

REVIEW

Functional and anatomical plant adaptations to water deficit in Brazilian dry ecosystems

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Abstract: This study aimed to synthesize and discuss the main structural and ecological mechanisms that enable plant persistence in Brazilian dry environments, with emphasis on the *Cerrado*, *Caatinga*, and *Restinga* ecosystems. An integrative literature review combined with a descriptive bibliometric analysis was conducted using studies published between 1992 and 2024, retrieved from major scientific databases. The review followed PRISMA-based procedures and included 29 eligible studies addressing anatomical, physiological, and ecological responses to environmental stress. The results revealed recurrent xeromorphic characteristics, including cuticular thickening, trichome occurrence, compact mesophyll organization, epidermal reinforcement, and tissue sclerification, which contribute to water conservation and environmental resistance. Conservative functional strategies, phenotypic plasticity, adaptive convergence, and drought-avoidance mechanisms were also frequently reported across the analyzed ecosystems. The findings indicate that plant survival under restrictive conditions depends on the integration of anatomical organization, functional traits, and ecological strategies. Furthermore, similar environmental pressures promote convergent adaptive responses among distinct biomes, highlighting the importance of these mechanisms for ecosystem resilience under ongoing climate change.

Keywords: Xeromorphism; Phenotypic plasticity; Environmental filtering; Sclerophylly; Ecophysiology; Drought tolerance.

1. Introduction

Plant species inhabiting seasonally dry and environmentally restrictive ecosystems exhibit a wide variety of anatomical, physiological, and functional adaptations that allow survival under conditions of water deficit, nutrient limitation, high irradiance, salinity, and recurrent fire events. These adaptive mechanisms are especially evident in Brazilian ecosystems such as the *Cerrado*, *Caatinga*, and *Restinga*, which are recognized for their marked environmental heterogeneity and strong selective pressures on plant communities (Scarano, 2002; Haridasan, 2008; Silva et al., 2017).

In these environments, plant structure and function are closely associated with ecological strategies that maximize water conservation, resource-use efficiency, and tolerance to climatic stress. The relationship

between plant form and environmental conditions has long been recognized as a central aspect of plant ecology and evolution. Xeromorphic traits, including thick cuticles, reduced leaf area, sclerenchymatous tissues, trichomes, stomatal regulation, and specialized vascular structures, are commonly associated with species growing under drought-prone conditions (Fahn and Cutler, 1992; Evert, 2006).

Such structural adaptations directly influence photosynthetic performance, transpiration rates, and hydraulic safety, contributing to plant persistence in stressful habitats (Smith et al., 1997; Chaves et al., 2003). In tropical dry ecosystems, these characteristics frequently reflect convergent evolutionary responses to similar environmental constraints despite taxonomic differences among species (Kuster et al., 2018; Richetti et al., 2024). Functional trait ecology has emerged as an important framework for understanding how plant

species respond to environmental gradients and ecosystem processes.

Functional traits are morphological, physiological, or phenological characteristics that directly influence plant performance and fitness (Violle et al., 2007). Variations in these traits affect resource acquisition strategies, competitive ability, and ecosystem functioning (Díaz and Cabido, 2001). Global ecological frameworks, such as the leaf economics spectrum and the fast-slow plant economics spectrum, have demonstrated that plant species exhibit coordinated trade-offs between rapid resource acquisition and conservative resource-use strategies (Wright et al., 2004; Reich, 2014).

In water-limited ecosystems, conservative strategies are frequently associated with increased tissue sclerophylly, reduced specific leaf area, and enhanced structural investment, allowing plants to withstand prolonged drought periods. Brazilian dry ecosystems provide important models for investigating plant adaptive strategies because they encompass diverse climatic and edaphic conditions. The *Cerrado*, one of the world's biodiversity hotspots, is characterized by acidic nutrient-poor soils, seasonal drought, and recurrent fire regimes, all of which strongly influence vegetation structure and functional composition (Miranda et al., 2002; Simon et al., 2009; Hoffmann et al., 2012).

Similarly, the *Caatinga* represents the largest tropical dry forest region in South America and experiences intense water limitation and high evapotranspiration rates, promoting the evolution of drought-tolerant traits (Prado, 2003; Santos et al., 2014; Silva et al., 2017). Restinga ecosystems, distributed along the Brazilian coastal plain, are also subjected to multiple environmental stresses, including salinity, high solar radiation, sandy nutrient-poor soils, and water deficit (Scarano et al., 2009). Several anatomical and ecological studies conducted in Brazilian ecosystems have demonstrated the occurrence of structural plasticity and adaptive convergence among species exposed to environmental stress.

Investigations involving species from Restinga and *Cerrado* vegetation identified modifications in epidermal organization, mesophyll arrangement, vascular tissues, and supporting structures associated with water economy and stress tolerance (Aguiar-Dias et al., 2012; Alvarez and Silva, 2012; Donato; Morretes, 2007; Rossatto et al., 2015). Similar adaptive responses have also been observed in species from

coastal dunes and xeric environments, reinforcing the ecological importance of anatomical adjustments in stressful habitats (Melo Jr. et al., 2019; Lemos et al., 2020; Richetti et al., 2024).

Despite substantial advances in studies involving plant ecological anatomy, functional traits, and drought tolerance in tropical ecosystems, the available evidence remains highly fragmented across different vegetation types, taxonomic groups, and methodological approaches. Most investigations have focused on isolated anatomical traits, specific plant groups, or single ecosystems, particularly the *Cerrado* or Restinga vegetation, whereas comparatively fewer studies have adopted integrative approaches capable of synthesizing adaptive convergence patterns among distinct Brazilian dry ecosystems.

Furthermore, although several investigations have described xeromorphic and functional responses to environmental stress, limited efforts have integrated anatomical, ecological, and bibliometric perspectives to identify recurrent adaptive patterns associated with drought tolerance, resource-use strategies, and environmental resistance across the *Cerrado*, *Caatinga*, and Restinga biomes. This fragmentation restricts broader ecological understanding of how structurally and functionally distinct plant groups respond to similar environmental pressures under water-limited conditions.

An important research question, therefore, emerges: which anatomical and functional adaptations are most recurrently associated with plant persistence and environmental resistance in the *Cerrado*, *Caatinga*, and Restinga ecosystems, and to what extent do these ecosystems exhibit patterns of adaptive convergence under similar ecological pressures? Integrating evidence from anatomical, ecological, and functional perspectives is essential for improving our understanding of plant resilience under ongoing climate change scenarios, especially in regions predicted to experience increased drought intensity and temperature extremes (Santos et al., 2014).

Additionally, integrative synthesis approaches combined with bibliometric analyses have become increasingly important for identifying scientific trends, knowledge gaps, and emerging perspectives in ecological and anatomical studies (Page et al., 2021; Zupic; Čater, 2015). Therefore, this study aims to synthesize and discuss the principal anatomical and functional adaptations exhibited by plants inhabiting Brazilian dry ecosystems, with emphasis on the *Cerrado*, *Caatinga*, and Restinga vegetation.

Furthermore, the study seeks to evaluate ecological convergence patterns and the role of plant functional traits in mediating plant responses to environmental stress conditions.

2. Material and Methods

2.1 Study Design

This study consisted of an integrative literature review combined with a descriptive bibliometric exploration focusing on the anatomical and functional adaptations of plants occurring in Brazilian dry ecosystems, particularly the *Cerrado*, *Caatinga*, and *Restinga* biomes. The integration of qualitative synthesis and bibliometric approaches enabled a comprehensive assessment of the current scientific knowledge regarding plant adaptive strategies under water-limited conditions.

The review was conducted following PRISMA 2020 reporting principles (Page et al., 2021), which were used to improve the transparency and organization of the search, screening, eligibility, and study selection stages. However, the study was not designed as a fully systematic review and should be interpreted as an integrative synthesis of the available literature. The methodological approach aimed to identify and synthesize the principal anatomical, functional, and ecological adaptations associated with drought resistance and environmental persistence in Brazilian dry ecosystems.

The bibliometric component was performed according

to the methodological framework proposed by Zupic & Čater (2015). This approach enabled the examination of publication trends, temporal evolution of research, thematic recurrence, keyword frequency, and major scientific directions related to plant adaptations to environmental stress. The bibliometric analysis was intended to provide complementary insights into the development of the research field rather than a comprehensive bibliometric mapping based on citation or collaboration networks.

The integration of literature review procedures and bibliometric indicators allowed not only the synthesis of the main scientific evidence available on the subject but also the identification of knowledge gaps, emerging research trends, and future perspectives in ecological anatomy, functional ecology, and plant adaptation to drought-prone environments.

The review focused on plant species occurring in the principal Brazilian dry ecosystems, particularly the *Cerrado*, *Caatinga*, and *Restinga*, which are distributed across distinct climatic, edaphic, and environmental conditions throughout Brazil (Figure 1).

The study was designed to address the following research question: Which anatomical and functional plant adaptations are most frequently associated with drought tolerance and environmental resistance in Brazilian dry ecosystems, and to what extent do these adaptive traits exhibit convergence among the *Cerrado*, *Caatinga*, and *Restinga* biomes?

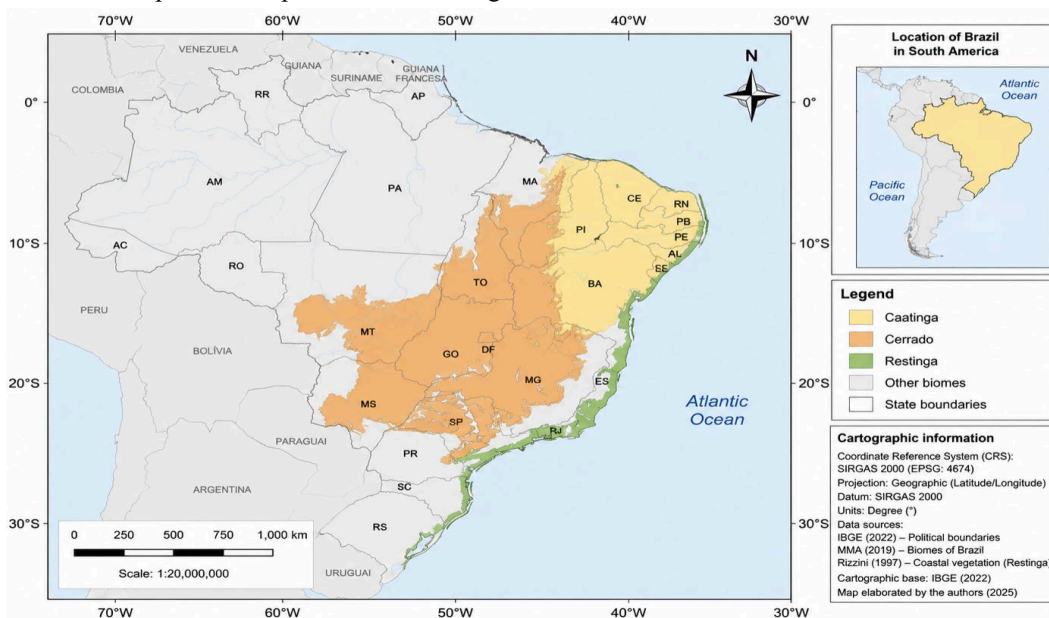


Figure 1. Geographic distribution of the main Brazilian dry ecosystems discussed in the review, including the *Cerrado*, *Caatinga*, and *Restinga*. The map illustrates the spatial distribution of these ecosystems across Brazil and highlights their major environmental characteristics, including seasonal drought, nutrient-poor soils, salinity, high irradiance, and recurrent fire occurrence. These environmental conditions act as important ecological filters shaping plant anatomical

and functional adaptations. Source: Adapted by the author from Rizzini (1997), MMA (2019), and IBGE (2022).

2.2 Bibliographic Search Strategy

Bibliographic searches were conducted in April 2026 using the Web of Science, Scopus, and SciELO databases, complemented by supplementary searches in Google Scholar. These databases were selected because of their broad coverage of peer-reviewed literature in plant ecology, plant anatomy, plant physiology, and functional biology, as well as their extensive indexing of studies related to Brazilian dry ecosystems.

Studies published between 1992 and 2024 were considered. This period encompasses the substantial expansion of research on functional ecology, ecological anatomy, phenotypic plasticity, and plant adaptive responses to environmental stress. Seminal publications published before this period were also consulted when relevant to the conceptual framework of xeromorphism, ecological anatomy, and drought-adaptation strategies.

The search strategy combined descriptors in English and Portuguese using the Boolean operators AND and OR to maximize the retrieval of relevant studies while maintaining thematic specificity. The principal search terms included plant functional traits, functional ecology, xeromorphic adaptations, leaf anatomy, ecological anatomy, water deficit, drought adaptations, structural plasticity, dry tropical ecosystems, *Cerrado*, *Caatinga*, and *Restinga*. Additional combinations involving terms related to adaptive convergence, sclerophylly, environmental filtering, and drought stress were also applied.

Whenever permitted by the database search systems, search terms were applied to titles, abstracts, and keywords. Searches were performed in both English and Portuguese to maximize the retrieval of studies published in national and international journals.

An example of the search string employed was:

- (“functional traits” OR “ecological anatomy” OR “xeromorphic adaptations”) AND (“Cerrado” OR “Caatinga” OR “Restinga”) AND (“water deficit” OR “drought” OR “environmental stress”)

Search strategies were adapted to the indexing and retrieval characteristics of each database. All retrieved records were exported to electronic spreadsheets, where duplicate records were identified and removed manually. Bibliographic information was subsequently standardized before the screening process.

Google Scholar was used as a supplementary search source to identify potentially relevant studies not retrieved from the primary databases. Because this search was conducted as a complementary retrieval strategy rather than as a primary source of evidence, no predefined stopping criterion regarding the number of pages or records screened was established during the original search process. Consequently, the exact number of pages examined could not be retrospectively determined. This limitation may affect the reproducibility of this stage of the review and is explicitly acknowledged in the limitations section.

2.3 Eligibility Criteria

The study included original scientific articles, literature reviews, and ecological studies addressing anatomical, physiological, or functional adaptations associated with water deficit in plant species from Brazilian dry ecosystems. Studies involving functional ecology, leaf anatomy, xeromorphic strategies, structural plasticity, adaptive convergence, and morphophysiological responses related to environmental stress were also considered.

Selected studies were required to present information related to structural or functional characteristics of plant species subjected to restrictive environmental conditions, including low water availability, high irradiance, nutrient limitation, salinity, or recurrent fire events. Studies involving species from the *Cerrado*, *Caatinga*, and *Restinga* biomes were prioritized due to the ecological relevance of these ecosystems within Brazilian dry environments.

Duplicate documents, conference abstracts, undergraduate monographs, dissertations, theses, non-peer-reviewed book chapters, publications without full-text access, and non-peer-reviewed documents were excluded. Studies unrelated to plant adaptations to water stress, studies focused exclusively on agronomic management, or publications lacking sufficient information for qualitative and bibliometric analysis were also excluded.

2.4 Study Selection Process

The study selection process followed the identification, screening, eligibility, and inclusion stages recommended by the PRISMA 2020 protocol. Initially, bibliographic searches conducted in the selected databases resulted in the identification of 126 potentially relevant scientific records related to the

research topic.

After the initial compilation of records, 28 duplicate studies identified across the databases were removed through manual and automated checking procedures, resulting in 98 studies for preliminary analysis. Subsequently, the screening stage was performed through evaluation of titles and abstracts according to the predefined inclusion and exclusion criteria.

During the screening process, 41 studies were excluded because they did not present a direct relationship with the objectives of the review. The principal reasons for exclusion included studies focused exclusively on agricultural physiology, forest management, crop production, agronomic approaches without ecological focus, studies conducted in ecosystems unrelated to the Cerrado, Caatinga, or Restinga biomes, and publications lacking anatomical or functional approaches associated with water deficit.

After this stage, 57 articles remained for full-text reading and eligibility assessment. During the full-text

analysis, 28 studies were excluded due to the absence of relevant anatomical information, exclusive taxonomic focus, lack of direct association with drought stress, insufficient methodological consistency, or unavailability of the complete text.

At the end of the eligibility stage, 29 scientific studies met all inclusion criteria and were incorporated into the final qualitative and bibliometric analysis of the review.

The selected studies primarily encompassed research conducted in the *Cerrado*, *Caatinga*, and *Restinga* biomes, including analyses of leaf anatomy, structural plasticity, xeromorphic strategies, functional traits, ecophysiological responses to water deficit, and adaptive convergence in plant species subjected to restrictive environmental conditions.

The complete description of the identification, screening, eligibility, and inclusion stages was synthesized in a flowchart developed according to PRISMA 2020 recommendations (Figure 2).

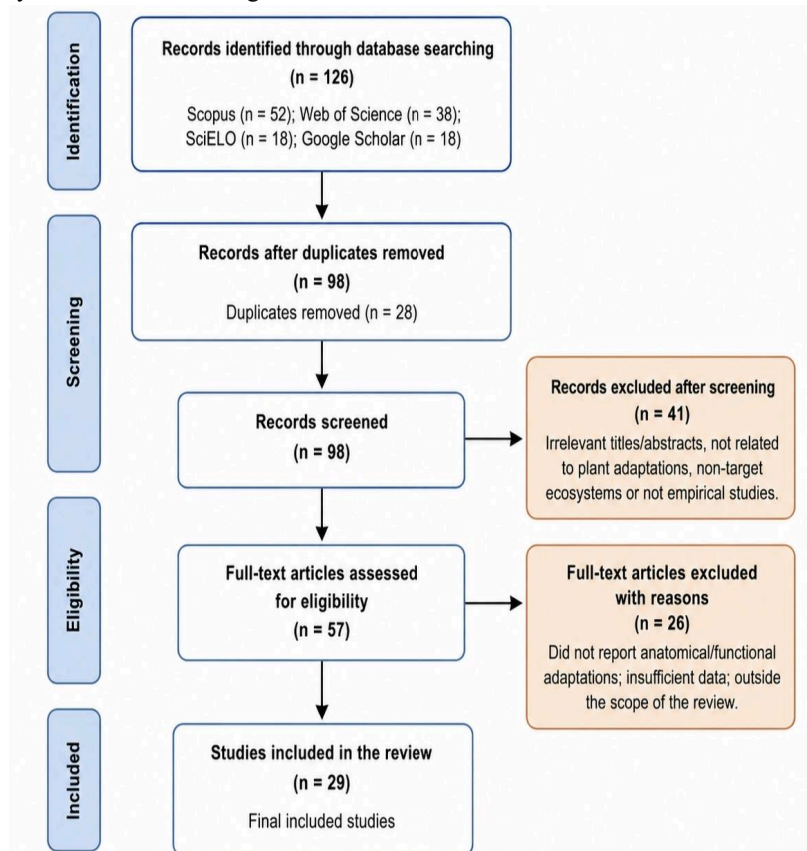


Figure 2. PRISMA 2020 flow diagram of the study selection process. The diagram shows the number of records identified, screened, assessed for eligibility, and included in the systematic review on functional and anatomical plant adaptations to water deficit in Brazilian dry ecosystems. Source: Adapted from Page et al. (2021).

A single reviewer conducted study screening, eligibility assessment, and data extraction. Therefore, no inter-reviewer agreement analysis was performed, and no formal conflict-resolution procedure was required. To minimize inconsistencies, all studies were evaluated according to predefined inclusion and exclusion criteria established before the screening process.

2.5 Methodological Quality Assessment

Methodological quality and potential sources of bias were considered throughout the study selection, data extraction, and evidence synthesis processes. During data extraction, particular attention was given to the clarity of study objectives, adequacy of methodological descriptions, transparency of data reporting, and consistency between reported findings and authors' conclusions. These aspects were examined to support the interpretation of the evidence and to identify potential limitations within the available literature.

However, a formal risk-of-bias assessment was not conducted. The studies included in this review comprised a heterogeneous body of literature, including empirical investigations, ecological case studies, review articles, conceptual papers, books, and book chapters. Given the diversity of publication types, study designs, research objectives, and methodological approaches represented in the final dataset, the application of a single standardized quality-assessment or risk-of-bias instrument was not considered appropriate.

Furthermore, no validated appraisal tool specifically designed for integrative reviews of ecological anatomy, plant functional ecology, and adaptive responses to environmental stress was identified. Consequently, the use of quantitative quality scores could have introduced artificial comparability among studies with substantially different methodological characteristics and scientific purposes.

To enhance transparency, methodological strengths and limitations reported by the original authors were considered during evidence interpretation and discussion. Particular attention was given to study design, sampling approaches, taxonomic scope, environmental context, and the extent to which conclusions were supported by the reported data. Accordingly, the findings of this review should be interpreted as a qualitative synthesis of the currently available literature rather than as a quantitative

assessment of evidence certainty.

This approach is consistent with recommendations for integrative reviews that seek to synthesize evidence derived from multiple study types and methodological traditions, where the primary objective is the identification of patterns, concepts, and research gaps rather than the estimation of effect sizes or the formal ranking of evidence quality.

2.6 Data Extraction and Organization

From the selected studies, information regarding authorship, year of publication, scientific journal, studied biome, analyzed taxonomic groups, evaluated anatomical structures, investigated functional traits, major observed adaptations, and methodological approaches applied in each study was extracted.

Additional information related to the geographic distribution of studies, institutional origin, predominant ecological approaches, and environmental factors associated with adaptive responses of the analyzed plant species was also recorded. The principal environmental factors considered included water deficit, salinity, high irradiance, nutrient limitation, and fire recurrence.

The collected data were organized into electronic spreadsheets for systematization, categorization, and descriptive analysis. This organization enabled the identification of recurrent ecological and anatomical patterns among different species and ecosystems, as well as comparisons among adaptive strategies described in the literature.

2.7 Bibliometric Analysis

The descriptive bibliometric analysis was conducted following the methodological framework proposed by Zupic and Čater (2015). This component was designed to complement the qualitative synthesis by providing an overview of publication trends, thematic patterns, and keyword relationships within the literature addressing anatomical and functional plant adaptations to water deficit in Brazilian dry ecosystems.

Bibliometric indicators included publication year, journal distribution, ecosystem representation, keyword recurrence, and thematic frequency among the studies included in the final dataset ($n = 29$). Temporal publication patterns were examined to identify trends in scientific interest related to ecological anatomy, functional ecology, xeromorphic adaptations, and plant

responses to environmental stress.

Author keywords were extracted from all included studies and compiled into a single corpus. Before analysis, keywords were standardized through spelling harmonization, singular-plural unification, and the merging of semantically equivalent terms to minimize redundancy and avoid artificial fragmentation of thematic categories. The complete keyword corpus and standardization procedures are provided in Supplementary Table S1.

Supplementary Table S1. The keyword corpus and standardization procedure used in the bibliometric analysis. Source: Author (2026).

Keyword frequency analysis was subsequently performed using the standardized corpus to identify the most recurrent themes associated with plant adaptations to water deficit. To further investigate thematic relationships, a keyword co-occurrence analysis was conducted using VOSviewer (version 1.6.20; Van Eck and Waltman, 2010). Terms were extracted from author keywords, and a minimum occurrence threshold of two was applied for inclusion in the network. Association strength normalization was used to calculate link strengths among terms, while thematic clusters were identified using the default VOSviewer clustering algorithm.

A total of 25 terms met the inclusion criterion and were retained for visualization and interpretation. The resulting network enabled the identification of thematic connections and major research directions within the field, highlighting recurrent topics such as xeromorphism, drought tolerance, functional traits, anatomical plasticity, adaptive convergence, sclerophylly, water-use efficiency, and ecophysiological responses to environmental stress.

The bibliometric analysis was intended as an exploratory characterization of the literature rather than a comprehensive bibliometric assessment. Accordingly, the analysis focused on publication trends, keyword frequencies, and keyword co-occurrence patterns. More advanced bibliometric approaches, including co-citation analysis, bibliographic coupling, collaboration networks, institutional mapping, country-level analyses, and citation impact assessment, were beyond the scope of the present study.

2.8 Qualitative Analysis of the Studies

The qualitative analysis focused on the ecological and anatomical interpretation of structural and

functional adaptations observed in the plant species investigated in the selected studies. Characteristics related to leaf tissue organization, cuticular thickening, trichome occurrence, sclerenchyma development, stomatal distribution, vascular modifications, and strategies associated with water conservation were evaluated.

Adaptations related to structural and functional plasticity in response to environmental conditions such as seasonal water deficit, high solar radiation, sandy soils, nutrient-poor substrates, salinity, and recurrent fire events were also analyzed. These characteristics were interpreted from the perspective of functional ecology and adaptive strategies developed by plant species inhabiting environmentally restrictive habitats.

The integration of systematic review and bibliometric analysis enabled a comprehensive synthesis of the scientific knowledge available regarding plant adaptations in Brazilian dry ecosystems.

Due to the substantial heterogeneity among the included studies regarding study design, taxonomic groups, ecosystems investigated, measured traits, and analytical approaches, a quantitative synthesis was not feasible. Consequently, no meta-analysis, effect-size estimation, or statistical comparison among ecosystems was performed. The study, therefore, relied on a qualitative synthesis of the available evidence.

2.9 Risk of Bias and Quality Assessment

Because the objective of this study was to provide an integrative and qualitative synthesis of the available literature, no formal risk-of-bias assessment or methodological quality scoring system was applied to the included studies. The reviewed publications exhibited substantial heterogeneity regarding study design, taxonomic focus, environmental conditions, and analytical approaches, which limited the applicability of standardized quality assessment frameworks. Consequently, the findings should be interpreted as a qualitative synthesis of published evidence rather than as a quantitative evaluation of evidence quality or certainty. Potential sources of bias associated with individual studies were considered during data interpretation and are further discussed in the limitations section.

3. Results

3.1 General overview of the selected studies

The integrative literature review and descriptive bibliometric exploration resulted in the inclusion of 29 scientific studies addressing anatomical and functional plant adaptations associated with environmental stress in Brazilian dry ecosystems. The selected publications, distributed between 1992 and 2024, indicate a progressive increase in scientific interest in ecological anatomy, functional ecology, and plant responses to water-limited environments.

The complete dataset comprising all 29 studies included in the review is provided in Supplementary Table S2. For each study, information regarding the ecosystem, study focus, and the principal anatomical or functional adaptations reported was extracted and synthesized.

Supplementary Table S2. Characteristics of the 29

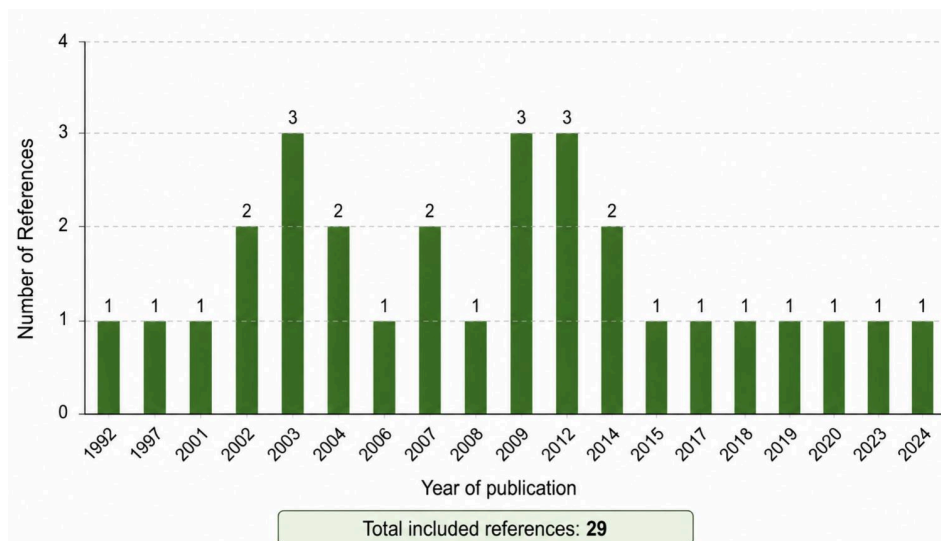


Figure 3. Temporal distribution of the studies included in the review. The graph represents the number of publications per year among the 29 articles selected after the application of the predefined inclusion and exclusion criteria. Publication frequency was calculated based on the year of publication reported in each eligible study. Source: Author, based on data extracted from the reviewed literature (2026).

The analyzed studies were predominantly concentrated in the Cerrado biome, which represented the largest proportion of publications included in the review. This pattern reflects the ecological relevance of the Cerrado as a major model for investigations involving fire ecology, seasonal drought, and functional plant strategies. The Caatinga biome also presented substantial scientific representation, especially in studies focused on semiarid vegetation and drought-related ecological responses. In contrast, investigations conducted in Restinga ecosystems were mainly associated with morphoanatomical variability, salinity tolerance, and responses to heterogeneous environmental conditions.

The bibliometric analysis demonstrated that the most

studies included in the qualitative synthesis and bibliometric analysis.

The temporal distribution of publications revealed relatively limited scientific production before 2010, followed by a substantial increase after 2015, reflecting the growing consolidation of trait-based ecology and climate-change research in tropical ecosystems. This expansion was particularly associated with studies investigating ecological strategies related to environmental resistance, phenotypic plasticity, and resource conservation in the Cerrado, Caatinga, and Restinga biomes.

As illustrated in Figure 3, scientific production involving plant adaptations in Brazilian dry ecosystems increased considerably over the last decade.

recurrent research themes involved ecological anatomy, plant functional traits, adaptive convergence, structural plasticity, and environmental resistance. Among the most frequently reported anatomical characteristics were epidermal reinforcement, trichome occurrence, compact mesophyll organization, tissue sclerification, reduced leaf area, and vascular modifications associated with hydraulic regulation in stressful environments.

3.2 Anatomical adaptations associated with water deficit

The qualitative synthesis demonstrated that xeromorphic anatomical characteristics were highly recurrent among plant species inhabiting Brazilian dry ecosystems. Most selected studies reported structural modifications associated with environmental resistance,

resource conservation, and persistence under water-limited conditions.

The principal xeromorphic anatomical traits identified in the reviewed studies and their associated ecological functions are summarized in Table 1.

Table 1. Main xeromorphic adaptations and their ecological functions in Brazilian dry ecosystems.

Xeromorphic adaptation	Anatomical characteristic	Ecological function
Thick cuticle	Thickened epidermal coating	Reduced water loss and surface protection
Trichomes	Leaf surface hairs	Thermal regulation and boundary-layer stabilization
Compact mesophyll	Reduced intercellular spaces	Increased structural resistance to dehydration
Sclerophylly	Thick and rigid leaves	Conservative resource-use strategy
Succulence	Water-storage tissues	Temporary water storage during drought periods

Source: Author (2026)

The principal xeromorphic anatomical traits identified in the reviewed studies are illustrated in Figure 4.

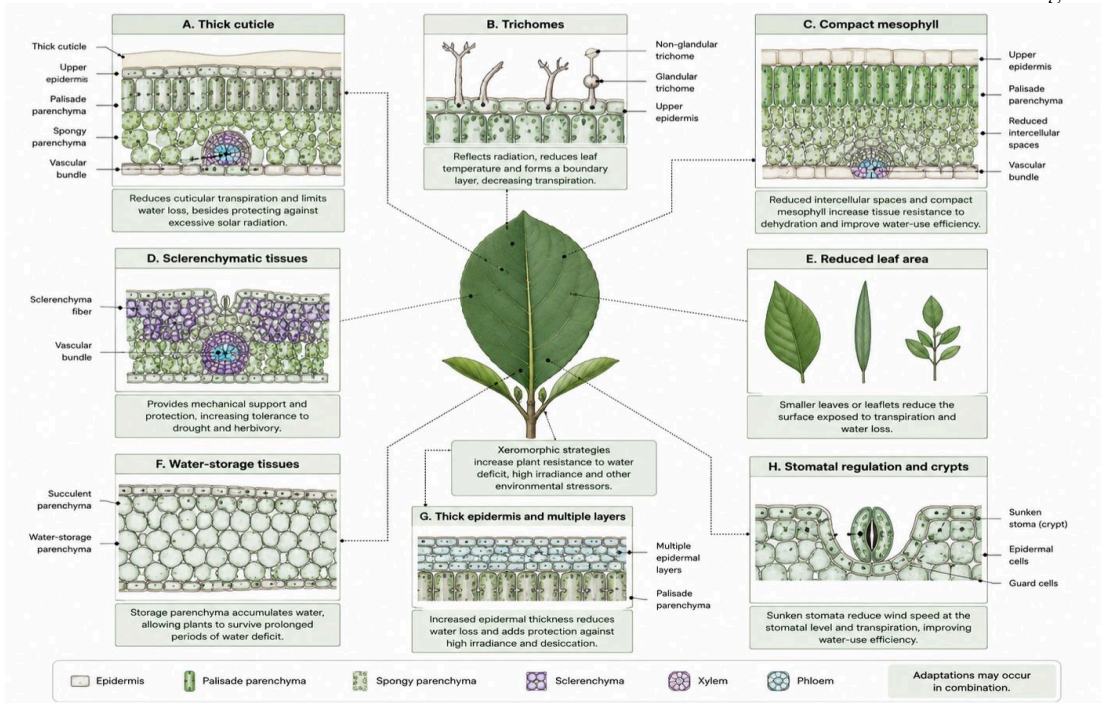


Figure 4. Conceptual illustration created by the authors based on the anatomical adaptations reported in the reviewed literature. The figure synthesizes recurrent xeromorphic traits associated with environmental resistance and drought tolerance in Brazilian dry ecosystems. Source: Author (2026).

Among the most recurrent anatomical characteristics identified in the analyzed studies, cuticular thickening represented one of the dominant patterns observed in species from the *Cerrado*, *Caatinga*, and *Restinga* ecosystems. Trichome occurrence was likewise frequently reported, particularly in species exposed to

elevated irradiance, seasonal drought, and saline environments.

Another recurrent feature involved compact mesophyll organization with reduced intercellular spaces, especially in species subjected to prolonged water limitation. Reinforced epidermal layers and sclerenchymatic tissues were also widely documented,

indicating substantial structural investment associated with mechanical protection and environmental resistance.

Several studies additionally identified reduced leaf area and elevated sclerophylly as important adaptive responses in nutrient-poor and environmentally restrictive habitats. Species occurring under chronic stress conditions frequently exhibited thick, rigid, and highly lignified leaves, reflecting conservative ecological strategies related to resource retention and structural durability.

In *Restinga* ecosystems, morphoanatomical plasticity represented a particularly recurrent pattern. Species exposed to contrasting local conditions, including salinity, sandy soils, high irradiance, and irregular water availability, demonstrated substantial variation in epidermal organization, vascular tissues, and mesophyll arrangement. These findings suggest elevated adaptive flexibility in response to environmental heterogeneity across coastal ecosystems.

3.3 Functional ecological strategies and adaptive convergence

The reviewed studies revealed strong relationships between plant anatomical organization and ecological resource-use strategies in Brazilian dry ecosystems. Conservative functional strategies predominated among species exposed to chronic environmental stress, particularly under conditions of seasonal drought, nutrient limitation, and high irradiance. These strategies were generally associated with elevated structural investment, increased tissue density, reduced specific leaf area, and greater resistance to dehydration.

Several investigations demonstrated that species from distinct taxonomic groups and ecosystems exhibited similar structural and functional responses under comparable environmental pressures, indicating recurrent patterns of adaptive convergence. This convergence was particularly evident among species occurring in the *Cerrado* and *Restinga* ecosystems, where morphoanatomical similarities were frequently observed despite phylogenetic differences.

Patterns of adaptive convergence among the *Cerrado*, *Caatinga*, and *Restinga* ecosystems are presented in Figure 5.

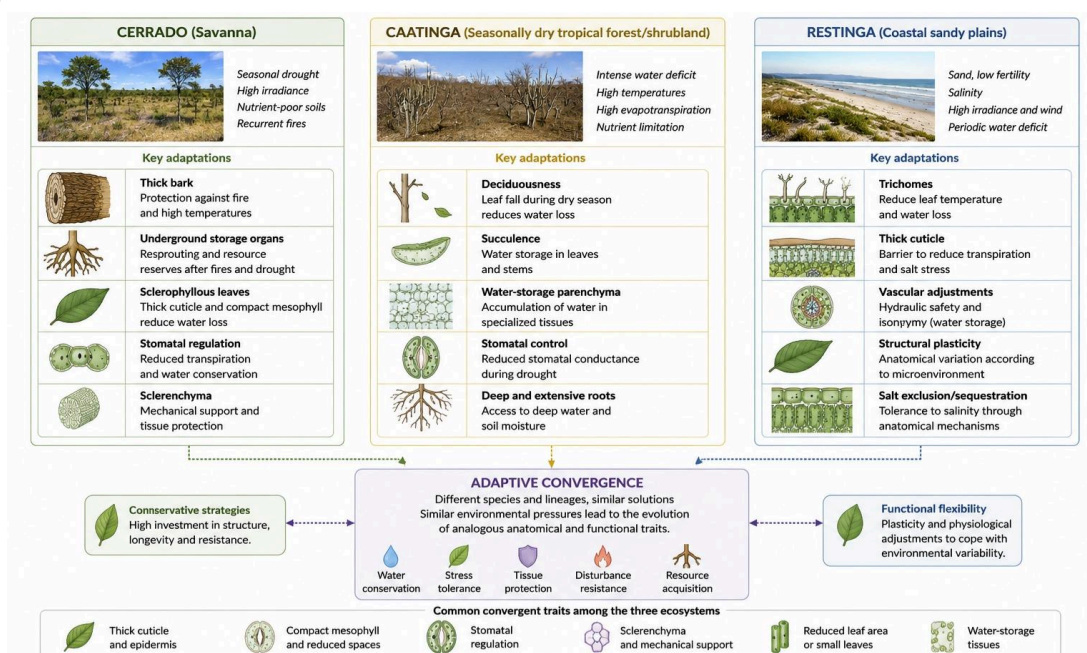


Figure 5. Conceptual representation of recurrent anatomical and functional traits reported in the reviewed literature for plant species occurring in the *Cerrado*, *Caatinga*, and *Restinga* ecosystems. The figure summarizes common adaptive responses associated with drought tolerance, environmental resistance, and resource conservation. It is intended as a conceptual synthesis of the reviewed evidence and does not represent a quantitative assessment of adaptive convergence. Source: Author (2026).

The integration of ecological anatomy and functional trait approaches demonstrated that plant persistence in Brazilian dry ecosystems depends on coordinated

interactions between structural organization, hydraulic regulation, and resource-use strategies. Functional mechanisms frequently associated with environmental resistance included reduced water loss, increased hydraulic protection, and temporary water-storage

capacity.

In the *Caatinga* biome, deciduousness and water-storage tissues represented some of the most recurrent drought-avoidance strategies. Many species exhibited seasonal leaf abscission during prolonged dry periods, contributing to reduced transpirational demand under semiarid conditions. Succulent tissues and specialized parenchymatic structures were likewise commonly reported as important mechanisms associated with temporary water storage and survival during seasonal drought.

Fire-related adaptations were particularly relevant in the *Cerrado* biome. Thick bark, underground storage organs, and resprouting capacity were recurrently associated with vegetation persistence under recurrent disturbance regimes. These characteristics reinforce the combined influence of drought and fire as major ecological filters shaping plant functional diversity and adaptive syndromes in neotropical savanna ecosystems.

3.4 Bibliometric trends and thematic distribution

The bibliometric analysis revealed a substantial

increase in the integration of plant anatomy, functional ecology, and ecophysiology over the last decade. Studies published after 2015 demonstrated a marked expansion of multidisciplinary approaches combining anatomical analyses, functional trait assessment, physiological measurements, and ecological interpretations associated with environmental stress in tropical ecosystems. This temporal trend reflects the growing scientific interest in understanding plant adaptive responses under scenarios of climate instability and increasing drought frequency (Figure 3).

Keyword recurrence analysis identified “functional traits”, “xeromorphism”, “drought tolerance”, “ecological anatomy”, and “structural plasticity” as the most frequent descriptors among the selected studies (Table 2). The predominance of these terms highlights the increasing importance of trait-based ecological approaches for investigating plant responses to restrictive environmental conditions. Furthermore, the recurrent association between anatomical and ecological descriptors demonstrates the progressive integration of structural botany, ecophysiology, and functional ecology in studies involving Brazilian dry ecosystems.

Table 2. Frequency of keywords extracted from the 29 studies included in the review. Frequencies were calculated after keyword standardization to merge equivalent terms, spelling variations, and closely related expressions.

Standardized keyword	Frequency
Functional traits	18
Xeromorphism	16
Drought tolerance	15
Ecological anatomy	13
Structural plasticity	11
Water deficit	10
Functional ecology	9
Sclerophylly	7
Adaptive convergence	6
Water-use efficiency	6

Notes: Frequencies were calculated from the keywords reported in the 29 studies included in the final dataset. Before analysis, equivalent terms, spelling variations, singular/plural forms, and closely related expressions were standardized to avoid artificial fragmentation of thematic categories. The resulting corpus was used to identify the most recurrent research themes associated with anatomical and functional plant adaptations to water deficit in Brazilian dry ecosystems. Source: Author (2026).

The thematic co-occurrence network generated using VOSviewer revealed strong conceptual connectivity among studies involving ecological anatomy, functional strategies, and plant responses to environmental stress (Figure 6). Three principal thematic clusters were identified. The first cluster was predominantly associated with structural adaptations, including terms related to cuticles, trichomes, mesophyll organization, and sclerophylly. The second cluster grouped studies focused

on functional ecology and physiological regulation, emphasizing resource-use strategies, hydraulic regulation, and environmental resistance. The third cluster was associated with ecological stressors and environmental filtering processes, particularly drought, salinity, fire, and climate change. Together, these clusters demonstrate the multidimensional character of plant adaptation studies in tropical dry ecosystems and reinforce the existence of strong thematic convergence across the analyzed literature.

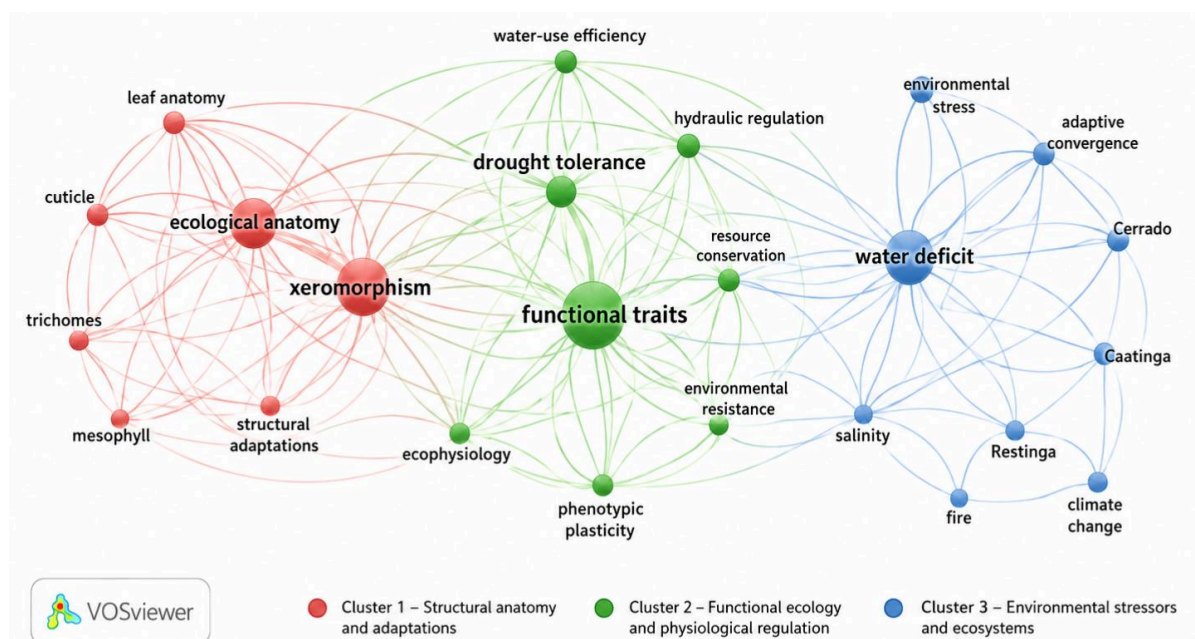


Figure 6. A keyword co-occurrence network was generated using VOSviewer based on the studies included in the review. Terms were extracted from author keywords, and a minimum occurrence threshold of 2 was applied. Association strength normalization was used to calculate link strengths among terms. A total of 25 terms met the inclusion criterion and were grouped into thematic clusters using the default VOSviewer clustering algorithm. Source: Author, based on data extracted from the reviewed literature (2026)

The bibliometric analysis additionally demonstrated that most investigations focused predominantly on leaf anatomical characteristics, whereas comparatively fewer studies addressed root systems, stem hydraulic architecture, and integrative whole-plant physiological mechanisms. This pattern highlights important knowledge gaps involving belowground adaptations and hydraulic responses associated with environmental resistance in drought-prone ecosystems. Furthermore, the available literature remains strongly concentrated on descriptive structural analyses, while comparatively fewer studies integrate anatomical, physiological, and ecological approaches simultaneously under natural environmental conditions.

Overall, the analyzed literature demonstrates that plant species inhabiting Brazilian dry ecosystems exhibit coordinated structural and functional strategies associated with persistence under restrictive environmental conditions. The recurrent occurrence of xeromorphic characteristics, phenotypic plasticity, and conservative resource-use strategies reinforces the adaptive complexity of tropical vegetation exposed to chronic drought, salinity, nutrient limitation, and recurrent disturbance regimes.

4. Discussion

4.1 Xeromorphic anatomy as an environmental resistance strategy

The reviewed studies suggest that xeromorphic anatomy constitutes a fundamental component of plant persistence strategies in Brazilian dry ecosystems. Rather than representing isolated structural traits, the recurrent occurrence of epidermal reinforcement, cuticular thickening, trichomes, compact mesophyll organization, and sclerenchymatic tissues reflects coordinated responses to multiple environmental stressors, including seasonal drought, elevated irradiance, nutrient limitation, salinity, and recurrent disturbance regimes.

The widespread occurrence of these anatomical characteristics across the *Cerrado*, *Caatinga*, and *Restinga* ecosystems highlights the strong influence of environmental filtering on plant functional diversity. Under conditions of chronic water limitation, structural traits that reduce water loss, increase tissue durability, and enhance resistance to environmental stress tend to be selectively favored, resulting in the repeated emergence of similar adaptive strategies among taxonomically distinct species. This pattern is consistent with classical interpretations of xerophytic vegetation, in which anatomical specialization plays a central role in maintaining plant performance under restrictive environmental conditions (Fahn and Cutler, 1992; Evert, 2006).

Among the most recurrent responses identified in the reviewed literature, epidermal reinforcement and cuticular thickening appear to contribute not only to surface protection but also to the maintenance of hydraulic integrity under prolonged drought. Likewise, trichomes may provide multiple ecological benefits by modifying leaf boundary-layer dynamics, reducing excessive radiation exposure, and contributing to microclimatic regulation at the leaf surface (Smith et al., 1997; Chaves et al., 2003). These traits collectively illustrate how anatomical organization can influence plant water balance and stress tolerance beyond purely structural functions.

The frequent occurrence of compact mesophyll tissues and reduced intercellular spaces further suggests an adaptive shift toward conservative resource-use strategies. Such anatomical arrangements are commonly associated with sclerophyllous vegetation and have been interpreted as structural adjustments that increase tissue resistance and reduce vulnerability to environmental stress (Rossatto et al., 2015). Similar patterns observed in species distributed across both Restinga and Cerrado environments (Aguiar-Dias et al., 2012) indicate that comparable environmental pressures may promote analogous anatomical solutions despite differences in habitat characteristics.

The ecological significance of tissue sclerification and lignification extends beyond drought resistance alone. These traits increase structural durability, enhance mechanical protection, and may contribute to longer tissue lifespan under conditions of nutrient scarcity and environmental instability (Ackerly, 2004). Such patterns are consistent with the fast-slow plant economics spectrum proposed by Reich (2014), in which species subjected to chronic stress tend to prioritize resource conservation, structural investment, and long-term persistence over rapid growth and resource acquisition.

Taken together, the reviewed studies indicate that xeromorphic anatomy functions as an integrated resistance strategy that links structural organization to ecological performance. The recurrent association of reinforced tissues, conservative functional characteristics, and enhanced environmental tolerance suggests that anatomical adaptations play a central role in mediating plant responses to environmental filtering processes across Brazilian dry ecosystems. Moreover, considering projections of increasing drought frequency and climatic variability in tropical regions, these structural traits may become increasingly important for maintaining vegetation resilience under future environmental change.

4.2 Functional traits and conservative ecological strategies

The reviewed studies suggest that functional traits play a central role in mediating plant responses to environmental constraints in Brazilian dry ecosystems. By influencing resource acquisition, physiological regulation, stress tolerance, and competitive performance, functional traits provide an important framework for understanding how species persist under conditions of seasonal drought, nutrient limitation, and recurrent disturbance (Díaz and Cabido, 2001; Violle et al., 2007). Across the analyzed literature, conservative ecological strategies emerged as one of the most consistent adaptive patterns associated with environmental resistance.

The recurrent occurrence of reduced specific leaf area, increased sclerophylly, and elevated tissue density indicates a widespread tendency toward resource-conservative strategies in environments characterized by chronic stress. These traits are closely aligned with the global leaf economics spectrum proposed by Wright et al. (2004), which predicts that species inhabiting resource-limited environments tend to prioritize tissue durability, resource conservation, and long-term persistence over rapid growth and resource acquisition. In this context, functional traits can be interpreted not merely as isolated characteristics but as components of integrated ecological strategies shaped by long-term selective pressures.

The Cerrado provides a particularly relevant example of how multiple environmental filters interact to shape plant functional diversity. Seasonal water limitation, acidic nutrient-poor soils, and recurrent fire regimes act simultaneously, favoring species capable of balancing hydraulic resistance, structural protection, and regenerative capacity (Haridasan, 2008). As proposed by Hoffmann et al. (2012), plant functional traits play a decisive role in determining ecological thresholds between savanna and forest formations, highlighting their importance in regulating vegetation structure and ecosystem dynamics.

The reviewed literature also emphasizes the close relationship between structural traits and physiological performance. Functional mechanisms such as hydraulic regulation, temporary water storage, and reduced transpirational demand appear to operate in conjunction with anatomical adaptations, forming integrated response systems that enhance plant persistence under water-limited conditions. This coordination between structure and function suggests that successful adaptation to drought depends not on individual traits alone, but on the interaction among multiple morphological, physiological, and ecological mechanisms that collectively improve resistance to environmental stress.

A notable pattern emerging from the reviewed studies is the recurrent occurrence of similar functional strategies across the *Cerrado*, *Caatinga*, and *Restinga* ecosystems.

Although these biomes differ substantially in climatic regimes, soil properties, and disturbance histories, they are characterized by environmental constraints that favor resource-conservative syndromes. This convergence suggests that environmental filtering acts as a powerful driver of functional trait selection, promoting analogous adaptive solutions in distinct ecological contexts. Such patterns reinforce the broader ecological principle that similar selective pressures can lead to the emergence of comparable functional strategies across geographically and environmentally distinct systems.

From a broader perspective, the predominance of conservative functional traits may have important implications under future climate-change scenarios. Projected increases in drought frequency, temperature extremes, and environmental disturbance are expected to intensify selective pressures in many tropical ecosystems. Consequently, traits associated with hydraulic safety, resource conservation, and stress tolerance may become increasingly important determinants of vegetation resilience, species persistence, and ecosystem stability in Brazilian dry environments. Understanding how these functional strategies respond to ongoing climatic change, therefore, represents a critical challenge for future ecological research and conservation planning.

4.3 Adaptive convergence among Brazilian dry ecosystems

One of the most consistent patterns emerging from the reviewed studies was the recurrent occurrence of adaptive convergence among plant species inhabiting distinct Brazilian dry ecosystems. Similar anatomical and functional traits were repeatedly observed in taxonomically unrelated species exposed to comparable environmental constraints, suggesting that environmental filtering acts as a major driver of trait selection across the *Cerrado*, *Caatinga*, and *Restinga* biomes. Rather than reflecting shared evolutionary history alone, these similarities indicate that chronic environmental stress can promote the independent emergence of analogous adaptive solutions in different ecological contexts.

The convergence of traits such as epidermal reinforcement, tissue compactness, vascular modifications, and increased sclerophylly highlights the importance of structural investment for plant persistence under restrictive conditions. Similar patterns have been reported in other stressful tropical environments, where environmental factors frequently exert stronger influences on functional trait expression than phylogenetic relatedness. For example, Kuster et al. (2018) documented substantial anatomical convergence in stems and roots of *Restinga* species distributed across coastal sandy plains, demonstrating how environmental pressures can shape

structural organization across diverse taxonomic groups. Likewise, Richetti et al. (2024) reported hydraulic and structural adjustments in species inhabiting coastal dunes in southern Brazil, reinforcing the role of convergent adaptation in promoting environmental resistance under conditions of drought, salinity, intense irradiance, and nutrient scarcity.

The reviewed literature also emphasizes the importance of phenotypic plasticity as a complementary mechanism underlying adaptive convergence. This pattern is particularly evident in *Restinga* ecosystems, where plants experience highly heterogeneous environmental conditions characterized by irregular water availability, saline influence, intense solar radiation, nutrient-poor substrates, and substrate instability (Scarano, 2002; Scarano et al., 2009). Under such conditions, the ability to modify structural and functional traits in response to local environmental variation may be as important as the possession of fixed adaptive characteristics. Consequently, phenotypic plasticity can enhance ecological resilience by allowing species to maintain performance across diverse and fluctuating microhabitats.

Evidence from studies involving *Eugenia* species, *Myrcia guianensis*, and *Schinus terebinthifolia* supports this interpretation. Variations in epidermal organization, mesophyll architecture, and vascular tissues observed across different environmental settings demonstrate that adaptive responses often involve a combination of conserved traits and environmentally induced plasticity (Alvarez; Silva, 2012; Donato; Morretes, 2007; Lemos et al., 2020; Melo Jr. et al., 2019). These findings suggest that adaptive convergence in Brazilian dry ecosystems is not restricted to the repeated occurrence of specific traits, but also includes the capacity of species to adjust their structural organization in response to changing environmental conditions.

From a broader ecological perspective, the recurrence of similar adaptive syndromes across the *Cerrado*, *Caatinga*, and *Restinga* reinforces the idea that comparable environmental pressures can generate analogous functional outcomes despite substantial differences in climate, soil characteristics, vegetation structure, and disturbance regimes. The repeated association of structural reinforcement, conservative resource-use strategies, hydraulic regulation, and phenotypic plasticity indicates that environmental stress exerts a strong selective influence on plant functional diversity. These patterns provide evidence that adaptive convergence represents an important mechanism contributing to ecosystem resilience and vegetation persistence across Brazilian dry environments.

Understanding these convergent responses may

become increasingly important under future climate-change scenarios. Projected increases in drought intensity, temperature extremes, and environmental instability are expected to strengthen selective pressures across tropical ecosystems. Consequently, identifying the traits and adaptive syndromes that consistently confer environmental resistance may improve predictions of species vulnerability, vegetation dynamics, and ecosystem resilience in a rapidly changing climate.

4.4 Drought-avoidance mechanisms in the *Caatinga* biome

The reviewed studies indicate that drought-avoidance strategies constitute a fundamental component of plant persistence in the *Caatinga* biome, one of the most water-limited environments in South America. Unlike adaptive responses primarily based on structural resistance to prolonged stress, drought-avoidance mechanisms reduce exposure to unfavorable conditions by minimizing water loss and optimizing the use of available water resources during periods of scarcity. In this context, seasonal deciduousness, succulence, and temporary water-storage structures emerged as some of the most recurrent adaptive responses identified in the reviewed literature.

The ecological significance of these strategies is closely linked to the pronounced climatic seasonality that characterizes the *Caatinga*. As highlighted by Prado (2003) and Silva et al. (2017), this semiarid ecosystem experiences highly irregular rainfall patterns, prolonged drought periods, and elevated evapotranspiration rates, creating strong selective pressures on plant water balance. Under such conditions, deciduousness represents an efficient mechanism for reducing transpirational demand during the dry season, allowing plants to temporarily suspend photosynthetic activity and conserve water until favorable conditions return. This phenological adjustment illustrates how temporal regulation of resource use can be as important as structural adaptation for survival in drought-prone environments.

Water-storage tissues and succulence provide an additional mechanism for coping with environmental unpredictability. By accumulating water during periods of greater availability, plants can maintain physiological activity during subsequent dry intervals, thereby buffering the effects of seasonal water deficits. These traits are particularly advantageous in environments where precipitation is not only limited but also highly variable in space and time. Their recurrent occurrence among *Caatinga* species highlights the importance of physiological buffering mechanisms in maintaining plant performance under fluctuating hydric conditions.

The reviewed literature further suggests that drought avoidance in the *Caatinga* is rarely achieved through a

single trait. Instead, plant persistence appears to depend on the integration of phenological, anatomical, and physiological responses operating at multiple organizational levels. Santos et al. (2014) emphasized that drought-tolerant species frequently exhibit coordinated adjustments involving tissue organization, water-use regulation, and stress tolerance mechanisms. Similarly, Souza et al. (2023) demonstrated that *Caatinga* tree species combine structural modifications, stomatal regulation, and conservative resource-use strategies to cope with restricted water availability. These findings reinforce the idea that successful adaptation to semiarid environments results from the interaction of complementary mechanisms rather than isolated traits.

From a broader ecological perspective, the prevalence of drought-avoidance strategies underscores the importance of adaptive flexibility in shaping vegetation dynamics within the *Caatinga*. The capacity to regulate water use, temporarily reduce physiological activity, and exploit short periods of resource availability contributes significantly to ecosystem resilience under recurrent climatic stress. This adaptive flexibility may become increasingly important under future climate-change scenarios, as projections indicate greater drought frequency, higher temperatures, and increased climatic variability across semiarid regions. Understanding how these mechanisms influence species persistence and community composition will therefore be essential for predicting vegetation responses and supporting conservation strategies in one of Brazil's most climate-sensitive ecosystems.

4.5 Fire-related adaptations in Cerrado vegetation

Fire emerged as one of the most important environmental drivers influencing plant functional diversity in the *Cerrado*, acting alongside seasonal drought, nutrient limitation, and climatic variability to shape vegetation structure and species persistence. The reviewed studies indicate that fire-related adaptations are not isolated responses to disturbance, but rather components of broader ecological strategies that enable plants to cope with multiple and interacting environmental stressors.

The ecological importance of fire in the *Cerrado* has been widely documented. As proposed by Miranda et al. (2002), recurrent fire events influence vegetation structure, nutrient cycling, species distribution, and community dynamics, functioning as a major environmental filter in neotropical savannas. From an evolutionary perspective, Simon et al. (2009) demonstrated that numerous *Cerrado* plant lineages have evolved adaptive traits associated with recurrent fire regimes, highlighting the long-term role of disturbance in

shaping the functional composition of these ecosystems.

The interaction between fire and drought appears to be particularly important in determining plant persistence. Seasonal water limitation can increase vegetation flammability and intensify fire impacts, while recurrent fires may further constrain plant establishment and growth. Consequently, species capable of simultaneously tolerating hydraulic stress and recovering from biomass loss are likely to be favored under these conditions. This interaction reinforces the concept that environmental filtering in the *Cerrado* operates through multiple selective pressures acting in combination rather than independently.

Among the most recurrent adaptive traits identified in the reviewed literature, bark thickening, underground storage organs, and resprouting capacity play key roles in enhancing resistance and resilience to disturbance. Thick bark provides thermal insulation during fire events, reducing damage to vital tissues and increasing post-fire survival. Underground storage organs contribute to resource conservation and facilitate regeneration following disturbance, while resprouting capacity allows rapid vegetative recovery after biomass loss. Together, these traits represent integrated adaptive syndromes that combine structural protection, regenerative capacity, and conservative resource-use strategies.

Beyond their role in post-disturbance recovery, these characteristics contribute to ecosystem stability by maintaining plant persistence under highly dynamic environmental conditions. The coexistence of drought-related and fire-related adaptations suggests that *Cerrado* species are shaped by a complex selective environment in which resistance to one stressor often complements

tolerance to others. Such integration between anatomical, physiological, and regenerative traits highlights the multidimensional nature of adaptation in tropical savanna ecosystems.

Understanding these adaptive mechanisms is becoming increasingly important under future climate-change scenarios. Projections of rising temperatures, more frequent drought events, and altered fire regimes suggest that interactions between hydraulic stress and disturbance may intensify in many tropical regions. Consequently, traits associated with fire resistance, regeneration, and resource conservation may become even more important determinants of vegetation resilience and ecosystem functioning. Future studies integrating plant hydraulics, fire ecology, and climate-change responses will be essential for improving predictions of vegetation dynamics and conservation outcomes in the *Cerrado*.

These findings reinforce the ecological significance of drought and fire as interacting environmental filters that shape plant functional diversity in Brazilian savannas. The recurrent occurrence of protective structures, regenerative mechanisms, and conservative functional strategies highlights the adaptive complexity of *Cerrado* vegetation and underscores the importance of integrated approaches for understanding plant persistence under changing environmental conditions.

The integrative relationships among environmental stressors, anatomical adaptations, functional responses, and ecological strategies identified in the reviewed studies are summarized in Figure 7.

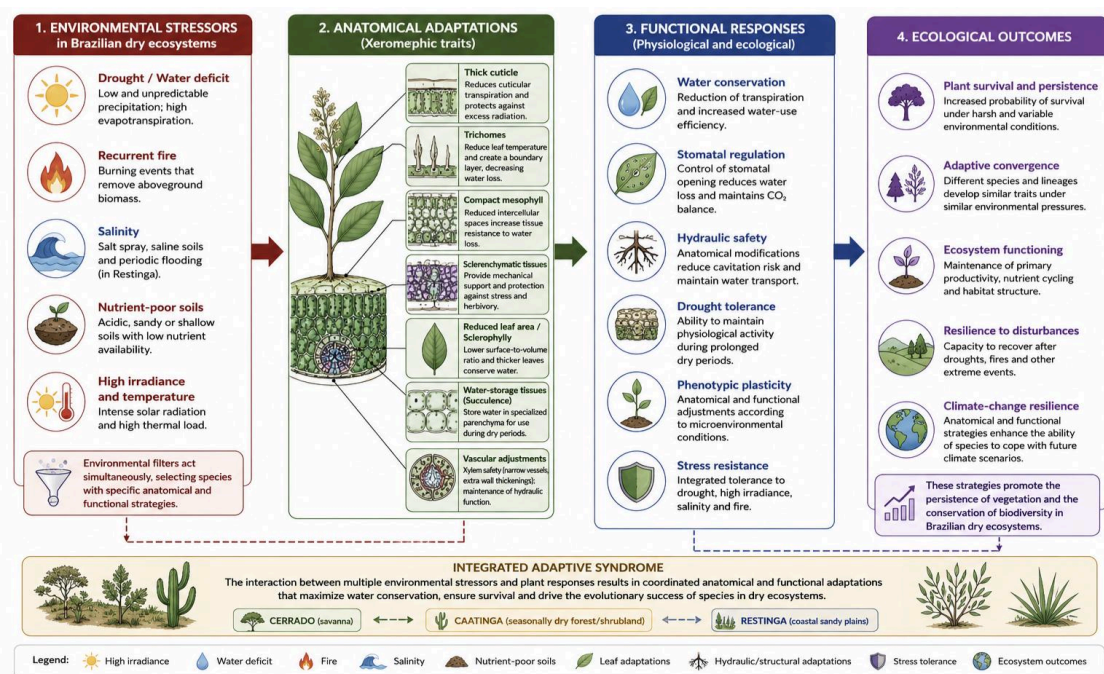


Figure 7. Conceptual model summarizing the relationships among environmental stressors, anatomical adaptations, functional responses, and ecological strategies associated with plant persistence in Brazilian dry ecosystems. Source: Author (2026).

4.6 Research gaps, methodological limitations, and future perspectives

The descriptive bibliometric exploration revealed a substantial increase in scientific interest in ecological anatomy, functional ecology, and plant responses to environmental stress over the last decade. The predominance of descriptors such as functional traits, xeromorphism, structural plasticity, and drought tolerance indicates a growing integration of anatomical, physiological, and ecological approaches in tropical plant science.

This trend reflects the increasing importance of trait-based ecology for understanding plant performance, environmental filtering, and ecosystem functioning under climate variability. The adoption of standardized protocols for functional trait assessment (Cornelissen et al., 2003) has further contributed to improving comparability among ecological studies and fostering integrative approaches linking structural organization, physiological regulation, and environmental stress responses.

Despite these advances, several methodological limitations should be considered when interpreting the findings of this review. No formal review protocol was registered before study selection. Because this study was conceived as an integrative qualitative review rather than as a prospective systematic review intended for

quantitative evidence synthesis, protocol registration was not performed before the search process. Nevertheless, this limitation may reduce methodological transparency and should be considered when interpreting the results.

A simplified methodological quality appraisal was conducted; however, no standardized risk-of-bias instrument specifically designed for ecological anatomical studies was available. Therefore, the assessment should be interpreted as an exploratory evaluation of study quality rather than a formal evidence-certainty analysis.

An additional limitation concerns the supplementary use of Google Scholar, for which no predefined stopping criterion regarding the number of pages or records screened was established, potentially reducing the reproducibility of this stage of the search process. Consequently, the results should be interpreted as a qualitative synthesis of the available literature rather than as a systematic evaluation of evidence strength.

Additional limitations are associated with the characteristics of the available literature itself. Publication bias may be present, as studies reporting significant or ecologically relevant adaptive responses are more likely to be published and indexed in scientific databases. Likewise, language bias may have occurred because the search strategy prioritized studies published in English and Portuguese, potentially excluding relevant evidence available in other languages. Furthermore, the included

studies exhibited substantial methodological heterogeneity regarding study design, taxonomic groups, ecosystems investigated, anatomical traits measured, and ecological approaches employed. Differences in study objectives, sampling designs, taxa investigated, and response variables prevented direct statistical comparisons and precluded the application of quantitative synthesis methods, including meta-analysis and effect-size estimation. As a result, the conclusions presented here are based on a qualitative integration of the available evidence.

The relatively small number of eligible studies ($n = 29$) represents an additional constraint on the generalization of the identified patterns. Although the selected publications provided valuable insights into plant adaptive strategies under water-limited conditions, the restricted dataset may not fully capture the ecological diversity and functional variability present across the *Cerrado*, *Caatinga*, and *Restinga* ecosystems. Consequently, the observed patterns should be interpreted as representative of the currently available literature rather than as definitive ecological generalizations applicable to all species and environmental contexts.

Important research gaps also remain evident in the analyzed literature. Most investigations focused predominantly on leaf anatomical characteristics, whereas comparatively fewer studies addressed root systems, stem hydraulic architecture, xylem functionality, and integrative whole-plant physiological responses. This imbalance reveals a strong bias toward aboveground analyses and highlights the need for greater investigation of belowground adaptations associated with water acquisition, hydraulic regulation, and environmental resistance in tropical dry ecosystems.

Moreover, descriptive approaches continue to predominate, with limited integration among anatomical, physiological, ecological, and experimental analyses conducted under natural environmental conditions. Although structural characteristics such as epidermal reinforcement, trichome occurrence, and tissue compactness are frequently interpreted as adaptive responses to drought, relatively few studies have quantitatively evaluated their ecological effectiveness and physiological performance under contrasting stress scenarios.

The literature also remains fragmented among ecosystems, taxonomic groups, and local environmental conditions. Comparative and multi-biome investigations integrating the *Cerrado*, *Caatinga*, and *Restinga* ecosystems are still relatively scarce, despite their importance for evaluating adaptive convergence under similar environmental pressures. Expanding comparative approaches across Brazilian dry ecosystems may

substantially improve current understanding of how structural and functional characteristics mediate plant persistence under chronic drought, salinity, nutrient limitation, and recurrent disturbance regimes.

Future investigations should therefore prioritize integrative and multidisciplinary approaches combining ecological anatomy, plant hydraulics, ecophysiology, functional ecology, climate modeling, and evolutionary perspectives. The incorporation of emerging techniques such as hydraulic conductivity analyses, remote sensing, phenotypic plasticity assessment, and molecular approaches may substantially improve our understanding of adaptive mechanisms associated with environmental resistance. Furthermore, studies evaluating vegetation responses under future climate-change scenarios are becoming increasingly important, particularly considering projections of intensified drought frequency, elevated temperatures, and increasing disturbance severity in tropical ecosystems.

Overall, the reviewed studies suggest that anatomical organization, functional strategies, and ecological responses are strongly interconnected in plant species inhabiting Brazilian dry ecosystems. However, the methodological limitations of the review, the heterogeneity of the available literature, and the restricted number of eligible studies indicate that these conclusions should be interpreted with caution. Future research integrating quantitative approaches, long-term monitoring, and multi-biome comparisons will be essential for advancing our understanding of plant adaptation, ecosystem resilience, and vegetation responses to ongoing environmental change.

5. Conclusion

The reviewed studies suggest that plant species inhabiting Brazilian dry ecosystems exhibit coordinated anatomical and functional strategies that contribute to persistence under chronic environmental stress. Across the *Cerrado*, *Caatinga*, and *Restinga* ecosystems, recurrent traits such as epidermal reinforcement, tissue compactness, trichome occurrence, sclerophylly, and water-storage capacity were consistently associated with responses to seasonal drought, elevated irradiance, nutrient limitation, salinity, and recurrent disturbance regimes.

The analyzed literature indicates that anatomical organization, functional traits, and ecological strategies are closely interconnected. Conservative resource-use patterns, structural reinforcement, phenotypic plasticity, and adaptive convergence emerged as important mechanisms allowing plant species to cope with environmental constraints across distinct ecological contexts. Although the three ecosystems differ

substantially in climate, soil characteristics, and disturbance regimes, similar environmental pressures appear to promote comparable adaptive responses, highlighting the role of environmental filtering in shaping plant functional diversity.

Distinct environmental drivers were particularly important within each biome. In the Cerrado, the interaction between drought and recurrent fire favored species exhibiting structural protection and regenerative capacity. In the *Caatinga*, drought-avoidance mechanisms such as deciduousness and temporary water storage contributed to persistence under semiarid conditions. In *Restinga* ecosystems, environmental heterogeneity was associated with elevated morphoanatomical plasticity and adaptive flexibility.

The integration of ecological anatomy, functional ecology, ecophysiology, and evolutionary perspectives has substantially improved our understanding of plant adaptation in tropical dry environments. However, important knowledge gaps remain, particularly regarding belowground traits, hydraulic architecture, long-term ecological responses, and quantitative evaluations of adaptive effectiveness under changing environmental conditions.

Because this review was based on a qualitative synthesis of a relatively small and methodologically heterogeneous body of literature, its conclusions should be interpreted as an integration of the currently available evidence rather than as quantitatively validated ecological patterns. Future studies incorporating comparative multi-biome approaches, long-term monitoring, experimental research, and quantitative synthesis methods will be essential for advancing our understanding of plant adaptation, ecosystem resilience, and vegetation responses to ongoing climate change in Brazilian dry ecosystems.

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Author's Contributions

The author conceived and designed the study, collected and analyzed the data, interpreted the results, drafted the manuscript, and approved the final version for publication.

Ethics

The author declares that this manuscript complies with current ethical standards. The study did not involve experimentation on humans or animals. All data used were obtained and utilized in accordance with applicable standards and guidelines. The author assumes responsibility for clarifying and resolving any ethical issues that may arise following publication.