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PANICUM MAXIMUM(JACQ.): INTEGRATIVE REVIEW

PANICUM MAXIMUM (JACQ.): REVISÃO INTEGRATIVA

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ABSTRACT

The Poaceae family represents one of the most important families of higher plants, with the genus Panicum being particularly noteworthy. The species *Panicum maximum* Jacq. or *Megathyrsus maximus*(Guinea grass) is widely used in animal production and has pharmacological potential still under exploration. This integrative review presents a comprehensive analysis of the botanical, ecophysiological, pharmacognostic, and phytoremediation aspects of this forage species as a natural product. Using a systematic search methodology in indexed databases (PubMed, Scopus, Web of Science, and Science Direct), recent studies on the following were identified and analyzed: (1) definition, taxonomy, and morphological characteristics; (2) phytochemical composition and biological activities; (3) fundamental physiological processes including photosynthesis, spectral reflection, and water dynamics; (4) ecophysiological responses to environmental factors; (5) mechanisms of phytoremediation potential. The results indicate that *Panicum maximum* presents metabolic and biochemical characteristics relevant for applications in the development of phytopharmaceuticals, agricultural sustainability, and phytoremediation. Significant gaps remain in investigations of phytochemical synergy, molecular mechanisms of pharmacological action, and toxicological safety studies in preclinical and clinical models. Its remarkable action stands out in models for phytoremediation and phytorecovery in arid soils, as well as in soils contaminated with heavy metals and pesticides (some of them endocrine disruptors and pro-carcinogens). Future perspectives point to research in genetic improvement and plant biotechnology of this important species, with indispensable participation and application during periods of geoclimatic instability on the planet.

Keywords: *Panicum maximum* Jacq., *Megathyrsus maximus*, Phytochemistry, Ecophysiology, Phytoremediation.

RESUMO

A família Poaceae representa uma das mais importantes famílias de plantas superiores, com destaque para o gênero Panicum. A espécíe *Panicum maximum* Jacq. ou *Megathyrsus maximus* (capim-colonião) é amplamente utilizada em produção animal e com potencial farmacológico ainda em exploração. Esta revisão integrativa apresenta uma análise abrangente dos aspectos botânicos, ecofisiológicos, farmacognósticos e fitoremediadores enquanto produto natural desta espécie forrageira. Utilizando-se uma metodologia sistemática de busca em bases indexadas (PubMed, Scopus, Web of Science e Science Direct), foram identificados e analisados estudos recentes sobre: (1) definição, taxonomia e características morfológicas; (2) composição fitoquímica e atividades biológicas (3) processos fisiológicos fundamentais incluindo fotossíntese, reflexão espectral e dinâmica hídrica; (4) respostas ecofisiológicas a fatores ambientais; (5) mecanismos do potencial fitorremediador. Os resultados indicam que *Panicum maximum* apresenta características metabólicas e bioquímicas relevantes para aplicações em desenvolvimento de fitofármacos, sustentabilidade agrícola e fitoremediação. Lacunas significativas permanecem nas investigações de sinergia fitoquímica, mecanismos moleculares de ação farmacológica e estudos de segurança toxicológica em modelos pré-clínicos e clínicos. Sua notável ação destaca-se em modelos para fitoremediação e fitorecuperação em solos áridos, bem como em solos contaminados com metais pesados e pesticidas (alguns deles disruptores endócrinos e pró-carcinogênicos). As perspectivas futuras apontam para pesquisas em melhoramento genético e biotecnologia vegetal desta importante espécie com indispensável participação e aplicação para o período de instabilidade geoclimática do planeta.

Palavras-chave: *Panicum maximum* Jacq., *Megathyrsus maximus,* Fitoquímica, Ecofisiologia, Fitoremediação.

INTRODUCTION

The Poaceae (Gramineae) family represents one of the most important families of monocotyledonous plants, comprising approximately 12,000 species distributed across 1,600 genera, found in virtually all terrestrial ecosystems (Grass Phylogeny Working Group, 2015). Within this diversity, the genus Panicum stands out for its high productive potential, ecological adaptability, and nutritional characteristics for forage use.

*Panicum maximum*Jacq., currently reclassified by many taxonomists as Megathyrsus maximus, is popularly known in Brazil as guinea grass. The species has several cultivars widely used in livestock farming that have acquired their own popular names, including:The most common names include: Guinea grass (the most traditional name and original species), Mombasa grass, Tanzania grass, Massai grass, Zuri grass, Tamani grass, Aruana grass, Kenia grass, Tobiatã grass (Giussani et al., 2001; Aliscioni et al., 2003; Simon; Jacobs, 2003). Specifically, Panicum maximum Jacq. (Guinea grass, Massai grass, or guineagrass), originating from the African continent, has become a species of great relevance in tropical and subtropical livestock systems (Jank et al., 2014).

*Panicum maximum*Jacq., also popularly known as Guinea grass, green grass, or Mombasa grass (depending on the cultivar), is a perennial grass of great zootechnical importance in Tropical America, Asia, and Africa. According to EMBRAPA (Jank et al., 2021), these grasses are of African origin and represent one of the pillars of Brazilian livestock farming, valued for their high productivity and excellent nutritional value.

Traditional populations in Tropical America, Africa, and Asia use P. maximum to treat: general inflammations, feverish states, gastrointestinal disorders, wounds and burns, microbial infections, and rheumatic pains (Doss et al., 2011). Recent ethnopharmacological scientific validations confirm many of these ethnobotanical uses, with promising prospects for the development of phytopharmaceuticals (WHO, 1992; BR, ANVISA, 2017). Beyond its well-documented agricultural importance, contemporary studies have highlighted the existence of secondary metabolites in Panicum maximum with potential biological and pharmacological activity, such as phenols, flavonoids, tannins, and essential oils, which demand further investigation into their mechanisms of action and therapeutic applicability (Silva et al., 2020; Santos; Oliveira, 2021).

The proposed mechanisms of action for P. maximum extracts include: Inhibition of pro-inflammatory enzymes (COX-1, COX-2) through phenolic compounds; Scavenging of free radicals by flavonoids and tannins; Inhibition of microbial growth by lipid peroxidation and protein denaturation; Inhibition of parasites through direct cytotoxic effect; Modulation of immune response via activation of macrophages and neutrophils, cytotoxic to HeLa cell lines (Table 1):

Table 1: Biological Activities Studied.

Biological Activity	**Number of Studies**	**Parts of the Plant**	**Type of Statement**	**Main Result**
Antifungal	6	Leaves, stems	Ethanol	Active in A. tamarii (15mm)
Anti-inflammatory	5	Leaves, roots	Ethanolic, aqueous	57-67% reduction in inflammation
Antioxidant	8	Leaves, stems	Ethanol, fractions	Variable IC50, active
Antimicrobial	4	Sheets	Ethanol	Active against bacteria
Antimalarial	2	Roots	Ethanolic, aqueous	Active against P. falciparum
Antiparasitic	2	Roots	Ethanol	Active against L. major
Analgesic	3	Leaves, roots	Ethanol	Analgesia 57-88%
Cytotoxic/ Anticancer	3	Sheets	Hexane fractions	Active in HeLa cells
Hepatoprotective	2	Sheets	Aqueous	Protection against CCl_4

Source: Adapted from Kanife et al. (2012); Okokon et al. (2013).

Additionally, the ability of these plants to absorb, translocate, and accumulate heavy metals and contaminants in degraded environments represents an opportunity for applications in phytoremediation, a technology that is still little explored for this species (Pires et al., 2019).

In this context, the present integrative scientific review aims to consolidate current knowledge about grasses (Poaceae) with an emphasis on Panicum maximum, addressing multidisciplinary aspects that converge on Botany, Ecophysiology, Pharmacognosy, and Phytoremediation. The scientific justification for this review lies in the need to integrate fragmented information from different fields of knowledge, facilitating the identification of gaps and opportunities for future research in the face of rapid and dramatic climate change.

METHODOLOGY

The searches were conducted in the following indexed databases: (1) PubMed/MEDLINE (National Library of Medicine); (2) Scopus (Elsevier); (3) Web of Science (Clarivate Analytics); (4) ScienceDirect (Elsevier). The coverage period included studies published between January 2010 and June 2026, prioritizing publications from the last 10 years to ensure contemporary scientific relevance. Additionally, collections of theses and dissertations on platforms such as ProQuest Dissertations & Theses Global and repositories of Brazilian universities were consulted.

The search strategy was developed using the Health Sciences Descriptors (DeCS) from BIREME and Medical Subject Headings (MeSH) when appropriate, associated using Boolean operators AND, OR, and NOT. The following search strings were used (with variations in different databases according to specific syntax). The following Boolean search equations were applied, shown in Table 1:

Table 1: Equations of the Boolean search strategy.

No.	Boolean Equation	Results	Selected
1	("Panicum maximum" OR "Megathyrsus maximus") AND (phytochemistry OR chemical composition OR "secondary metabolites"	15	12
2	(Poaceae OR grasses OR gramineae) AND (photosynthesis OR C4; physiology OR ecophysiology; OR physiological OR ecophysiological OR physiology OR "photosynthetic rate" OR "water use efficiency" OR "light absorption" OR "stomatal conductance")	42	24
3	(phytoremediation) AND (grasses OR Poaceae) AND (heavy metals) OR phytoextraction OR phytoaccumulation OR phyto-remediation) AND (grasses OR Poaceae OR "Panicum" OR grass*) AND ("heavy metals" OR cadmium OR chromium OR lead OR contamination OR pollution)	31	19
4	("Panicum maximum") AND (ecophysiology OR drought stress OR "salt stress" OR "water stress" OR "temperature stress" OR "environmental stress" OR adaptation)	12	8
5	(Poaceae OR grasses) AND (taxonomy OR taxonomic OR Panicoideae OR Paniceae) AND (phylogeny OR phylogenetic OR "molecular phylogeny" OR "phylogenetic analysis")	18	11

Source: *Prepared by the Authors.*

The following were included: (i) articles in Portuguese, English, and Spanish; (ii) experimental studies, case studies, narrative reviews, and book chapters; (iii) publications in journals indexed in the cited databases; (iv) works addressing Poaceae, Panicum/Megathyrsus, grass physiology, phytopharmacology, phytoremediation, and chemical composition.

The following were excluded: (i) duplicate articles; (ii) unpublished and unindexed grey literature; (iii) studies exclusively on genomics without phenotypic data; (iv) publications prior to 2012 (with the exception of classics relevant to historical context); (v) articles in languages not covered; (vi) inaccessibility (publications without full text or informative abstract available); (vii) lack of methodological rigor in studies with inadequate experimental design or lack of methodological detail.

This review was prepared in accordance with international guidelines following recommendations from: PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), AACODS Checklist (Authority, Accuracy, Coverage, Objectivity, Currency, Significance), GRADE (Grading of Recommendations Assessment, Development and Evaluation), and EQUATOR Network Guidelines. Methodological quality was assessed according to criteria appropriate for the type of study (JADAD for clinical trials, STROBE for observational studies, CASP for qualitative studies).

Of the total records retrieved, the primary Boolean search yielded 154 articles and book chapters, totaling 97 articles, plus those from the primary and secondary Boolean searches. Given the heterogeneity of studies (different species, models, outcomes), a formal meta-analysis was not appropriate. A narrative synthesis was performed, organizing results by thematic topic. Each section of the review integrates findings from multiple studies, discussing: agreement or disagreement between studies, possible causes of variation, strength of evidence, and practical implications.

This is, therefore, an integrative systematic review of the scientific literature with a qualitative approach associated with a narrative synthesis of the findings.

RESULTS

The trend showed a gradual increase in publications, with a peak in research on Pani between 2018 and 2020.*wa maximum*JaqwThe geographical distribution of published studies showed Latin America predominating (25%), followed by Europe: 23%, Africa 19%, and Asia 15%. Brazil represents approximately 15% of the Latin American sample, suggesting the regional importance of P. maximum and its cultivars (Table 1):

Table 1: Studies on *P. maximum* by Cultivar/Accession

Cultivar/Accession	Number of Studies	Topics
Panicum maximum(general, unspecified)	12	Phytochemistry, pharmacology, taxonomy
cv. Mombasa	5	Physiology, phytoremediation, production
cv. Massai	8	Phytoremediation (Cd), ecophysiology

Wild/collected	3	Phytoremediation, phytochemistry
Not specified	15	Several
TOTAL	**43**	

Source: *Built by the Authors.*

There is a predominance of basic research in publications, whose contributions have become invaluable for the present period of climate uncertainties and abrupt degeneration of nature with contamination of natural sources, also through persistent chemical residues from wars and pesticides, making it necessary to provide a clear response to the environmental demand in the search for species with phytoremediation and bioremediation potential (Piao et al., 2010; 2014).

This plant species stands out for its high biomass productivity, high nutritional value, and ability to adapt to different edaphoclimatic conditions. In addition to its use as forage, recent studies demonstrate significant medicinal potential, with anti-inflammatory, antifungal, antiparasitic, cytotoxic activities against the HeLa cancer cell line, antioxidant and immunomodulatory properties, as well as phytoremediation capabilities (Vitasse et al., 2015; 2018; Varricchio et al., 2026).

DEFINITION AND TAXONOMIC CLASSIFICATION

Poaceae is a family of monocotyledonous plants characterized by alternate leaves with blade and sheath, inflorescences in spikes or panicles, and reduced flowers (florets) protected by glumes and lemmas. The family is divided into several subfamilies, with Panicoideae being one of the most important, containing approximately 3,300 species in 206 genera (Edwards; Smith, 2010).

The Poaceae family of monocotyledons, predominantly herbaceous, is characterized by the presence of very reduced flowers organized in structures called spikelets. Historically designated Gramineae, the family was officially renamed Poaceae for the first time in 1976, in accordance with the International Rules of Botanical Nomenclature (now the International Code of Nomenclature for Algae, Fungi and Plants) (ICNAFP, 2018).

Taxonomic Reclassification of *Panicum maximum*

The classification and taxonomic position of *Panicum maximum* Jacq. is shown inTable 2.The specific epithet "maximum" (Latin for "maximum") alludes to the size of the plants. From a phylogenetic point of view, recent molecular analyses using DNA sequencing (GPWG, 2015; Kellogg, 2015) have confirmed that Poaceae constitutes a well-defined monophyletic clade within the order Poales, with its common ancestor estimated to be approximately 55 million years ago. The family is phylogenetically close to the families Cyperaceae (rushes) and Juncaceae (sea breams), sharing primitive monocotyledonous characteristics.

Molecular phylogenetic studies (Giussani et al., 2001; Aliscioni et al., 2003) have revealed that the genus Panicum L. is polyphyletic, leading to the segregation of several taxa into independent genera. *Panicum maximum* (Jacq.) was reclassified as *Megathyrsus maximus* by Simon and Jacobs in 2003, remaining transferred to this genus to the present (SORENG et al., 2017). However, the nomenclature Panicum maximum is still widely used in scientific and commercial literature.

Table 2: Taxonomic classification of *Megathyrsus maximus*.

Taxonomic Category	**Classification**
Kingdom	Plantae
Division	Magnoliophyta
Class	Liliopsida (Monocotyledons)
Order	Poales
Family	Poaceae (Gramineae)
Subfamily	Panicoideae
Tribe	Paniceae
Subtio	Melinidinae
Gender	Megathyrsus (Pilg.) BKSimon & SWLJacobs
Species	M. maximus (Jacq.) BKSimon & SWLJacobs

Source: Adapted from Giussani et al. (2001); Aliscioni et al. (2003); Simon; Jacobs (2003).

Regarding nomenclature and synonymy, Megathyrsus maximus has several scientific synonyms: *Urochloa maxima* (Jacq.) RDWebster; *Panicum maximum* Jacq.; *Panicum hirsutissimum* Steud. These multiple nomenclatures reflect the complexity of the taxonomic history of the genus Panicum and the importance of this species in botanical research. The species Panicum maximum has several botanical synonyms, the main ones being: *Panicum turgicum* Forssk., *Panicum obtusum subsp. maximum* (Jacq.) CA Gardner, and *Megathyrsus maximum* (Jacq.) BK Simon & SWL Jacobs. Vernacular names vary according to the geographical region: in African countries it is commonly called guineagrass or buffelgrass; in Brazil, capim-colonião, capim-massai, capim-de-colonião or capim-raiz roxa; in Portugal, capim-príncipe; in Asia, panic maximum or maximum panic (Jank et al., 2014).

Genetic Variability and Cultivars

*P. maximum*It exhibits great genetic variability expressed in several cultivars developed through selection and conventional genetic improvement. The main commercial cultivars include: (1) Tanzania: tall (150-180 cm), with high dry matter production and drought resistance; (2) Massai: medium (80-120 cm), with better digestibility and nutritional quality; (3) Mombasa: tall (150 cm), with high yield and tolerance to toxic aluminum in acidic soils; (4) Common Guinea Grass: traditional ecotype, with great adaptability; (5) Gema: variant with intermediate characteristics (Jank et al., 2018; Santos; Oliveira, 2021).

Essential Oils exhibit potential antimicrobial, antifungal, and insect-repellent activity (Costa et al., 2019). Phytochemical screenings detected the presence of alkaloids in *P. maximum* at varying concentrations (2-5% of dry weight). Identified alkaloids include gramine (an indole-alkaloid characteristic of Poaceae) at concentrations of 0.8-2.5 mg g^{-1}, in addition to other minor alkaloids. The presence of graminea has ecological implications such as protection against herbivory (Santos; Oliveira, 2021).

Studies in animal models, such as albino rats, under acute exposure to extracts (single dose of up to 2000 mg/kg orally) did not reveal mortality or signs of severe toxicity, suggesting a high LD_{50}. However, gaps in knowledge persist, including the need for studies of chronic toxicity, teratogenicity, mutagenicity, and evaluation of effects on the reproductive and endocrine systems (Okokon et al., 2013).

In a bacterial mutagenicity test (Ames Test) according to OECD Guideline 471, performed with strains of *Salmonella typhimurium* and *Escherichia coli*, the P. maximum extract showed no mutagenic potential. A micronucleus test in mammalian lymphocytes (OECD 487) also did not reveal a significant increase in the frequency of micronuclei after exposure to the extract at concentrations up to 100 μg mL^{-1}, concluding that there was no genotoxicity (Costa et al., 2021).

Potential adverse reactions in humans include: the presence of gramine (alkaloid) which may cause bronchoconstriction in sensitized or asthmatic individuals; potential allergic reaction in individuals with sensitivity to Poaceae (hay fever); tannins in high concentrations may cause dryness of the oral mucosa; possible interaction with anticoagulant medications through ion chelation mechanisms related to vitamin K. Further clinical investigation of these potential risks is recommended (Oliveira et al., 2021).

MORPHOLOGY

Grasses (Poaceae) have a characteristic morphology, with cylindrical stems (culms) possessing well-defined nodes and internodes. The leaves are distichous (arranged in two planes), with a distinct blade and sheath, and a membranous ligule. The root system is predominantly fibrous, fasciculated, adapted for efficient soil exploration and absorption of water and nutrients.

Megathyrsus maximus, *Panicum maximum* (Jacq.) is a perennial grass that grows in clumps, characterized by:

- Height: varies from 0.5 to 3.5 m, depending on the cultivar and environmental conditions.
- Culms: erect and robust, 5-10 cm in diameter.

- Nodes: densely hairy
- Sheaths: papillose and hairy, usually pubescent at the collar.
- Ligula: 4-6 mm in length
- Leaves: flat, laminar, bright green, 15-76 cm long by 1-3.5 cm wide, glabrous on the margins.
- Inflorescence: panicle with numerous branches and seeds 1-3 mm long.

Intraspecific morphological variability is considerable, with several cultivars exhibiting different growth patterns, leaf architecture, and biomass production. Cultivars such as "Mombasa" and "Massai" are widely used in animal production systems due to their superior agronomic performance.

- Root System

*P. maximum*It is characterized by having a fasciculated (fibrous), deep, and branched root system, typical of Poaceae. The roots are predominantly mesorhizal, with lateral branches that can penetrate deep into the soil (up to 2.0-2.5 meters under optimal conditions), giving the species a high capacity for water exploration in deep soil layers (Dias-Filho; Martuscello, 2015). Young roots are yellowish-white in color, becoming brownish with maturity. Optical microscopy reveals the presence of ectomycorrhizae associated with the roots, particularly fungi of the genera Rhizophagus and Funneliformis (Family Glomeraceae), which enhance the absorption of phosphorus and other minerals (Oliveira et al., 2019).

- Stem and Culm

The stem, called a culm in grasses, has a characteristic structure with well-defined internodes and nodes. In *P. maximum*, the culm is erect, subcylindrical, smooth or slightly villous, with a variable height depending on the cultivar (80-180 cm). The color is typically green, but may present reddish or purplish pigmentation at the base and upper nodes, this characteristic being important for differentiating cultivars. The internodes are hollow (central cavity filled with air or spongy parenchyma), facilitating growth in length and mechanical resistance to wind. The nodes (thickened at the base) have an axillary bud that, under certain conditions, gives rise to tillers (new lateral culms) that contribute to the development of the clump (Santos; Oliveira, 2021).

- Sheets

The leaves are arranged alternately-distichous along the culm. Structurally, each leaf comprises: (a) leaf blade (limbus) - linear to linear-lanceolate, with an obtuse to acuminate apex, serrated or finely serrated edges, variable length (30-90 cm) and width of 8-20 mm; (b) sheath - enveloping, green or pigmented, with or without trichomes; (c) ligule - membranous, shortly ciliate, with an approximate height of 2-4 mm. The adaxial (dorsal) surface is glabrous to pilose, while the abaxial (ventral) surface has more evident hairiness (Silva et al., 2020).

Microscopically, the leaf epidermis contains wavy epidermal cells with thickened walls, paracytic (collateral) stomata arranged in rows in the interveinal areas, uniseriate trichomes, and bulliform (large, empty) cells that provide leaf turgor and water retention mechanisms (Silva et al., 2020).

- Inflorescence and Reproductive Structures

The inflorescence of *P. maximum* is a terminal panicle, presenting primary and secondary branches (contracted panicle). Each branch bears spikelets (small structures containing reduced flowers), characteristic of Poaceae. The spikelets are lanceolate, dorsally compressed, 3-5 mm long, composed of glumes (basal bracts) and anthecia (floral structures). The spikelet typically contains 2 anthecia: a lower sterile one with a rudimentary flower, and an upper fertile one with a bisexual flower (Dias-Filho; Martuscello, 2015).

The stamens (number = 3) produce yellow anthers with abundant pollen production. The style is bifurcated with plumose stigmas (white to purplish) that facilitate the capture of anemophilous pollen grains (dispersed by wind). The reproduction of *Panicum maximum* is predominantly anemophilous (Dias-Filho; Martuscello, 2015).

PLANT PHYSIOLOGY

Photosynthesis in Poaceae: C3, C4 and CAM Pathways

Photosynthesis is one of the most important physiological processes involved in plant growth and biomass production (Long, 1999; GPWG II, 2012). In Poaceae, three main metabolic pathways are identified:

Characteristic of grasses from temperate climates or shaded environments, C3 pathway plants exhibit Rubisco photosynthesis, which initially fixes CO2 into 3-phosphoglycerate, forming three-carbon molecules. These plants have moderate but efficient photosynthetic rates in environments with limited light and exhibit a higher rate of photorespiration (Winslow; Knapp; Heitschmidt, 2013).

Predominant in tropical and warm-climate grasses, including most tropical Poaceae. Panicum maximum is a C4 photosynthetic species (four-carbon photosynthesis), as are other grasses of agronomic importance such as Zea mays and Sorghum bicolor (Sage; Sage; Kocacinar, 2012).

C4 photosynthesis involves a CO2 concentration mechanism that works in concert with two cell types: mesophyll cells and vascular bundle sheath cells. This mechanism gives C4 plants a higher photosynthetic rate, lower stomatal conductance, and greater water use efficiency compared to C3 plants, especially in environments with high solar radiation, high temperatures, and water deficit (Sage; Sage; Kocacinar, 2012; Winslow; Knapp; Heitschmidt, 2013). The CAM (Crassulacean Acid Metabolism) photosynthetic pathway is present.It is found in few grasses, being typical of succulent plants. It involves CO2 fixation during the night and release during the day, thus minimizing losses through transpiration (Winslow; Knapp; Heitschmidt, 2013).

*P. maximum*As a C4 species, *P. maximum* exhibits a higher photosynthetic rate in high-light, high-temperature, and water-deficient environments compared to C3 species. Photosynthetic rates in C4 species range from 30 to 60 μmol CO2 m^{-2} s^{-1} under optimal conditions, while C3 species typically exhibit rates of 5-25 μmol CO2 m^{-2} s^{-1}. This fundamental physiological advantage allows *P. maximum* to maintain high productivity even under moderate water stress (Winslow; Knapp; Heitschmidt, 2013).

Reflection and Absorption of Light

Light absorption mainly comprises the red (600-700 nm) and blue (400-500 nm) regions of the visible spectrum. Green light (500-600 nm) is partially reflected, which is why plants appear green to the human eye. Studies on the optical properties of *P. maximum* leaves indicate an ability to optimize absorption in different light qualities, with photosynthesis being little limited by shading in canopy structures, due to leaf orientation and the distribution of photosynthetic pigments in the leaves (Winslow; Knapp; Heitschmidt, 2013).

Light is primarily absorbed by chlorophyll and accessory pigments (carotenoids, xanthophylls) located in the thylakoids of chloroplasts. Grass leaves have a characteristic leaf structure with a light-colored upper epidermis, palisade parenchyma rich in chloroplasts, and spongy parenchyma with intercellular spaces that facilitate the diffusion of carbon dioxide (CO2). The distribution of chloroplasts in vascular bundle sheath cells (in C4 plants) optimizes CO2 refixation and photosynthetic efficiency (Winslow; Knapp; Heitschmidt, 2013).

Photosynthesis and Carbon Metabolism in Panicum maximum

*P. maximum*Kranz is a C4 (Crassulacean Acid Metabolism) grass, characterized by highly efficient photosynthesis under high light and high temperatures. The C4 photosynthetic pathway involves the initial fixation of CO_2 into phosphoenolpyruvate (PEP) by the enzyme PEP carboxylase (PEPCase), generating oxaloacetate, which is subsequently reduced to malate. This is transported to the vascular bundle sheath cells, where it is decarboxylated, releasing CO_2 that is then fixed by the Calvin cycle (reduction and regeneration of RuBP by RuBisCO), with subsequent regeneration of PEP. This anatomical (Kranz anatomy) and biochemical specialization confers significant advantages: (a) lower photorespiration (carbon loss); (b) higher CO_2 assimilation rate (Amax) under high irradiance; (c) better water use efficiency (WUE). (d) higher productivity in tropical environments (Pinheiro et al., 2018).

Recent studies have quantified that *P. maximum* exhibits a gross photosynthesis rate (Pg) ranging from 25-35 μmol CO_2 m^{-2} s^{-1} under saturating irradiance (1000-1200 μmol photons m^{-2} s^{-1}) and optimum temperature (28-32 °C), with a photosystem II quantum efficiency (ΦPSII) between 0.65-0.75 (Dias-Filho, 2018). Leaf respiration (Rd) is around 1.5-2.5 μmol CO_2 m^{-2} s^{-1}, resulting in a net photosynthesis rate (An) between 22-33 μmol CO_2 m^{-2} s^{-1}. Comparatively, C3 species (such as some temperate forage plants) exhibit reduced Amax under thermal stress conditions, demonstrating the ecological adaptation of *P. maximum* to tropical environments.

Reflection and Absorption of Light

The response of *P. maximum* to incident light is determined by anatomical and biochemical characteristics of the leaf that modify the spectral reflectance at different wavelengths. Reflectance spectrophotometry in the 400-2500 nm range revealed that *P. maximum* exhibits: (a) low reflectance (5-10%) in the violet (400-450 nm) and blue (450-495 nm) regions, corresponding to the chlorophyll a and b absorption bands; (b) high reflectance (8-12%) in the green region (495-570 nm), explaining the green color of the leaves observed by the human eye; (c) minimum reflectance (3-7%) in the red region (620-750 nm), corresponding to the maximum chlorophyll absorption for photosynthesis; (d) very high reflectance (40-55%) in the near-infrared region (NIR, 750-1400 nm) reflecting mainly through the anatomical structure (bulliform cells, spongy parenchyma) that aims to scatter infrared light; (e) substantial absorption in the water absorption region (1400-2500 nm) (Costa et al., 2019).

These spectral profiles are relevant for remote sensing, allowing species discrimination and monitoring of their physiological status using vegetation indices such as NDVI (Normalized Difference Vegetation Index) = (NIR - RED)/(NIR + RED), which in *P.*

maximum typically ranges between 0.6-0.8 under conditions of sufficient water and nutrients (Costa et al., 2019).

Water Dynamics, Retention and Absorption

Stomatal control of water loss is a critical function in grasses, especially in C4 species. In *P. maximum*, leaf water potential is maintained by: Stomatal regulation sensitive to vapor pressure deficit and soil water status; Accumulation of organic solutes (proline, carbohydrates) that reduce osmotic potential, allowing maintenance of turgor; Deep and efficient root system that explores water in deeper soil layers; Cuticle and leaf sheaths that reduce non-stomatal transpiration.

The techniques shown in Table 3 represent the arsenal available for in-depth investigation of physiological processes in *P. maximum*. The choice of technique depends on the research objectives, equipment availability, and the researcher's expertise. Portable techniques (photosynthesis, thermography) allow for non-invasive field measurements, while laboratory techniques (spectrophotometry, microscopy) provide more detailed analyses of biochemical and ultrastructural processes.

Table 3: Equipment and Measurement Techniques in Physiology.

Technique/Equipment	Frequency	Measured Parameter	Relevance
Portable photosynthesis analyzer	8	Photosynthetic rate, Stomatal conductance	Photosynthesis in the field
Chlorophyll fluorescence	4	Photosynthetic efficiency, stress	Photosystem II
Water potential (pressure chamber)	5	Ψ leaf, turgor	Water relations
Proline (ninhydrin) content	3	Accumulation of solutes	Osmotic stress
Enzyme activity (spectrophotometry)	6	SOD, catalase, peroxidase	Antioxidant system
Electron microscopy	2	Cellular ultrastructure	Stress-related injuries
Infrared thermography	1	Leaf temperature	Perspiration

Caption: Frequency refers to the number of studies (out of a total of 97 analyzed) that used each technique in physiological investigations of P. maximum.
Source: Adapted from Knapp (1993), Taylor et al. (2011), Lavres Junior et al. (2018) and Rabêlo et al. (2016).

Studies of water use efficiency (WUE) in *P. maximum* under different water regimes demonstrate that this species exhibits higher WUE than many tropical grasses, with photosynthesis/stomatal conductance ratios ranging from 3 to 8 mmol mol^{-1}, depending on the cultivar and water deficit conditions (Taylor et al., 2011). This characteristic makes *P. maximum* particularly suitable for cultivation in semi-arid regions and under supplemental irrigation.

Water retention and dynamics in *P. maximum* involve physiological and anatomical mechanisms that allow its adaptation to periods of water deficit. Under conditions of sufficient water, the leaf water potential (Ψ) ranges from -0.5 to -1.0 MPa during the period of maximum transpiration (at midday). Under water stress (soil water deficit), there is a marked reduction in water potential (-2.0 to -3.0 MPa), accompanied by stomatal closure to reduce transpiration loss (Santos; Oliveira, 2021).

Stomach conductance (gs in *P. maximum*, saturation varies according to environmental conditions: under maximum stomatal opening (morning), saturation reaches 200-400 mmol H_2O m^{-2} s^{-1}; under moderate water stress, it reduces to 50-100 mmol m^{-2} s^{-1}; under severe water deficit, it falls to 20-50 mmol m^{-2} s^{-1} or less. This stomatal regulation is mediated by plant hormones (abscisic acid or jasmonic acid) and intracellular calcium ion signaling (Pinheiro et al., 2019).

Bulliform cells (large, specialized epidermal cells) present in the leaves of *P. maximum* play an important role in water regulation. Under adequate hydration conditions, these cells are turgid, keeping the leaf blade extended and maximizing light capture. Under water deficit, the bulliform cells lose turgor, causing wrinkling of the leaf blade (rolling) and a reduction in the surface area exposed to solar radiation, minimizing transpiration loss. This mechanism is reversible, with complete recovery of turgor upon rehydration (Dias-Filho, 2017).

Furthermore, the accumulation of compatible solutes (proline, betaine, sorbitol, trehalose) in leaf cell vacuoles reduces the osmotic potential, allowing the maintenance of turgor under low soil water potential conditions. Biochemical studies have quantified 3- to 5-fold increases in proline concentration in P. maximum tissues under moderate to severe water stress (Costa et al., 2020). In other living organisms, proline acts primarily in collagen synthesis, cellular redox balance, and the response to metabolic stress (Varricchio et al., 2026).

Ecophysiology

Ecophysiology examines the physiological responses of organisms to environmental stressors, integrating biochemical, physiological, and ecological processes. For grasses, the main stressors include drought, salinity, extreme temperatures, and nutritional deficiencies.

Responses to Environmental Factors:

- Temperature

*Panicum maximum*It is classified as a C4 thermophile, exhibiting optimal growth at high temperatures. The baseline growth temperature (below which there is no measurable growth) is around 10 to 13 °C. The optimal temperature for growth (maximum leaf elongation and tillering rate) ranges from 28 to 35 °C. Above 35-40 °C, there is a progressive reduction in growth due to thermal stress, mainly limiting cell division and cell elongation. Ecophysiological studies have shown that under reduced nighttime temperatures (< 20 °C), even on warm days, there is a decrease in the rate of leaf appearance and tillering in *P. maximum* (Dias-Filho; Martuscello, 2015).

- Solar Radiation and Photoperiod

As a C4 plant adapted to high-light environments, *P. maximum* has a high light saturation point, ranging between 1000-1200 μmol photons m^{-2} s^{-1}, meaning the plant continues to increase its photosynthetic rate even under irradiance close to maximum solar radiation (1600-1800 μmol photons m^{-2} s^{-1} at midday on clear days in the tropics). Under shading (a 30-50% reduction in direct radiation), there is a marked reduction in growth and dry matter production, demonstrating its requirement for high light levels (Dias-Filho, 2018).

Regarding photoperiod, *P. maximum* is a "short-day" or "photoperiod-neutral" plant (ability to flower in a wide range of photoperiods). However, at equatorial latitudes (near 0°), the plant flowers for almost the entire year, while at higher latitudes (above 15°), there are periods of reproductive dormancy during the winter months, even under moderately high temperatures (Jank et al., 2014).

- Water Availability

*P. maximum*It requires adequate water availability during its growth period, with a minimum annual rainfall of 400-500 mm for acceptable production. Under rainfall (below 300 mm annually), growth is severely limited. Genetic diversity among cultivars results in differences in tolerance to water deficit: the Tanzania and Mombasa cultivars show greater resistance to prolonged dry periods compared to Common Guinea grass (Dias-Filho, 2017).

- Soils and Mineral Nutrition

P. maximum adapts well to soils with pH ranging from 4.5 to 8.0, but performs best at pH 5.5-6.5 (slightly acidic). The species exhibits moderate tolerance to toxic aluminum (characteristic of the Mombaça cultivar), allowing its cultivation in acidic soils where other forage crops have limitations. Regarding nutrients, *P. maximum* requires adequate levels of nitrogen (N), phosphorus (P), potassium (K), and micronutrients (Zn, Mn, B, Cu). For maximum dry matter production, the following is recommended: N: 100-300 kg ha^{-1} $year^{-1}$; P: 20-50 kg ha^{-1}; K: 80-150 kg ha^{-1}. Nitrogen deficiencies result in a drastic reduction in tillering; phosphorus deficiencies result in compromised root systems; and potassium deficiencies result in reduced cell turgor and stress tolerance (Silva et al., 2020).

COMMON APPLICATIONS OF *Panicum maximum*

- Use as Forage

P. maximum is one of the most important forage grasses in tropical animal production systems. It presents desirable characteristics: High dry matter production (up to 33 t ha^{-1}

year^{-1} under optimal conditions); Crude protein content of ~16% when well managed; High palatability for animals; Ability to produce multiple annual cuts; Good response to nitrogen fertilization; Tolerance to acidic soils and P deficiency.

- Biofuel Production

Grasses, including *P. maximum*, are being investigated as a biomass source for second-generation bioethanol production. High lignocellulose content and biomass productivity make *P*. *maximum* promising for conversion via fermentation and thermochemical processes.

- Environmental Remediation

P. maximum presents significant potential for phytoremediation of soils contaminated by heavy metals and for wastewater treatment, representing a sustainable ecological tool for the recovery of degraded areas (Santos et al., 2006; Olatunji et al., 2014), a property that is so relevant to the current state of the planet, with soil degraded by wars, the use of pesticides, and the presence of areas devastated, for several reasons.

PHYTOREMEDIATOR POTENTIAL

Phytoremediation refers to the use of plants to remove, detoxify, or immobilize contaminants in soils, sediments, and water. *Panicum maximum* has been attracting interest as a potential species for phytoremediation applications, particularly for heavy metals and organic pollutants.

- Absorption of Heavy Metals

Research indicates that plants grown in soils contaminated with heavy metals (Table 4) show increases in phenolic compounds, alkaloids, and saponins, potentially related to the response to oxidative stress (Olatunji et al., 2014; Rabêlo et al., 2016; Hasan et al., 2024).

Table 4: Heavy metals studied in phytoremediation.

Metal	Number of Studies	% of Accumulation Studied	Accumulation Order	Applications
Cadmium (Cd)	8	11-52%	Third	Mine remediation, agricultural soils
Lead (Pb)	5	13-45%	Second	Urban soil remediation
Chromium (Cr)	4	13-65%	First	Industrial effluents
Zinc (Zn)	2	Variable	Variable	Mined soils
Copper (Cu)	2	Variable	Variable	Mining areas
Nickel (Ni)	1	Variable	Variable	Contaminated soils

Source: Prepared by the authors based on Olatunji et al. (2014), Rabêlo et al. (2016) and Hasan et al. (2024).

Experimental studies have demonstrated that *P. maximum* is capable of absorbing significant amounts of heavy metals from the soil. Pires et al. (2019) cultivated P. maximum in soil contaminated with cadmium (Cd) at high levels (50 mg kg^{-1}) and observed an accumulation of 15-25 mg kg^{-1} of Cd in the aboveground biomass (leaves and stems - Santos et al., 2018; Oliveira et al., 2020).

Similarly, for lead (Pb), accumulations of 8-18 mg kg^{-1} were quantified in aerial tissues when cultivated in contaminated soils (80 mg kg^{-1} of Pb) (Santos et al., 2018; Oliveira et al., 2020). For nickel (Ni), an accumulation of 5-12 mg kg^{-1} was observed under moderate contamination conditions (30 mg kg^{-1}) (Oliveira et al., 2020).

The bioconcentration factor (BCF = concentration in plant tissue / concentration in soil) for P. maximum was estimated at: Cd (BCF = 0.30-0.50), Pb (BCF = 0.10-0.22), Ni (BCF = 0.17-0.40), indicating a moderate capacity for concentration of these metals. The translocation factor (TF = concentration in the aerial part / concentration in the root) was particularly high for Cd (TF = 0.80-1.20), suggesting efficient translocation of this metal from the root to the aerial part, a desirable characteristic for phytoextraction (Oliveira et al., 2020).

Metal absorption in *P. maximum* occurs through active transport mechanisms mediated by metal transporters in the plasma membrane of root cells. Molecular studies have identified the expression of genes encoding metal transporters (IRT1, ZIP, NRAMP) in P. maximum roots under metal contamination conditions (Pinheiro et al., 2020).

There is also potential for phytoextraction of heavy metals. Studies by Olatunji et al. (2014) demonstrated that *P. maximum* accumulates heavy metals in significant concentrations:Cr^{3+}: 13-65%; Pb^{2+}: 13-45%; Cd^{2+}: 11-52% of the soil concentration. The observed accumulation order was $Cr^{3+} > Pb^{2+} > Cd^{2+}$. Although *P. maximum* is classified as a moderate accumulator, its high biomass production and rapid growth make it promising for remediation. Metal tolerance mechanisms present in the species include: Chelation by amino acids and phytochelators; Vacuolar compartmentalization; Reduced transport; Synthesis of metal-binding proteins.

Furthermore, studies in *P. maximum* cv. Massai under different Cd concentrations revealed that the plant tolerates foliar Cd concentrations greater than 100 mg kg^{-1} of dry weight without exhibiting visual symptoms of toxicity, indicating efficient tolerance (Rabêlo et al., 2016; Coulibaly et al., 2020).

- Decontamination of Organic Waste

Preliminary studies indicate the potential of *P. maximum* for the degradation of organic pollutants, including pesticides. The presence of detoxifying enzymes (peroxidases, catalases, glutathione S-transferases) in its tissues suggests the capacity to metabolize xenobiotics (Costa et al., 2020).

- Remediation of Soil Contaminated by Wastewater:

Recent studies (Hasan et al., 2024) indicate that *P. maximum*, when irrigated with treated wastewater, efficiently accumulates saline elements, with potential for remediation of salinized soils.

Studies on variations in primary and secondary metabolites of *P. maximum* under wastewater pollution have demonstrated significant alterations in the phytochemical profile, suggesting the activation of defense mechanisms. The species has shown the ability to accumulate multiple pollutants simultaneously, and is being investigated as a tool for the treatment of agro-industrial and municipal effluents (Hasan et al., 2024).

DISCUSSION

In its phytochemistry, *P. maximum* exhibits tannins, which are polyphenols with astringent, antimicrobial, and antioxidant properties. Present in moderate to high concentrations in *P. maximum*, especially in leaves, they contribute to anti-inflammatory and antimicrobial activities. Saponins, on the other hand, are triterpenic or steroidal glycosides with surfactant properties. Detected in P. maximum, they exhibit antimicrobial, immunomodulatory, and anti-inflammatory activities (Kanife et al., 2012).

Flavonoids are polyphenols (C_{15}) known as powerful free radical scavengers. Identified in extracts of *P. maximum* through HPLC and GCMS, they exhibit antioxidant activity. Meanwhile, phenols and phenolic acids, including gallic acid, caffeic acid, and others, exhibit high antioxidant and anti-inflammatory potential. Terpenoids, including mono-, di-, and triterpenes, exhibit antimicrobial activities. (Kanife et al., 2012).

GC-MS analyses of active fractions of *P. maximum* identified specific compounds including fatty acids (palmitic acid, stearic acid), phytosterols (β-sitosterol, stigmasterol) and hydrocarbons, suggesting potential for the synthesis of biomolecules of interest (Doss et al., 2011).

Ecophysiology

Responses to Water Stress

Under water deficit, *P. maximum* exhibits (Taylor et al., 2011): Reduction in photosynthetic rate proportional to the severity of stress; Decrease in stomatal conductance (gs), which prioritizes water conservation over carbon gain; Increase in proline and non-reducing carbohydrate content, functioning as osmolytes; Activation of antioxidant systems (superoxide dismutase, catalase, peroxidase) to minimize oxidative damage; In addition to biomass redistribution in favor of roots.

Adaptations to Extreme Temperatures

As a tropical species, *P. maximum* exhibits optimal growth at temperatures of 25-35°C. Under elevated temperatures (>35°C), the species maintains photosynthetic activity through: Heat shock proteins (HSP); Altered membrane lipid composition; Adjustment of nitrogen and carbon balance. Under reduced temperatures, *P. maximum* exhibits slowed growth, with almost total cessation below 10°C (Teisher et al., 2017).

Responses to Nutritional Deficiencies

Nitrogen (N) is an essential macronutrient, a constituent of proteins and nucleic acids. Studies in *P. maximum* under different N doses demonstrate linear responses to N addition, with increases of up to 10% in crude protein content with increasing N doses. Recent studies indicate that N use efficiency in *P. maximum* is related to root biomass and soil N mineralization capacity, varying with management and fertilization history.

Phytoremediation

Phytoremediation is an eco-friendly technology that uses plants to remove, inactivate, or metabolize pollutants present in soil, water, or air. Grasses have ideal characteristics for phytoremediation (Silva et al., 2016; Lavres Junior et al., 2018) due to: extensive root system, high biomass, rapid growth, dense soil cover, tolerance to pollutants, and adaptability to adverse conditions.

Despite recent advances, significant knowledge gaps persist:

- Molecular mechanisms: Genomic and proteomic level investigations of *P. maximum* under environmental stress and application of extracts lack depth;

- Drug-plant interactions: Potential interactions between components of *P. maximum* and conventional drugs require systematic investigation;
- Genetic variability: Comparative studies of different cultivars and wild accessions are limited, especially regarding phytochemical composition and medicinal potential;
- Agronomic factors: The impact of different cultivation practices, harvest times, and post-harvest processing on bioactive composition requires further investigation.

Future research prospects include:

- Genetic improvement: Selection of cultivars with higher levels of secondary metabolites and superior tolerance to environmental stresses;
- Precision agriculture: Using technologies such as remote sensing, artificial intelligence, and vertical farming to optimize the production of biomass and biocomposts;
- Circular bioeconomy: Integration of *P. maximum* into regenerative agricultural systems, with full utilization of biomass (forage, pesticides, biofuels, fibrous materials);
- Climate change: Investigation of *P. maximum* as an adaptive tool in scenarios of increased temperature and water variability, particularly in semi-arid and degraded regions.

LIMITS OF THE REVIEW

This study covered only three languages, considering that Chinese and Japanese have rich equipment for phytochemical and phytopharmaceutical recovery assessments; some indexed articles were not available online; regarding grey literature, dissertations and technical reports whose practical and theoretical elements could have made relevant contributions were excluded. Publications after July 2026 were not included.

Furthermore, the heterogeneity of the publications led to significant methodological variation among studies, which hindered quantitative synthesis. Regarding publication bias, a tendency to publish only positive results was evident.

In summary, the systematic analysis of the literature revealed several relevant gaps in knowledge about *Panicum maximum*:

There is a lack of systematic research on synergistic interactions between phenolic compounds, flavonoids, and tannins present in *P. maximum*. Such studies are fundamental for optimizing pharmaceutical formulations and understanding biological mechanisms of action.

Although biological activities have been demonstrated, the molecular mechanisms (interactions with receptors, enzyme inhibition, signaling pathways) require further investigation at the proteomics and transcriptomics levels;

- No randomized controlled clinical trials have been identified evaluating the efficacy and safety of P. maximum preparations in human populations. Not even case series studies. Such studies are essential for pharmaceutical validation;

Comparative investigations between cultivars (Tanzania, Massai, Mombasa) and wild ecotypes are limited regarding phytochemical composition and associated biological activities; genetic variability in secondary metabolism needs to be evaluated.

Although the ability to absorb heavy metals has been demonstrated, optimization studies for phytoremediation (cultivation conditions, metal species, remediation time) and the development of phytoremediation biofactories are scarce;

- Biotechnology and genetic improvement: Research involving gene editing techniques (CRISPR-Cas9), genetic transformation, or marker-assisted selection to increase bioactive metabolites is practically non-existent.

CONTRIBUTION

This integrative systematic review contributes to the bioprospecting of *Panicum maximum* Jacq by bringing together ethnobotanical and ethnopharmacological studies combined with modern analytical chemistry approaches to investigate traditional uses that are not yet documented, both pharmacological and biotechnological.

Future prospects for research on *P. maximum* encompass multiple dimensions:

(1) Precision agriculture: Use of digital agronomy, remote sensing and mathematical modeling to optimize P. maximum production aiming to increase secondary metabolites under different environmental conditions.

(2) Applications in environmental conservation: Development of large-scale phytoremediation technologies for the restoration of areas degraded by mining, industrial contamination and toxic war residues (persistent in the environment, acting as endocrine disruptors and direct pro-carcinogens);

(3) Bioprospecting of endophytes: Investigation of endophytic microorganisms associated with *P. maximum* as producers of biologically active secondary metabolites.

CONCLUSIONS

Panicum maximum (*Megathyrsus maximus)* represents a promising field within the multidisciplinary context of Botany, Ecophysiology, Pharmacognosy, and Natural Products. The biological activities demonstrated *in vitro* and in preclinical models (cytotoxic to neoplastic cell lines, antimicrobial, anti-parasitic, antioxidant, anti-inflammatory, hepatoprotective) validate the scientific interest in its pharmacological applications.

This systematic review consolidated evidence on its morphology, physiological processes (C4 photosynthesis, water dynamics), ecological adaptability, phytoremediation potential, and phytochemical composition.

However, significant gaps remain in investigations of molecular mechanisms, clinical studies in humans, optimization of phytoremediation applications, and the use of biotechnological tools to increase bioactive metabolites.

Therefore, the convergence of research in these areas, coupled with rigorous scientific validation and regulatory compliance, could transform *P. maximum* from a forage crop of agricultural importance into a key species for multiple applications in medicine, environmental sustainability, and the green economy.

The establishment of interdisciplinary research networks integrating specialists in Botany, Plant Physiology, Ecology, Natural Products Chemistry, Pharmacology, and Clinical Medicine Researchers is strongly recommended for the systematic advancement of knowledge about this species.

This compilation is justified by the growing demand for alternative sources of natural biocompounds and the need for a better understanding of the potential of grasses, not only pharmacologically, but especially as phytoremediation agents aimed at the phytorecovery of devastated areas of the planet.

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