antioxidant mechanisms, which prevent the oxidation of cellular structures.

Water is essential to maintain turgor and sustain plant growth, so its scarcity generates severe limitations to development. As a response to water deficit, one of the main adaptive strategies is stomatal closure, which reduces water loss to the environment (Reich, 2014). However, this same strategy limits photosynthesis and, consequently, plant growth (Frosi et al., 2017).

Species such as Myracrodruon urundeuva, Iron-tendered libidibia (Mart. ex Tul.) L.P. Queiroz and Mimosa tenuiflora (Willd.) Poir. showed reduced gas exchange, decreased growth and accumulation of free amino acids and soluble proteins when subjected to water stress (Almeida et al., 2021a, 2020, 2021b). Similar results were reported by Santos et al. (2021b), reinforcing that both salinity and water deficit intensely affect the physiological processes essential to the development of Caatinga species.

2 FINAL CONSIDERATIONS

The evidence found showed that salinity and water deficit act as the main limiting factors to the establishment of Caatinga species, directly affecting the processes of germination, initial growth and physiological functioning. Although many species have adaptive mechanisms capable of mitigating part of these effects, the intensity and combination of stresses often result in significant reductions in plant performance. The differentiated responses between species highlight the importance of selecting more tolerant species for the recovery of areas. Therefore, understanding how these stresses and their interactions are essential to support strategies for management, conservation and recovery of degraded areas in the Caatinga.

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