



Review

Ecological Functioning and Environmental Applications of *Schoenoplectus californicus* in Freshwater Wetlands: A Review

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Abstract

Schoenoplectus californicus (C.A.Mey.) Soják is a dominant freshwater wetland macrophyte with ecological, technological, and biocultural importance. This multidisciplinary review synthesizes its ecological functioning and environmental applications through a systematized analysis of 66 studies screened by title, abstract, and full text. The literature was classified into seven thematic categories: water treatment and phytoremediation; wetland ecology, biomass, and ecosystem functioning; functional ecology, growth, and landscape connectivity; morphology, anatomy, and functional adaptation; biocultural dimensions, sustainable construction, and technological applications; nutritional and ethnobotanical uses; and cultural heritage and traditional management. Research was concentrated mainly in water treatment and phytoremediation (19 studies, 28.8%), followed by wetland ecology, biomass, and ecosystem functioning (13 studies, 19.7%) and biocultural dimensions, sustainable construction, and technological applications (13 studies, 19.7%). Functional ecology, growth, and landscape connectivity represented 5 studies (7.6%), morphology, anatomy, and functional adaptation represented 4 studies (6.1%), while nutritional and ethnobotanical uses and cultural heritage and traditional management each represented 6 studies (9.1%). Overall, the evidence shows that *S. californicus* is a multifunctional wetland species whose value emerges from the interaction among ecological functioning, contaminant retention, biomass production, structural adaptation, technological innovation, traditional knowledge, and biocultural continuity.

Keywords: freshwater wetlands; phytoremediation; ecosystem functioning; aquatic macrophytes; sustainable construction; biocultural heritage; nutrient dynamics

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1. Introduction

1.1. Taxonomic Identity, Distribution, and Nomenclatural Scope

Schoenoplectus californicus (C.A.Mey.) Soják, commonly known as totora, is a perennial emergent macrophyte characteristic of freshwater wetlands in the Americas [1]. It belongs to the family Cyperaceae and is characterized by a robust vegetative apparatus composed of an extensive rhizomatous system, roots, and erect culms; the rhizomes enable vigorous clonal expansion and explain the formation of large, densely concentrated stands. Its distinctive reproductive apparatus consists of pseudolateral inflorescences formed by clustered spikelets that produce achenes [2,3]. Its presence is particularly relevant in marshes, shallow lakes, littoral zones, and other wetland environments where emergent vegetation contributes to the physical and biological organization of aquatic ecosystems. In these habitats, totora frequently forms dense stands that define the structure of wetland landscapes and influence ecological processes at different spatial scales [4].

The taxonomic treatment of this species requires particular attention because South American literature has used different scientific and vernacular names to refer to the same or closely related forms. Terms such as “totora” and “tatora” have been applied in ethnobotanical, ecological, and regional studies, while names such as *Scirpus californicus* (C.A.Mey.) Steud., *Schoenoplectus tatora* (Kunth) Palla, and *Schoenoplectus californicus* subsp. *tatora* (Kunth) T.Koyama have also appeared in the literature. Therefore, this review treats *S. californicus* at the species level, following a broad taxonomic scope. When the reviewed sources used alternative names or infraspecific categories, the nomenclature was checked and harmonized, while the original taxonomic wording of each source was considered during interpretation. This criterion avoids merging taxonomic, ecological, and ethnobotanical meanings without clarification.

Table 1 presents the name cited in each original source, the accepted or harmonized name, author citation, taxonomic status, database consulted, and the decision adopted in this review. This makes clear that older combinations and regional names were not merged uncritically, but were interpreted according to a transparent taxonomic criterion. To avoid taxonomic ambiguity, the nomenclature used in the reviewed literature was harmonized according to verified plant-name databases (Table 1).

Table 1. Taxonomic names, accepted status, consulted databases, and harmonization criteria used in this review.

Name as Cited in the Literature	Family	Rank	Verified Author Citation	IPNI/Taxonomic Record	Current Taxonomic Status	Harmonized Name Adopted in This Review	Decision Applied in the Manuscript
<i>Schoenoplectus californicus</i>	Cyperaceae	Species	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	IPNI LSID: urn:lsid.org:names:229810-2	Accepted species	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Principal accepted name used throughout the manuscript.
<i>Scirpus californicus</i>	Cyperaceae	Species	<i>Scirpus californicus</i> (C.A.Mey.) Steud.	IPNI/POWO/FO consulted	Synonym/un-accepted name under current taxonomic treatment	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Retained only when cited in the original source; harmonized to <i>S. californicus</i> for synthesis.
<i>Schoenoplectus tatora</i>	Cyperaceae	Species	<i>Schoenoplectus tatora</i> (Kunth) Palla	IPNI/POWO consulted	Synonym of <i>Schoenoplectus californicus</i>	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Treated as a synonym used in older

							or regional literature.
<i>Scirpus californicus</i> subsp. <i>tatora</i>	Cyperaceae	Subspecies	<i>Scirpus californicus</i> subsp. <i>tatora</i> (Kunth) T.Koyama	IPNI LSID: urn:lsid.org:names:230246-2	Infraspecific synonym/under current harmonized treatment	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Mentioned only when the original reference uses this infraspecific name; interpreted at species level.
<i>Schoenoplectus californicus</i> subsp. <i>tatora</i>	Cyperaceae	Subspecies	<i>Schoenoplectus californicus</i> subsp. <i>tatora</i> (Kunth) T.Koyama	IPNI/herbarium and taxonomic records consulted	Infraspecific name used in Andean and Lake Titicaca literature	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Used with taxonomic caution; not counted as a separate taxon in the synthesis.
<i>Schoenoplectus californicus</i> var. <i>spoliatus</i>	Cyperaceae	Variety	<i>Schoenoplectus californicus</i> var. <i>spoliatus</i> (Barros) Vegetti	IPNI LSID: urn:lsid.org:names:2987168-1	Infraspecific name/synonymized in current taxonomic backbones	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Not treated as an independent taxonomic unit unless specifically cited by an original source.
<i>Scirpus californicus</i> var. <i>spoliatus</i>	Cyperaceae	Variety	<i>Scirpus californicus</i> var. <i>spoliatus</i> Barros	IPNI/POWO consulted	Synonym of <i>Schoenoplectus californicus</i>	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Considered a synonym; not separated analytically.
"Totora"	Cyperaceae	Vernacular name	Not applicable	Not applicable	Vernacular name	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Used only as a common name after first defining the scientific name.
"Tatora"	Cyperaceae	Vernacular/regional name	Not applicable	Not applicable	Vernacular or regional designation	<i>Schoenoplectus californicus</i> (C.A.Mey.) Soják	Used only when discussing regional, ethnobotanical, or cultural literature.

Note. The review adopts *Schoenoplectus californicus* (C.A.Mey.) Soják as the harmonized taxonomic name at the species level. Historical combinations, synonyms, vernacular names, and infraspecific names were retained only when necessary to reflect the terminology used in the original sources. These names were not treated as independent taxa in the thematic synthesis, avoiding taxonomic duplication and overestimation of records.

Description. *Schoenoplectus californicus*, commonly known as totora, is a perennial emergent macrophyte that grows in freshwater wetlands, shallow lakes, marshes, and littoral zones. The species forms dense stands with erect aerial stems and extensive below-ground structures, contributing to vegetation structure, habitat formation, and wetland stability. Its vegetative growth is especially relevant in high-altitude Andean aquatic ecosystems, where it supports biomass production and ecological functioning [5] (Figure 1).



Figure 1. Field morphology of *Schoenoplectus californicus* (C.A.Mey.) Soják in freshwater wetland habitats.

This taxonomic clarification is not merely nomenclatural, but also ecologically relevant for the interpretation of the reviewed evidence. Studies that use different scientific names, infraspecific categories, or vernacular terms may still refer to the same dominant emergent macrophyte and to comparable wetland functions. Therefore, harmonizing the nomenclature at the species level allows the ecological evidence to be interpreted consistently, while avoiding the artificial separation of records that describe similar vegetation structure, habitat formation, biomass production, and wetland processes. This approach provides the basis for linking the taxonomic identity of *S. californicus* with its functional role in freshwater wetlands.

1.2. Ecological Functions and Ecosystem Services of Totorá Wetlands

The ecological importance of *S. californicus* is mainly associated with its role as a dominant structural macrophyte. By forming extensive stands, the species contributes to habitat complexity, vegetation architecture, sediment stabilization, primary productivity, and biological interactions within freshwater wetlands [4,6]. These attributes make totora more than a conspicuous plant species; it acts as an ecological organizer of wetland environments.

Totora stands also provide habitat and refuge for associated organisms, including aquatic and semi-aquatic plant assemblages, arthropod communities, periphytic organisms, and other components of wetland biodiversity [7–10]. Through these interactions, *S. californicus* supports trophic dynamics, biological connectivity, and ecosystem integrity. In addition, wetlands dominated by this species may contribute to ecosystem services such as carbon storage, aquatic productivity, nutrient cycling, and biological support functions [11,12].

However, the ecological value of totora depends on the conservation of wetland structure and environmental quality. Changes in the cover, density, or vitality of *S. californicus* may indicate disturbance processes associated with eutrophication, pollution, hydrological alteration, or the expansion of invasive species [13]. Therefore, the species can be interpreted both as a structural component of wetlands and as a potential indicator of ecological degradation.

The conceptual pathway shows that totora wetlands dominated by *S. californicus* contribute to biomass production and vegetation structure, which influence the ecological

status of the wetland. Conserved conditions promote high biodiversity, whereas disturbed conditions may lead to degradation associated with eutrophication and invasive species. Overall, the diagram emphasizes that wetland stability and ecological functioning depend on the interaction between vegetation structure, ecosystem services, and biological support (Figure 2).

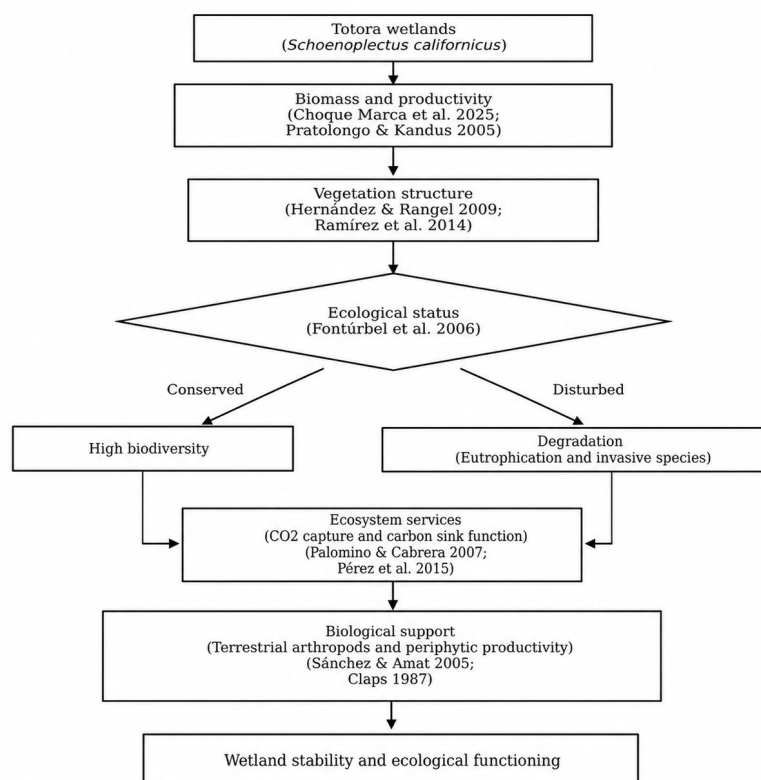


Figure 2. Conceptual pathway linking biomass, ecological status, biodiversity, and ecosystem functioning in *Schoenoplectus californicus* wetlands [4,6–13].

The ecological functions described above also explain why *S. californicus* has been evaluated in environmental applications. Its capacity to form dense stands, stabilize sediments, produce high biomass, develop extensive belowground structures, and support biological interactions creates favorable conditions for nutrient retention, pollutant immobilization, microbial activity, and water-quality regulation. Thus, the transition from ecological functioning to phytoremediation and water treatment is not incidental; rather, it reflects the use of natural plant traits and wetland processes in engineered or semi-natural treatment systems. For this reason, the environmental applications of *S. californicus* should be interpreted as an extension of its ecological role in freshwater wetlands.

1.3. Environmental Applications: Water Treatment, Purification, and Phytoremediation

The ecological traits that allow *S. californicus* to dominate freshwater wetlands also explain its applied value in water treatment and phytoremediation systems. Aquatic macrophytes are commonly used in natural and constructed wetlands because they promote sediment retention, nutrient uptake, microbial activity, pollutant transformation, and contaminant stabilization. In this context, totora has received attention due to its tolerance to disturbed environments, high biomass production, and extensive root and rhizome systems [14–16].

Previous studies have reported the use of *S. californicus* in wastewater treatment, constructed wetlands, filtration systems, and contaminated environments [17–19]. These

applications suggest that the species contributes not only to pollutant retention, but also to the ecological stability and operational simplicity of low-cost treatment systems. Its presence in treatment wetlands may improve system performance by combining physical filtration, biological uptake, and support for microbial processes involved in contaminant transformation.

Recent evidence has also described *S. californicus* as a bioindicator of potentially toxic elements, including As, Cd, Cr, Ni, Pb, and Hg, with phytostabilization potential in urban Ramsar wetlands [20]. This finding expands the applied relevance of the species because it links remediation capacity with environmental monitoring. Thus, the value of totora in water purification and phytoremediation is closely connected to its ecological traits, rather than being an isolated technological use.

1.4. Knowledge Gap and Purpose of the Systematized Review

Although the literature on *S. californicus* has increased across wetland ecology, botany, ethnobotany, environmental engineering, and sustainable resource management, the available information remains dispersed across disciplinary approaches. Ecological studies often emphasize vegetation structure, biomass, biodiversity, and ecosystem functioning, whereas applied studies focus on wastewater treatment, phytoremediation, contaminant retention, or constructed wetlands. At the same time, ethnobotanical and socio-economic studies highlight the historical use of totora in subsistence activities, artisanal practices, and community-based management systems [21–23].

This fragmentation creates a central knowledge gap: the ecological, environmental, and cultural dimensions of *S. californicus* have rarely been integrated under a common analytical framework. As a result, it remains difficult to understand how taxonomic interpretation, wetland functioning, environmental applications, and sustainable use are connected in the scientific literature. This gap is especially relevant because the same species is simultaneously treated as a wetland engineer, a biological resource, a phytoremediation tool, and a culturally important plant.

Therefore, this multidisciplinary systematized review aims to organize and synthesize the scientific evidence on *S. californicus*, considering its taxonomic treatment, ecological functions, environmental applications, and socio-ecological relevance. By integrating these dimensions, the review seeks to clarify the current state of knowledge and identify research needs for the conservation, management, and sustainable use of totora wetlands.

The novelty of this review lies in its integrative treatment of *S. californicus* as a multifunctional wetland species rather than as a taxon associated with a single research field. Previous studies have generally examined the species from isolated perspectives, such as phytoremediation, wetland ecology, biomaterial use, ethnobotany, or traditional management. In contrast, this review organizes the available evidence into seven interconnected thematic dimensions and links taxonomic interpretation, ecological functioning, water treatment, functional adaptation, technological applications, nutritional uses, and biocultural continuity within a common analytical framework. Therefore, the review does not aim to be an exhaustive inventory of all records available for the taxon, but a systematized synthesis of verifiable studies that directly contribute to understanding the ecological and environmental relevance of *S. californicus*.

Based on the final corpus of 66 reviewed studies, the updated integrative framework highlights *S. californicus* (totora) as a remediation resource within wetland socio-ecological systems. The framework organizes the evidence into seven interconnected thematic dimensions: water treatment and phytoremediation; wetland ecology, biomass, and ecosystem functioning; functional ecology, growth, and landscape connectivity; morphology, anatomy, and functional adaptation; biocultural dimensions, sustainable construction, and technological applications; nutritional and ethnobotanical uses; and cultural heritage

and traditional management. This structure shows that totora is not limited to a single ecological function, but links contaminant retention, water purification, habitat structure, biomass production, functional adaptation, biomaterial development, food-related uses, traditional knowledge, and cultural continuity. Overall, the framework reinforces the need for an interdisciplinary approach to understand, conserve, and sustainably manage *S. californicus* wetlands (Figure 3).

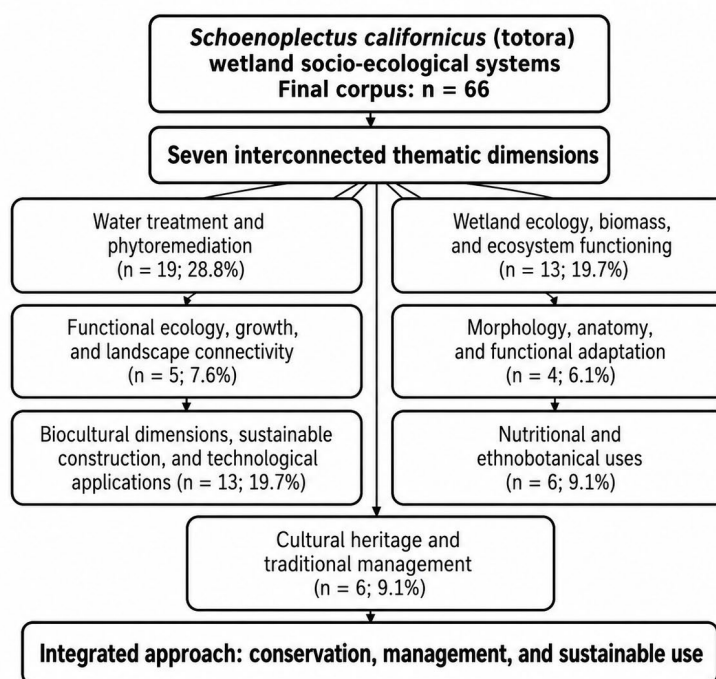


Figure 3. Updated integrative framework of the seven thematic dimensions of *Schoenoplectus californicus* in wetland socio-ecological systems, based on the final corpus of 66 reviewed studies.

2. Materials and Methods

2.1. Review Design

This study was conducted as a systematized literature review aimed at identifying, selecting, organizing, and synthesizing scientific evidence on *S. californicus*. The review addressed ecological, anatomical, technological, ethnobotanical, nutritional, and cultural dimensions of the species. The methodological process followed five sequential stages: literature search, duplicate removal, title and abstract screening, full-text eligibility assessment, and qualitative synthesis. PRISMA was used as a traceability guide to document the identification, screening, eligibility, and inclusion stages; however, the study is presented as a systematized review rather than as a full systematic review (Table A1). As this was a literature review, no chemicals, reagents, instruments, commercial materials, cell lines, or specialized analytical software were used.

2.2. Search Strategy

The literature search was conducted between 25 February and 5 June 2026. Scientific records were retrieved from Scopus, Web of Science Core Collection, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, SciELO, Redalyc, and Scilit. Google Scholar and DOAJ were used as complementary sources to identify additional studies not captured in the main databases. Crossref, publisher websites, journal platforms, and indexing records were consulted to verify DOI information, taxonomic consistency, and bibliographic accuracy.

Searches combined English and Spanish terms related to the species and its ecological, technological, and biocultural dimensions. The main search terms were "*Schoenoplectus californicus*", "totora", "tatora", "wetlands", "phytoremediation", "constructed wetlands", "water treatment", "morphology", "anatomy", "biomaterial", "ethnobotany", "traditional knowledge", "nutrition", "cultural heritage", and "ecosystem services". When database interfaces allowed it, searches were restricted to title, abstract, and keywords.

Scilit was included to broaden the coverage of recent and complementary literature on *S. californicus*. In this source, records were searched using the scientific name of the species, and articles were downloaded when they were available in open access or had accessible full text through the journal platform. All retrieved records were screened according to the inclusion and exclusion criteria established for the review. Records were excluded when the species was only mentioned incidentally, when the taxonomic identity could not be verified, when the document lacked sufficient bibliographic information, or when the thematic contribution was outside the objectives of the review. This expanded search strategy supported a final corpus of 66 studies included in the qualitative synthesis.

2.3. Eligibility Criteria

Studies were included when they met the following criteria: (i) they directly addressed *S. californicus* or totora; (ii) they analyzed ecological, anatomical, technological, ethnobotanical, nutritional, or cultural aspects in which the species had a central or clearly relevant role; and (iii) they presented empirical findings, analytical assessments, or documented evidence related to the objectives of the review. Priority was given to peer-reviewed journal articles published in English or Spanish.

Studies were excluded when they were duplicates, outside the thematic scope of the review, focused mainly on other species without direct relevance to *S. californicus*, lacked sufficient scientific or technical support, or presented incomplete bibliographic information that prevented verification. Grey literature was not included in the central corpus unless it provided clearly identifiable and verifiable contextual information.

2.4. Screening and Selection

All records retrieved from the selected databases and complementary sources were compiled in a master database. After duplicate removal, the remaining records were screened by title, abstract, and keywords. Records that did not directly address *Schoenoplectus californicus*, totora, or clearly related nomenclatural variants were excluded at this stage. Potentially relevant studies were then assessed in full text according to the inclusion and exclusion criteria defined for the review. The PRISMA diagram and traceability matrix were updated to document the identification, duplicate removal, screening, eligibility, exclusion, and final inclusion stages, resulting in a final corpus of 66 studies.

2.5. Data Extraction and Synthesis

For each selected study, information was extracted using a structured review matrix. The extracted variables included author(s), year of publication, country or study location, database source, journal title, thematic area, research approach, objective, methodological characteristics, main findings, scientific contribution, and DOI availability.

The 66 included studies were classified into seven non-overlapping thematic categories: water treatment and phytoremediation; wetland ecology, biomass, and ecosystem functioning; functional ecology, growth, and landscape connectivity; morphology, anatomy, and functional adaptation; biocultural dimensions, sustainable construction, and technological applications; nutritional and ethnobotanical uses; and cultural heritage and traditional management.

Classification was based on three criteria: the main objective of the study, the principal variables or evidence analyzed, and the central contribution of the article to the review. Each article was assigned to a single dominant thematic category for quantitative reporting. When an article addressed more than one topic, secondary or transversal themes were recorded in the review matrix and considered in the qualitative interpretation, but they were not counted as additional records. This procedure avoided double counting and prevented the overestimation of thematic frequencies while preserving the multidimensional character of studies that connected ecological, technological, and biocultural aspects of *S. californicus*.

The synthesis was conducted using a qualitative and comparative approach. The included studies were analyzed according to their objectives, methodological designs, main findings, and contribution to the broader understanding of *S. californicus*. This process allowed the identification of dominant research lines, convergent findings, underrepresented topics, methodological limitations, and conceptual links among ecological, technological, and biocultural dimensions. Bibliographic consistency and DOI availability were verified through Crossref, publisher websites, indexing platforms, and journal records. References without a visible DOI were retained only when they were relevant, verifiable, and scientifically justified.

3. Results and Discussion

3.1. Bibliometric and Thematic Structure of the Reviewed Literature

The 66 studies included in this review reveal a broad but uneven thematic structure, in which research on *S. californicus* is concentrated mainly in ecological, environmental, and technological applications. Water treatment and phytoremediation was the most represented area, with 19 studies (28.8%), confirming that the strongest applied evidence is associated with wastewater treatment, nutrient removal, metal retention, bioaccumulation, phytostabilization, and emerging-contaminant transformation [17,24,25].

Wetland ecology, biomass, and ecosystem functioning included 13 studies (19.7%), showing that *S. californicus* should not be interpreted only as a dominant macrophyte, but also as a structural and biogeochemical component of wetland systems. Recent evidence links the species with habitat suitability, hydrological variability, urban wetland functioning, and silicon cycling [26–28]. Similarly, biocultural dimensions, sustainable construction, and technological applications also accounted for 13 studies (19.7%), indicating that totora is increasingly being evaluated beyond its traditional uses, particularly in relation to its thermal, mechanical, thermoacoustic, antifouling, fiber-based, and circular-economy potential [29–31].

Less represented but still relevant research areas included functional ecology, growth, and landscape connectivity, with 5 studies (7.6%), and morphology, anatomy, and functional adaptation, with 4 studies (6.1%). These categories contribute to understanding plant performance, nutrient uptake, root establishment, soil-related functions, and the relationship between stem composition, mechanical behavior, and material functionality [32–36]. Nutritional and ethnobotanical uses represented 6 studies (9.1%), while cultural heritage and traditional management also included 6 studies (9.1%). These findings expand the interpretation of *S. californicus* by documenting both the decline of traditional totora use in Lake Titicaca and the emerging pharmacological potential of its rhizomes [37,38].

Functional ecology, growth, and landscape connectivity included 5 studies (7.6%), whereas morphology, anatomy, and functional adaptation included 4 studies (6.1%). These areas remain less represented, although they are essential for explaining the mechanisms that support plant performance, adaptation, and material functionality. Nutritional and ethnobotanical uses included 6 studies (9.1%), and cultural heritage and

traditional management also included 6 studies (9.1%). Together, these categories indicate that *S. californicus* should be interpreted as a multifunctional wetland species with ecological, technological, nutritional, ethnobotanical, and biocultural relevance (Table 2).

Table 2. Final thematic distribution.

Theme	n	%
Water treatment and phytoremediation	19	28.8
Wetland ecology, biomass, and ecosystem functioning	13	19.7
Functional ecology, growth, and landscape connectivity	5	7.6
Morphology, anatomy, and functional adaptation	4	6.1
Biocultural dimensions, sustainable construction, and technological applications	13	19.7
Nutritional and ethnobotanical uses	6	9.1
Cultural heritage and traditional management	6	9.1
Total	66	100%

The updated synthesis shows that research on *S. californicus* is mainly concentrated in water treatment and phytoremediation, followed by wetland ecology and biocultural or technological applications. The temporal trend indicates a clear increase in publications from the 2000s onward, with the highest production in the 2010s and 2020–2025 period. Scopus and WoS were the main database sources, while Peru, Argentina, Bolivia, and Chile contributed most of the reviewed studies, reflecting the ecological and socio-cultural relevance of the species in South American wetlands (Figure 4).

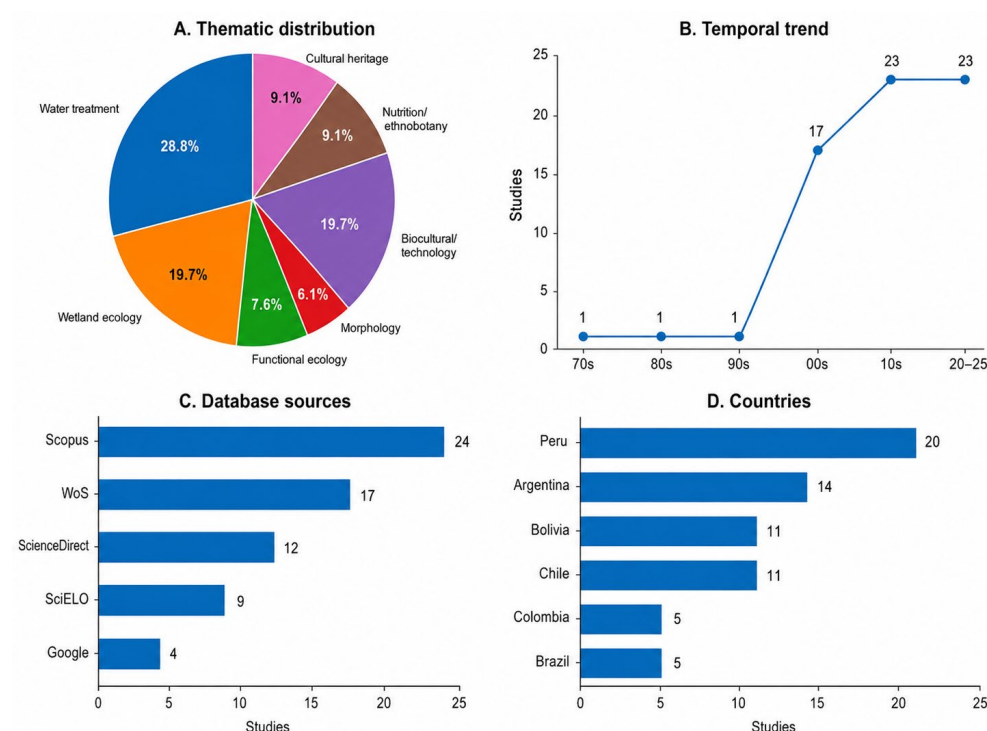


Figure 4. Synthesis of 66 reviewed studies on *Schoenoplectus californicus*: (A) thematic distribution, (B) temporal trend, (C) database sources, and (D) geographic distribution. **Note:** Each study was counted only once according to its dominant thematic contribution. Secondary or transversal themes were recorded in the extraction matrix and considered in the qualitative synthesis, but they were not counted as independent records in order to avoid double counting and overestimation of percentages. Percentages may not total exactly 100% because of rounding.

The 66 reviewed studies were mainly retrieved from internationally indexed databases, especially Scopus (36.4%) and Web of Science (25.8%), followed by ScienceDirect (18.2%). In addition, SciELO/Redalyc (13.6%) and Google Scholar or complementary sources (6.1%) contributed regional and supplementary evidence relevant to *Schoenoplectus californicus*. Geographically, research was concentrated in South America, with Peru showing the highest contribution (30.3%), followed by Argentina (21.2%), Bolivia and Chile (16.7% each), and, to a lesser extent, Colombia and Brazil (7.6% each). Overall, this pattern confirms that current scientific knowledge on *S. californicus* is supported by major bibliographic databases and is mainly produced in countries where totora wetlands have strong ecological, cultural, and environmental relevance (Figure 5).

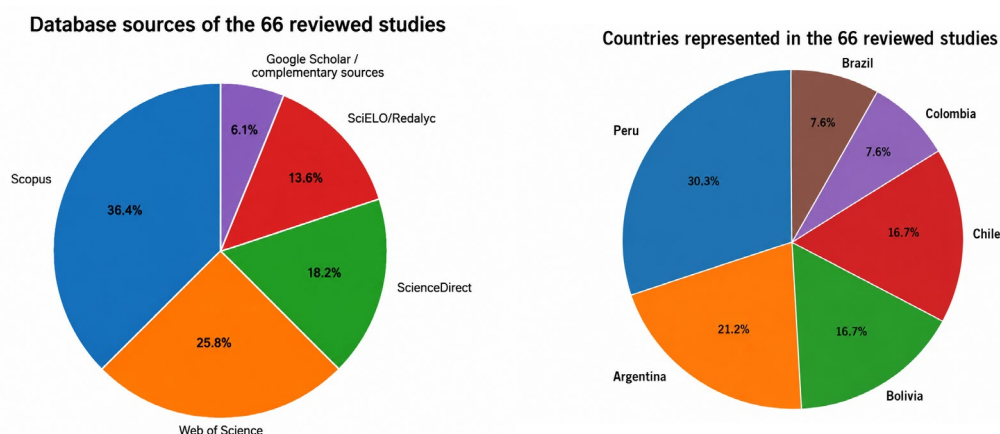


Figure 5. Updated percentage distribution of the 66 reviewed studies on *Schoenoplectus californicus* according to database sources and country of origin. Percentages may not total exactly 100% because of rounding.

3.2. Water Treatment, Phytoremediation, and Engineered Systems

The updated evidence strengthens the interpretation of *S. californicus* as a useful species in water treatment and phytoremediation, but also shows that its performance depends on system design, contaminant type, biological interactions, and operational conditions. In constructed and floating wetlands, root establishment and plant development contribute to nutrient removal, while treatment efficiency is shaped by hydraulic and substrate conditions [16,36,39,40].

Metal-related studies show a consistent pattern of tolerance, accumulation, and phytostabilization. Bioaccumulation and bioconcentration of toxic metals have been reported in natural wetlands, while controlled studies demonstrated retention or removal of Cu, Zn, Fe, Pb, and other metal elements in roots and stems [25,41,42]. These results support the use of *S. californicus* as a macrophyte for phytoremediation and environmental monitoring.

The evidence also shows that contaminant transformation is not explained by the plant alone. Rhizobacteria associated with *S. californicus* and *Typha dominguensis* reduced chemical oxygen demand under laboratory conditions, while sulfamethoxazole removal in microcosms depended on the combined action of plant, sediment, algae, and microbial communities [43,44]. Thus, *S. californicus* should be interpreted as part of an integrated treatment system rather than as an isolated remediation agent.

Plant-derived materials provide an additional treatment pathway. Activated carbon from totora improved water-quality indicators, while natural filters and alum-assisted treatment systems showed that macrophyte-based technologies can contribute to water purification under specific conditions [45–47]. However, these applications require

standardization of material preparation, contact time, dosage, regeneration capacity, and long-term safety.

Comparative evidence indicates that water treatment and phytoremediation represent the main research line on *S. californicus*, with 19 studies, equivalent to 28.8% of the 66 reviewed records. In wastewater treatment Chuchón and Aybar [18] reported 99.9850% removal of fecal coliform bacteria and 86.2% removal of BOD₅, although the effluent still reached 1.29×10^5 MPN/100 mL and 46.35 mg/L BOD₅. In constructed wetlands Rojas et al. [16] reported similar removal efficiencies between *Phragmites australis* and *S. californicus*, with COD removal of 18–30% in winter and 45–55% in spring, while total nitrogen removal ranged from 25 to 65% in winter and 25–35% in spring. These results show that *S. californicus* has relevant treatment potential, but its efficiency depends on seasonality, system design, hydraulic conditions, and operational maturity [16,18].

The comparative evidence shows that *S. californicus* and totora-derived materials have consistent potential for water treatment, phytoremediation, metal retention, organic-load reduction, and pollutant filtration; however, treatment efficiency depends on system design, contaminant type, hydraulic conditions, material preparation, and experimental scale (Table 3).

Table 3. Comparative evidence on water treatment, phytoremediation, and engineered systems involving *Schoenoplectus californicus* or totora-derived materials.

Authors/Year	System or Configuration	Contaminant or Water-Quality Indicator	Removal Efficiency or Main Reported Result	Duration	Scale	Main Limitation for Interpretation
Aguilar et al. [45] (2024)	Water remediation using activated carbon derived from totora	General water-quality index and physico-chemical parameters	Improved water-quality indicators after treatment with totora-derived activated carbon	Not specified in the current synthesis	Material-based/experimental application	The evidence supports adsorbent potential, but performance depends on material preparation, dosage, contact time, regeneration capacity, and long-term safety.
Castañeda and Flores [14] (2014)	Domestic wastewater treatment using wetland macrophytes	Domestic wastewater indicators	Demonstrated a sustainable and low-cost treatment alternative	Not specified in the current synthesis	Applied/treatment system	The result supports ecological treatment, but system design and operational conditions limit direct comparison with other studies.
Chuchón and Aybar [18] (2008)	Wastewater treatment plant with macrophyte-based system	Coliforms and BOD ₅	Reported high removal of coliforms and BOD ₅	Not specified in the current synthesis	Applied/wastewater treatment plant	Treatment performance may depend on hydraulic loading, maintenance, plant density, and local operating conditions.
Blanco [17] (2019)	Phytoremediation in contaminated	Potentially toxic metals	Demonstrated tolerance of <i>S. californicus</i> to metal contamination	Not specified in the current synthesis	Field or contaminated wetland context	Tolerance does not necessarily indicate complete removal; metal partitioning among roots,

	wetland environments					stems, sediments, and water must be interpreted carefully.
Rodríguez et al. [19] (2019)	Bioconcentration and bioaccumulation assessment	Metals accumulated in plant tissues	Reported metal accumulation in tissues of <i>S. californicus</i>	Not specified in the current synthesis	Natural wetland/field evidence	Bioaccumulation indicates retention potential, but extraction, disposal, and trophic-transfer risks require further evaluation.
Rojas et al. [16] (2013)	Constructed wetlands comparing <i>Phragmites australis</i> and <i>S. californicus</i>	Wastewater treatment indicators	Reported similar treatment efficiency between macrophyte species	Not specified in the current synthesis	Constructed wetland/comparative system	Seasonal variation and differences in hydraulic or substrate conditions may influence treatment performance.
Moyano Arévalo, Naranjo Vargas, and Santillán Mariño [46] (2018)	Natural fiber filtration using totora fibers	Pollutants retained through natural filtration	Reported pollutant reduction through natural fiber filtration	Not specified in the current synthesis	Material-based filtration system	The result is promising, but efficiency depends on fiber preparation, filter design, flow rate, and replacement frequency.
Neyrot et al. [44] (2024)	Microcosm with plant, sediment, algae, and microbial communities	Sulfamethoxazole	Removal depended on the combined action of plant, sediment, algae, and microbial communities	Not specified in the current synthesis	Microcosm	The evidence supports system-level transformation, but microcosm behavior may differ from constructed or natural wetlands under variable environmental conditions.

Overall, *S. californicus* can be regarded as a key species in ecological water treatment, not because it guarantees uniform remediation outcomes, but because it provides a flexible and functionally robust plant basis for phytoremediation, wetland depuration, pollutant retention, and environmental stabilization. In the final corpus, 19 of the 66 reviewed studies corresponded to water treatment and phytoremediation (Table 4).

Table 4. Representative research outcomes on *Schoenoplectus californicus* and related macrophyte-based systems in water depuration, wastewater treatment, and phytoremediation.

Authors	Year	System/Approach	Species/Material	Main Finding	Contribution
Aguilar et al. [45]	2024	Water remediation using plant-derived material	Activated carbon from totora (<i>S. californicus</i>)	Improved water quality index and physico-chemical parameters	Supports the use of totora as an adsorbent material for water remediation
Castañeda & Flores [14]	2014	Domestic wastewater treatment	Wetland macrophytes	Demonstrated a sustainable and low-cost treatment alternative	Supports macrophyte-based systems as ecological technology

Chuchón & Aybar [18]	2008	Wastewater treatment plant	Macrophyte system	Reported high removal of coliforms and BOD ₅	Shows that treatment performance depends on system design and operation
Blanco [17]	2019	Phytoremediation	<i>S. californicus</i>	Demonstrated tolerance to metals	Supports the application of <i>S. californicus</i> in contaminated wetland environments
Rodríguez et al. [19]	2019	Bioconcentration	<i>S. californicus</i>	Reported metal accumulation in plant tissues	Indicates potential use in metal retention, bioaccumulation, and extraction processes
Rojas et al. [16]	2013	Constructed wetlands	<i>P. australis</i> and <i>S. californicus</i>	Reported similar treatment efficiency between macrophyte species	Highlights the influence of seasonal variation on treatment performance
Palacios et al. [15]	2020	Artificial wetland	Totora	Reported good operational performance	Supports the practical value of totora in engineered wetland systems
Moyano Arévalo, Naranjo Vargas & Santillán Mariño [46]	2018	Natural fiber filtration	Totora fibers/natural fibers	Reduced pollutants through natural filtration	Supports the use of totora fibers as a low-cost filtration material
de Cabo et al. [39]	2019	Riparian rehabilitation	Macrophytes	Supported the restoration of riparian vegetation	Provides ecological support for wetland and riparian recovery

Note: This table presents representative studies from the water treatment and phytoremediation category. The final thematic corpus includes 19 studies in this category within the total set of 66 reviewed studies.

3.3. Wetland Ecology, Biomass, Biodiversity, and Ecosystem Services

The updated evidence reinforces the role of *S. californicus* as a structural and functional component of wetlands. In addition to biomass production and habitat formation, the species contributes to biogeochemical regulation through amorphous silica production and phytolith formation [26]. This expands the interpretation of totora wetlands from vegetation stands to systems that regulate biomass, habitat, and elemental flows.

Recent studies also show that the distribution of *S. californicus* responds to climatic and hydrological variability. In the Ramsar Carlos Anwandter wetland, suitable habitat areas fluctuated over time, and *S. californicus* declined with increasing temperature and water level but expanded with higher precipitation [27]. This suggests that climate and hydrological change may alter the spatial stability of totora stands.

Urban wetland evidence indicates that ecological patterns may persist even under strong anthropogenic pressure. In the Santa Rosa wetland, macrophyte communities remain functionally coupled with physicochemical limnological conditions despite solid waste, livestock grazing, organic contamination, and urban expansion [28]. Therefore, the pending hypothesis is that totora-dominated or macrophyte-rich wetlands may maintain functional processes even when their structure is altered.

3.4. Functional Ecology, Nutrient Dynamics, and Ecological Plasticity

The functional evidence shows that growth, nutrient uptake, and root development are central mechanisms behind the ecological and treatment value of *S. californicus*. Root growth during plant establishment improves nutrient removal in constructed floating wetlands, linking early vegetative development with treatment performance [36,48].

Comparative evidence from *Schoenoplectus validus* microcosms also shows that nitrogen and phosphorus loading interactively affect biomass, nutrient accumulation, and NH_4 and P removal [40]. Although this study does not evaluate *S. californicus* directly, it is useful as comparative evidence for understanding nutrient-dependent responses within closely related *Schoenoplectus* systems.

Soil-related evidence suggests an additional functional role. *Scirpus californicus* has been reported as a soil conditioner capable of improving sandy and clay soil fertility [35]. This result should be included with taxonomic caution, but it supports the idea that the species may influence not only aquatic processes, but also edaphic conditions relevant to restoration and plant establishment.

3.5. Morphology, Anatomy, and Functional Adaptation

Morphological and anatomical evidence should be strengthened because recent studies connect plant structure with ecological adaptation and technological performance. The macromolecular composition of totora stems, especially cellulose, lignin, and related structural components, is associated with mechanical properties relevant to material use [34,49–51].

This evidence indicates that the utility of totora as a biomaterial is not independent of its ecology. The same structural traits that support persistence in wetland environments also influence resistance, flexibility, and processing potential. Therefore, morphology should be discussed as a bridge between adaptation, biomass quality, and technological functionality.

3.6. Biomaterials, Sustainable Construction, and Technological Applications

The updated evidence substantially expands the technological dimension of *S. californicus*. Recent studies show that totora-based materials can be evaluated through thermal, mechanical, durability, thermoacoustic, and circular-economy criteria [29,30,52–57]. This changes the discussion from traditional use toward experimentally tested sustainable construction.

Totora panels and hybrid materials show particular relevance. Sustainable construction studies in Ecuador and hybrid panels made with totora and recycled LDPE-Al indicate that this species can be incorporated into low-impact material systems [31,58]. Similarly, thermal studies reported conductivity values compatible with renewable insulation materials [59].

The technological potential also extends beyond construction. Totora fibers have been proposed as a source for papermaking, while extracts of *S. californicus* showed anti-attachment and toxicological effects relevant to antifouling applications [50,60,61]. These studies support a broader interpretation of totora as a source of fibers, bioproducts, and environmental technologies.

At the same time, the literature in this field remains less consolidated than the phytoremediation or wetland ecology literature. Even so, the available evidence clearly shows that the significance of *S. californicus* cannot be reduced to its ecological or technological functions alone. Instead, as shown by previous research [62,63], totora also operates as a cultural resource sustained through long-term interaction between people and wetlands. Figure 6 broadens the interpretation of the species by showing that its multifunctionality

also includes historical continuity, local knowledge, and community-based management, all of which are central to understanding *S. californicus* as biocultural heritage.

Totora biocultural heritage is shaped by the interaction between archaeology, ancestral technology, ethnography, ethnohistory, artisanal use, and socio-environmental threats. These dimensions reveal that *S. californicus* is not only an ecological species, but also a cultural resource linked to traditional knowledge, material production, fishing practices, historical continuity, and community identity. However, wetland loss, fishing decline, and knowledge erosion threaten this heritage, which may affect both cultural continuity and wetland ecological functioning (Figure 6).

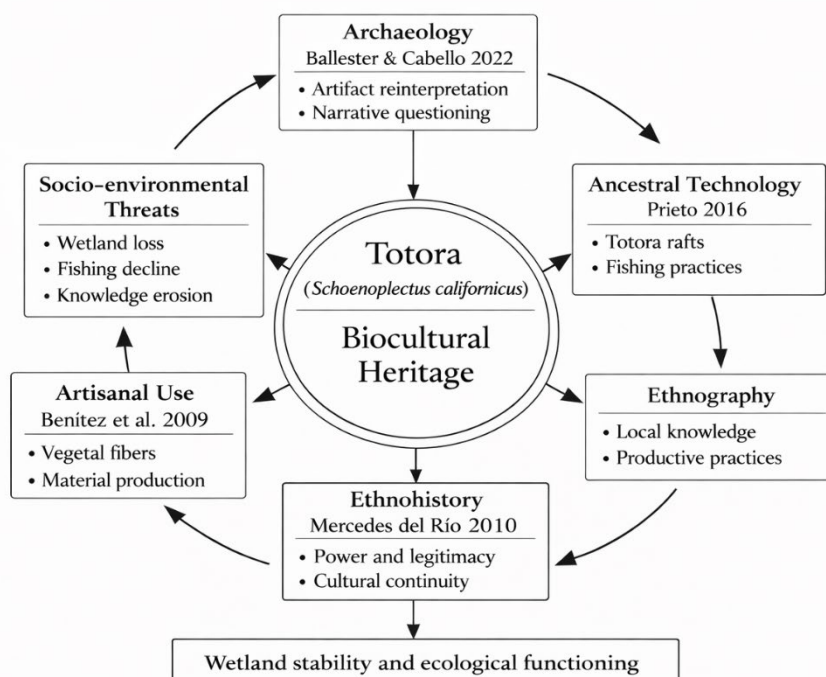


Figure 6. Conceptual framework of *Schoenoplectus californicus* as a biocultural heritage species [23,38,50,62,63].

3.7. Nutritional, Ethnobotanical, and Biocultural Dimensions

The updated evidence reinforces the need to discuss totora as a biocultural species. The decline of totora use in Lake Titicaca shows that the loss of traditional practices is associated with market integration, replacement by industrial materials, and weakening of collective management systems [38]. This finding is important because conservation should include both wetland protection and transmission of local ecological knowledge.

Evidence from socio-ecological and heritage-related contexts highlights the value of totora in cultural landscapes [62], while other studies associate its persistence with historical continuity and traditional systems [63]. In the same direction, complementary evidence shows that totora remains linked to collective practices, local management, and community decision-making [21,23]. Thus, the figure supports an interpretation of biocultural heritage in which ecological presence, traditional management, and cultural memory are closely interconnected.

At the same time, new evidence expands the ethnobotanical dimension toward bioprospecting. Rhizomes of *S. californicus* contain flavonoids, phenolic compounds, tannins, amino acids, and stilbenes, and have shown antioxidant, anxiolytic, sedative, and analgesic activity in experimental models [37,64,65]. This line is promising, but it requires further studies on mechanisms, safety, dosage, and pharmacological validation.

3.8. Integrative Synthesis and Research Gaps

The updated corpus of 66 studies confirms that *S. californicus* is not only a wetland macrophyte, but also a remediation resource, a biogeochemical component, a biomaterial, a food-related resource, a biocultural species, and a potential source of bioactive compounds. The strongest evidence is concentrated in treatment systems and wetland functioning, while technological applications now represent an equally important emerging field.

However, the evidence remains uneven. Treatment and biomaterial studies have increased, but mechanistic studies on physiology, long-term contaminant fate, climate response, harvesting effects, and socio-ecological feedbacks remain limited. Future research should integrate field monitoring, experimental trials, biomass management, contaminant pathways, material performance, and traditional knowledge to explain how totora wetlands function under environmental and cultural change.

Figure 7 reinforces this integrative view by showing that the relevance of *S. californicus* is organized around three closely connected dimensions: ecological processes, traditional knowledge, and socio-economic functions. From the ecological side, the studies by Pratolongo and Kandus [8] and Ramírez et al. [22] linked totora to biomass dynamics, vegetation structure, and wetland functioning, while Pérez et al. [12] associated its stands with carbon-related functions and broader ecosystem services. At the same time, Macía and Balslev [4] and Banack et al. [21] documented traditional uses, subsistence practices, and artisanal applications, whereas Prieto [23] showed that the species remains embedded in community-based management systems. This biocultural continuity is further strengthened by Ballester and Cabello [62], who linked totora to material culture and historically transmitted practices. In parallel, Gavilanez and Zurita-Polo [66] showed that the species also contributes to food, forage, and livelihood-related uses, with resource value shaped partly by local management. Therefore, Figure 7 does not simply summarize thematic areas; rather, it shows that ecological functioning, traditional knowledge, and socio-economic uses are mutually reinforcing dimensions within a single biocultural system (Figure 7).

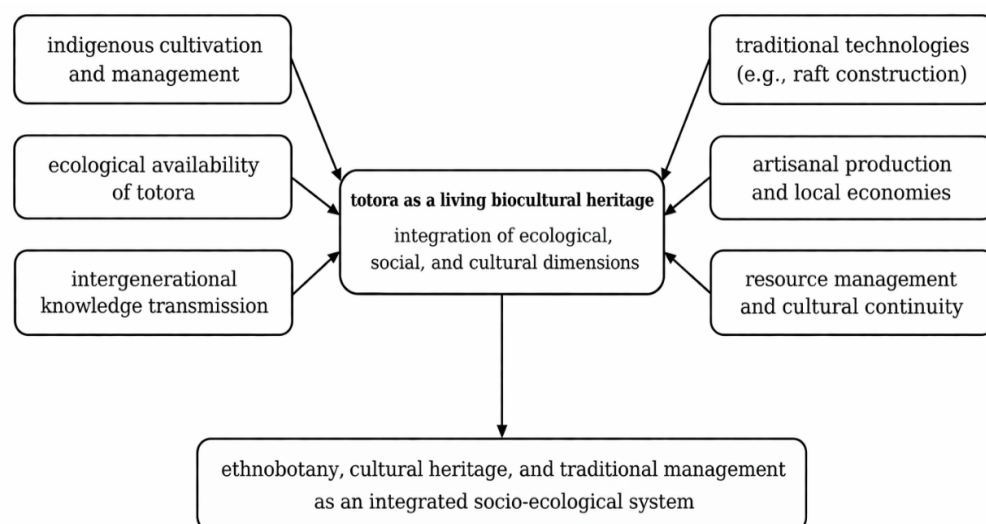


Figure 7. Totora (*Schoenoplectus californicus*) as a biocultural system integrating ecological processes, traditional knowledge, and socio-economic functions.

4. Conclusions

1. The best documented applications of *Schoenoplectus californicus* are water treatment and phytoremediation, which represent the largest evidence base, with 19 studies

(28.8%) focused on wastewater treatment, nutrient removal, metal retention, bioaccumulation, and phytostabilization. Moderately supported evidence corresponds to wetland ecology, biomass, ecosystem functioning, and sustainable technological applications, each represented by 13 studies (19.7%). Promising but still limited research lines include functional ecology, morphology, nutritional uses, ethnobotany, and traditional management, which together show the novel value of the species beyond remediation, but still require stronger experimental and socio-ecological evidence.

2. Despite this broader evidence base, the literature remains thematically unbalanced. Functional ecology, growth, and landscape connectivity account for 5 studies (7.6%), whereas morphology, anatomy, and functional adaptation represent only 4 studies (6.1%). Nutritional and ethnobotanical uses and cultural heritage and traditional management each include 6 studies (9.1%). This imbalance indicates that the mechanistic, anatomical, functional, nutritional, and cultural dimensions of *S. californicus* remain less explored than its role in phytoremediation and wetland functioning.
3. The main contribution of this multidisciplinary systematized review is to show that the value of *S. californicus* does not lie in a single ecological or technological use, but in the convergence of ecological functioning, contaminant retention, biomass production, structural adaptation, biomaterial potential, traditional knowledge, and biocultural continuity. Future research should therefore prioritize integrative frameworks capable of linking wetland functioning, phytoremediation performance, plant traits, biomaterial applications, nutritional uses, and traditional management within a common analytical perspective.

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Appendix A

Table A1. Traceability matrix of studies included in the qualitative synthesis.

ID	Reference	Year	Data-base/Source	Title/Abstract Screening	Full-Text Eligibility	Final Inclusion	Final Thematic Category	DOI Verified	Notes
1	Aguilar et al. [45]	2024	Google Scholar	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Activated carbon from totora

2	Castañeda & Flores [14]	2014	Redalyc/Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	No DOI shown in manuscript	Domestic wastewater treatment
3	Chuchón & Aybar [18]	2008	Sci-ELO/Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	No DOI shown in manuscript	Treatment plant/macro-phyte system
4	Blanco [17]	2019	Scopus/MDPI	Included	Eligible	Included	Water treatment and phyto-remediation	Yes	Heavy-metal suitability
5	Rodríguez et al. [19]	2019	Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	Yes	Bioconcentration factors
6	Noriega-Rico et al. [33]	2026	Scopus	Included	Eligible	Included	Functional ecology, growth, and landscape connectivity	Yes	Population genetics, wetland fragmentation, and functional connectivity
7	Rojas et al. [16]	2013	Scopus/Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	No DOI shown in manuscript	Nutrient removal in constructed wetlands
8	Palacios et al. [15]	2020	Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	No DOI shown in manuscript	Artificial wetland performance
9	Moyano Arévalo et al. [46]	2018	Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	No DOI shown in manuscript	Natural fiber filtration and pollutant reduction
10	de Cabo et al. [39]	2019	DOAJ/Google Scholar	Included	Eligible	Included	Water treatment and phyto-remediation	Yes	Riparian rehabilitation
11	Harguin-teguy et al. [41]	2023	Scopus	Included	Eligible	Included	Water treatment and phyto-remediation	Yes	Cu, Pb, and Zn removal/tolerance
12	Romero et al. [24]	2023	Wiley Online Library/Scopus	Included	Eligible	Included	Water treatment and phyto-remediation	Yes	Mine effluent laboratory assessment
13	Choque et al. [6]	2025	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Distribution and biomass
14	Pratolongo & Kandus [8]	2005	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	Aboveground biomass dynamics
15	Hernández-R. & Rangel [7]	2009	SciELO	Included	Eligible	Included	Wetland ecology, biomass,	No DOI shown in manuscript	Wetland vegetation

							and ecosystem functioning		
16	Ramírez et al. [4]	2014	SciELO	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Floristic diversity
17	Sánchez & Amat-García [10]	2005	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	Arthropod diversity and trophic support
18	Palomino & Cabrera Carranza [11]	2007	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	CO ₂ capture ecosystem service
19	Pérez et al. [12]	2015	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	Quantification of CO ₂ capture
20	Claps [9]	1987	Manual reference check/Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	Periphyton pigments and productivity
21	Fontúrbel et al. [13]	2006	Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	No DOI shown in manuscript	Ecological condition and flora
22	de Lange et al. [2]	2010	Wiley Online Library/Google Scholar	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Ecological occurrence and distribution
23	Arce & Achá [32]	2025	ScienceDirect/Scopus	Included	Eligible	Included	Functional ecology, growth, and landscape connectivity	Yes	Allometry and nutrient uptake
24	Neubauer et al. [48]	2012	Google Scholar/Scopus	Included	Eligible	Included	Functional ecology, growth, and landscape connectivity	Yes	Biomass allocation and plant performance
25	Pabón et al. [5]	2025	Google Scholar	Included	Eligible	Included	Functional ecology, growth, and landscape connectivity	Yes	Growth response and ecological plasticity
26	Apóstolo [49]	2005	Google Scholar	Included	Eligible	Included	Morphology, anatomy, and functional adaptation	No DOI shown in manuscript	Anatomical characters
27	Benítez et al. [50]	2009	Google Scholar	Included	Eligible	Included	Morphology, anatomy, and functional adaptation	Yes	Fiber-related native plants

28	Corsino et al. [51]	2013	Google Scholar	Included	Eligible	Included	Morphology, anatomy, and functional adaptation	No DOI shown in manuscript	Scape architecture
29	Galindo & Córdoba Sánchez [20]	2025	Taylor & Francis Online/Scopus	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Bioindication and phytostabilization of potentially toxic elements in a Ramsar urban wetland
30	Aza et al. [52]	2023	ScienceDirect/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Thermal, mechanical, and fire behavior of totora panels
31	Hýšková et al. [56]	2020	ScienceDirect/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Composite materials
32	Hidalgo-Cordero & García-Navarro [55]	2018	ScienceDirect/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Construction material potential
33	Hidalgo et al. [54]	2019	Google Scholar	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Bound fiber rolls
34	Jiménez et al. [53]	2024	Scopus/Google Scholar	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Modular insulating systems
35	Gavilanez & Zurita-Polo [66]	2021	DOAJ	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Totora flour
36	Loza et al. [65]	2025	Google Scholar	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Edible organs and nutritional content
37	Loza-Del Carpio & Roque-	2022	Google Scholar	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Prescribed burning and forage value

Huanca [64]									
38	Rondón et al. [3]	2003	SpringerLink/Google Scholar	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Ethnobotanical investigation
39	Macía & Balslev [22]	2000	SpringerLink/Google Scholar	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Use and management of totora treated here as ethnobotany
40	Banack et al. [21]	2004	SpringerLink/Google Scholar	Included	Eligible	Included	Cultural heritage and traditional management	Yes	Indigenous cultivation and conservation
41	Prieto [23]	2016	Google Scholar	Included	Eligible	Included	Cultural heritage and traditional management	No DOI shown in manuscript	Ethnographic and archaeological approach
42	Ballester & Cabello [62]	2022	DOAJ/Google Scholar	Included	Eligible	Included	Cultural heritage and traditional management	Yes	Biocultural and historical continuity
43	del Rio [63]	2010	SciELO/Google Scholar	Included	Eligible	Included	Cultural heritage and traditional management	Yes	Historical continuity and traditional systems
44	Heiser [1]	1978	SpringerLink	Included	Eligible	Included	Cultural heritage and traditional management	Yes	Broad totora context retained as historical-cultural background
45	Boleji et al. [25]	2021	Google Scholar/journal platform	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Bioconcentration and bioaccumulation of toxic metals in <i>Scirpus californicus</i> from natural wetlands
46	Campos-Florián et al. [37]	2026	MDPI/Scopus	Included	Eligible	Included	Nutritional and ethnobotanical uses	Yes	Chemical profile, antioxidant capacity, psychopharmacological exploration, and analgesic activity of <i>S. californicus</i>

47	Cañarejo Antamba & Delgado Yáñez [59]	2026	Google Scholar/journal platform	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Totora as a thermal bio-material for construction in Ecuador
48	De Rito et al. [26]	2024	Taylor & Francis/Scopus	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Amorphous silica contribution of <i>S. californicus</i> to the silicon cycle in shallow lakes
49	Flores et al. [42]	2023	Google Scholar/journal platform	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Heavy-metal removal using <i>Phragmites australis</i> and <i>S. californicus</i>
50	Hidalgo-Cordero & Aza-Medina [29]	2023	ScienceDirect/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Thermal performance of elements made with totora using different production processes
51	Hidalgo-Cordero et al. [57]	2021	Taylor & Francis Online/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Durability of totora binderless boards against wood-decaying organisms
52	Hidalgo-Cordero et al. [34]	2023	Taylor & Francis Online/Scopus	Included	Eligible	Included	Morphology, anatomy, and functional adaptation	Yes	Macromolecular stem composition and relationship with mechanical properties
53	Huaquisto-Cáceres et al. [30]	2023	Scopus/journal platform	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Eco-efficient thermoacoustic panels made of totora and gypsum
54	Izzati et al. [35]	2021	Google Scholar/journal platform	Included	Eligible	Included	Functional ecology, growth, and landscape connectivity	Yes	Bulrush as a soil conditioner for improving sandy and

									clay soil fertility
55	Jara Vinueza et al. [58]	2024	MDPI/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Sustainable construction with cattail fibers: physical and mechanical properties
56	Jara-Vinueza et al. [31]	2025	MDPI/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Mechanical behavior and application potential of totora and recycled LDPE-Al hybrid panels
57	Masias-Flores et al. [43]	2025	Google Scholar/journal platform	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Rhizobacteria from <i>Scirpus californicus</i> and <i>Typha dominguensis</i> reduced COD in wastewater
58	Morales et al. [60]	2026	Wiley/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	<i>S. californicus</i> evaluated as an antifouling candidate with anti-attachment and toxicological effects
59	Neyrot et al. [44]	2024	ScienceDirect/Scopus	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Fate of sulfamethoxazole in <i>S. californicus</i> microcosms and effects on microbial communities
60	Rigotti et al. [36]	2021	SpringerLink/Scopus	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Root growth and nutrient removal during plant establishment in constructed floating wetlands
61	Villar et al. [38]	2024	SpringerLink/Scopus	Included	Eligible	Included	Cultural heritage and traditional management	Yes	Declining use of totora in Lake Titicaca and implications for

									traditional management
62	Wille et al. [61]	2023	SpringerLink/Scopus	Included	Eligible	Included	Biocultural dimensions, sustainable construction, and technological applications	Yes	Totora fibers evaluated as a new source for papermaking
63	Labra & Jaramillo [27]	2025	MDPI/Scopus	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Climate and hydrology shape the distribution of dominant native and alien macrophytes in a Ramsar wetland
64	Malecki-Brown et al. [47]	2010	ScienceDirect/Scopus	Included	Eligible	Included	Water treatment and phytoremediation	Yes	Alum application improved water quality in a municipal wastewater treatment wetland and affected macrophyte growth and nutrient uptake
65	Rivera-Cáceda et al. [28]	2026	MDPI/Scopus	Included	Eligible	Included	Wetland ecology, biomass, and ecosystem functioning	Yes	Spatiotemporal analysis of aquatic macrophytes and limnological variability in an impacted urban wetland
66	Zhang et al. [40]	2008	ScienceDirect/Scopus	Included	Eligible	Included	Water treatment and phytoremediation	Yes	<i>Schoenoplectus validus</i> microcosms/comparative evidence

Note: Each study was assigned to only one dominant thematic category to avoid double counting. Secondary or transversal themes were recorded in the review matrix and considered during the qualitative synthesis, but they were not counted as independent records in the thematic distribution.

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