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Valorisation of cattail (*Typha*) biomass: Fibre extraction, properties, and applications in sustainable material systems

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ABSTRACT

The cattail plant (*Typha* spp.) is a low-cost, renewable, and multifunctional natural fibre resource with strong potential for sustainable and circular material systems. This review explores the extraction methods, properties, and application potential of cattail fibres. Fibre origin and the extraction route are key factors affecting fibre microstructure and performance. Mechanical extraction typically yields fibres with high variability, whereas optimized alkali, enzymatic, and hybrid treatments substantially enhance fibre quality. Consequently, reported tensile strengths for leaf and stem fibres span from below 100 MPa in untreated form to values exceeding 1000 MPa under optimized processing conditions. On a specific property basis, optimized cattail leaf/stem fibres perform competitively compared to conventional fibres, albeit with greater variability. In composites, cattail fibres act as effective lightweight reinforcements, offering improved mechanical performance, energy absorption, and damping. Cattail seed fibres, despite limited tensile capacity, exhibit exceptional bulk resilience and hydrophobicity, enabling insulation, cushioning, filtration, and oil-sorption applications. Overall, cattail fibres emerge as versatile materials whose performance is governed by method-property relationships, supporting their potential as next-generation sustainable materials.

1. Introduction

Natural fibres for a long time have played a pivotal role in human civilization, providing essential raw materials for textiles, construction, packaging, and a wide range of artisanal products (Behera et al., 2025b). In recent decades, growing environmental concerns over petroleum-based synthetic fibres and plastics have revitalized interest in natural fibres (Islam et al., 2022; Islam et al., 2025b; Nagaraja et al., 2024). Compared to synthetic counterparts, natural fibres are renewable, biodegradable, environmentally benign, and offer diverse performance attributes. The shift towards natural fibres is further driven by advances in fibre surface modification, composite processing technologies, and hybrid material design, which have significantly improved the mechanical reliability and functional performance of bio-based materials (Behera et al., 2025a; Kurien et al., 2023a). Their applications span across traditional textile use to healthcare, tissue engineering, environmental remediation, and bio-based composites (Fan et al., 2018; Kozłowski and Mackiewicz-Talarczyk, 2020; Kumar and Saxena, 2025; Mukherjee et al., 2023; Muntongkaw et al., 2021; Nagaraja et al., 2024; Prasad et al., 2024; Shanmugam et al., 2021). Additionally, natural fibre-reinforced composites are increasingly central to sustainable materials engineering due to their low embodied energy, renewability, and end-of-life biodegradability.

Despite advancements in natural fibre production, many conventional natural fibres face supply limitations and competition with food systems, necessitating exploring alternative sources (Behera et al., 2025a; Kurien et al., 2023a; Pickering et al., 2016). Within the broad category of plant-based fibres, nonconventional and underutilized plant species have attracted attention for their potential to diversify the fibres' raw material base and support sustainable development (Karimah et al., 2021; Pattnaik et al., 2024; Raja et al., 2025). Recent studies have highlighted the strategic importance of fibres derived from rapidly renewable, low-input biomass sources, particularly those from marginal lands or aquatic ecosystems (Behera et al., 2025c). Among such

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resources is the cattail plant (*Typha* spp.) which has emerged as a promising source of both structural and functional natural fibres.

Typha is a perennial semi-aquatic genus widely distributed across temperate and tropical regions, thriving in wetlands, marshes, and along riverbanks (Bansal et al., 2019; Kadlec and Wallace, 2008). Its rapid growth, high biomass yield, and adaptability to degraded or nutrient-rich waters make it an ecologically significant and invasive species (Gotore et al., 2021; Sandoval-Herazo et al., 2021; Stewart et al., 2023; Zorai et al., 2022). Historically used for mats, baskets, and thatching, cattail fibres are increasingly attracting attention for engineered applications (Fig. S1) including composites, insulation, sorption media, oil spill cleanups, acoustics, and water treatment (Parvin et al., 2025).

Cattail's versatility stems from its distinctive fibre properties, with the coarse leaf fibres possessing excellent strength for structural applications while the fine fluffy seed fibres offer high surface area, oleophilicity, and hydrophobicity (Parvin et al., 2025; Prasad et al., 2024; Schuck, 2023). Cattail leaf fibres are rich in cellulose and hemicellulose, thus exhibit very good mechanical properties and compatibility with polymer matrices, making them good candidates for reinforcement in composite materials (Dieye, 2019; Kannan et al., 2025a; Mbeche et al., 2020). Cattail seed fibres on the other hand are characterized by low density, halved-bamboo like structures, and waxy hydrophobic surfaces, hence can excel as thermal and acoustic insulators as well as oleophilic sorbents for environmental remediation (Khan, 2021; Parvin et al., 2025; Xu et al., 2020).

In the context of global sustainability, the exploitation of cattail fibres offers several advantages. Its cultivation can be integrated into wetland conservation or invasive species control programs, potentially creating synergistic benefits for both biodiversity and water quality improvement (Alufasi et al., 2022; Bansal et al., 2019; Grosshans et al., 2011). Additionally, its rapid growth supports the potential for large-scale production without displacing food crops (Zorai et al., 2022). The cattail plant's ability to sequester carbon and uptake excess nutrients from eutrophic waters further enhances its ecological profile (Tanner, 2001). Such multifunctionality aligns strongly with contemporary sustainability frameworks that emphasize ecosystem services, resource efficiency, and material circularity as key criteria for next-generation fibre resources (Behera et al., 2025a; Kannan et al., 2025a; Kurien et al., 2026). Nevertheless, the pathway to cattail's commercialization is hampered by limitations in harvesting logistics, fibre extraction technologies, lack of established supply chains and industry standards, and market development (Nagaraja et al., 2024).

Compared to conventional bast fibres such as flax, jute, and hemp, cattail fibres remain underexplored with regard to characterization, process optimization, and life cycle assessment (Parvin et al., 2025). Variability in fibre quality due to species differences, growth conditions, and extraction methods complicates efforts to establish reliable performance benchmarks (Admas and Assefa, 2025; Hossain et al., 2024; Rezig et al., 2025; Shadhin et al., 2022). Similar challenges have been widely reported for other emerging natural fibres, underscoring the need for systematic studies that link processing parameters with structure-property relationships and end-use performance (Kannan et al., 2025b; Kurien et al., 2023b).

Despite increasing interest in cattail-derived fibres, existing studies remain fragmented. Most investigations focus either on leaf/stem fibres for construction and composites or on seed fibres for sorption with limited integration of both fibre types within a unified sustainability framework. Furthermore, reported fibre properties vary widely due to differences in species, harvesting stage, and extraction routes, making direct comparison difficult. Few studies link extraction methods, fibre structure, mechanical performance, and end-use functionality. In addition, techno-economic and circularity considerations are often discussed qualitatively rather than through structured comparison. These gaps limit the translation of laboratory findings into scalable, sustainable material systems. Hence, a critical synthesis of cattail fibre production, properties, applications, and sustainability implications is required to clarify its true potential as a next-generation natural fibre resource.

Therefore, this review analyses cattail fibre extraction methods, their physical, chemical, and mechanical properties, and explores their applications across textiles, composites, construction, and environmental remediation. By identifying key challenges and opportunities, this review aims to inform future research directions, technology development, and policy frameworks that could support the sustainable utilization of cattail fibres in a circular economy.

2. The cattail "*Typha*" plant

The genus *Typha* (*T.*) comprises about 30 species, with materials studies mainly concentrating on *T. latifolia* (broadleaf cattail), *T. angustifolia* (narrowleaf cattail), and *T. domingensis* (southern cattail) (Table 1). The cattail plant (Fig. 1a), with most of its parts (Fig. 1b) being useful, has highly been valued by human societies for a long time because of its material, nutritional, and medicinal applications (Bansal et al., 2019). The plant grows in temperate to tropical wetlands across the globe, with *T. latifolia* dominating temperate Northern hemisphere wetlands, *T. angustifolia* favouring deeper or brackish waters, and *T. domingensis* prevalent in warm/subtropical zones (Fig. 1c) (Parvin et al., 2025). As they can dominate any wetlands, these species perform key ecological functions such as, habitat for wildlife, and soil and nutrients stabilization in marshes (da Cunha Cruz et al., 2020; Shih and Finkelstein, 2008; Yu, 2021).

The effects of global warming and fertilizer run-off from agricultural activities have led to rapid expansions of the cattail plant in many regions. The plant's high net primary productivity, rapid rhizomatic spread, and adaptability to marginal lands underpin its large biomass yields (Adriano et al., 1980; Bansal et al., 2019; Li et al., 2010). Recently, it has been shown that *T. latifolia* can achieve high leaf biomass with strong carbon capture potential. Thus, controlled cultivation of the plant, especially as a fibre crop, can contribute significantly to climate change mitigation (Parvin et al., 2025; Robles et al., 2023). Despite its presence in many places, cattail remains underutilized at the industrial level, its use largely confined to traditional uses such as mat weaving, artisanal crafts, or as animal fodder (Clements, 2022).

From a circularity perspective, controlled exploitation of the cattail plant for raw material supply can complement invasive-control programs while significantly contributing to climate change mitigation (Lishawa et al., 2020; Lishawa et al., 2015). However, supply planning must consider seasonal access, water-level variability, and tighter control in protected wetlands (da Cunha Cruz et al., 2023; Kõiv-Vainik et al., 2025; Svedarsky et al., 2019). Evolving work on controlled harvesting and onsite pre-processing can reduce logistics emissions and stabilize material quality (Berry et al., 2017; Parvin et al., 2025).

3. Cattail fibres

The increasing interest in sustainable and renewable fibre sources has brought more focus on cattail as a potential natural fibre resource. Cattail plants produce a high biomass yield with fibrous leaf and stem structures suitable for many applications (Parvin et al., 2025). The plant provides two distinct types of fibres: structural fibres rich in cellulose and hemicellulose from the stems and leaves (Fig. 2a), and highly hydrophobic seed hairs (Cao et al., 2016; Manimaran et al., 2022).

At the micro-structure level, cattail leaves and stems exhibit a composite anatomy. They possess a waxy cuticle, an epidermis, vascular bundles embedded in parenchyma, and abundant aerenchyma responsible for their fibres' low density (Fig. 2b, c, d, i). Fibres are extracted from these stems or leaves through various manual or chemical techniques (Corrêa et al., 2015; Gaye et al., 2023). On the other hand, seed fibres are obtained from the long cylindrical cattail fruit structure (Fig. 2e) which turns into a dense mass of silky hairs attached to seeds when it matures (Fig. 2f). It is reported that a single cattail head can produce up to 300,000 cattail tufts each having a down-like architecture

Table 1
Characteristics and yields of the major *Typha* species.

Species	Stand ecology	Notable features	Dry biomass yield (t/ha/yr)	Fibre yield (%)	Reference
T. latifolia (Broadleaf cattail)	Freshwater marshes, shallow wetlands	Large aerenchyma lacunae; thick epidermal cuticle; robust vascular bundles	3.6–30	9–50	(Bansal et al., 2019; Grosshans, 2014; Parvin et al., 2025; Rahman et al., 2021)
T. angustifolia (Narrowleaf cattail)	Deeper/brackish waters	Narrow leaves; more slender fibres; higher silica in epidermis	1–25	~70	(Geurts and Fritz, 2018; Parvin et al., 2025; Razaq et al., 2015; van den Berg et al., 2024)
T. domingensis (Southern cattail)	Warm/subtropical wetlands	Intermediate leaf morphology; moderate wax content	5–25	~8–42 (leaf) ~81–85 (seed)	(Carhuancho et al., 2022; Khider et al., 2012; Naveena Shri and Amsamani, 2024; Pandey et al., 2022; Parvin et al., 2025)

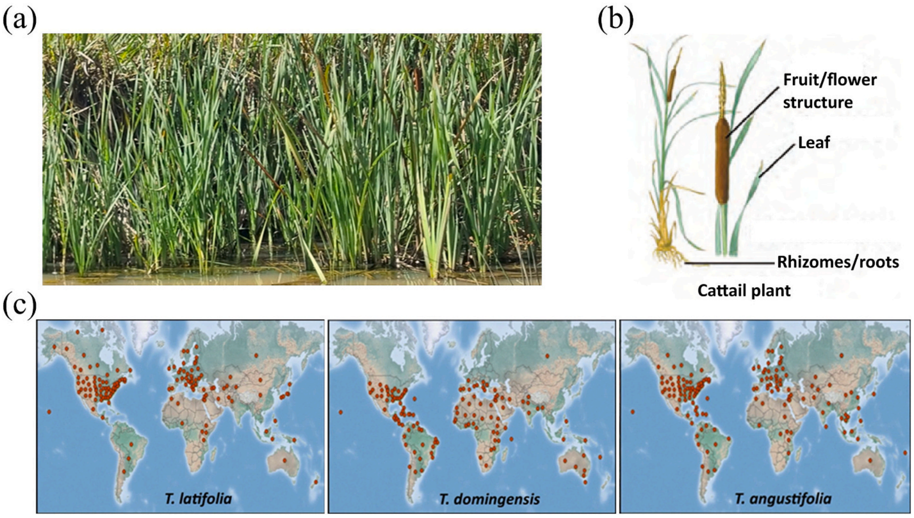

Fig. 1. (a) Wild growing cattail plants, (b) parts of a cattail plant (adapted from (Parvin et al., 2025), unrestricted use), and (c) distribution of *Typha latifolia*, *Typha domingensis*, and *Typha angustifolia* across the globe (adapted from (Bansal et al., 2019), unrestricted use).

consisting of a root, stem, and seed attached to several fibres (Fig. 2g) (Cao et al., 2016). These fibres which aid in the seed's dispersal are highly hydrophobic, extremely fine, lightweight, and hollow-like (Fig. 2h), which maximizes their specific surface area and pore volume (Cui et al., 2014; Xu et al., 2020; Zhang et al., 2018). The unique and diverse fibre features of cattail translate into attractive functional properties including low density, high porosity, high sorption capacity, excellent insulation capacity, and biodegradability (Hasan et al., 2022).

3.1. *Cattail cultivation for fibre production*

The cultivation of the cattail plant as a fibre resource presents an economic advantage due to its high biomass yield (Parvin et al., 2025). Reports indicate that up to 30 t of dry cattail matter can be obtained annually per hectare, depending on species, site conditions, and harvesting modes (Grosshans, 2014; Pratt and Andrews, 1978). Seasonal variations strongly influence fibre quality, with cattails harvested in summer yielding fibres with higher cellulose content compared to winter harvests (Haldan et al., 2022). Of importance, though, is whether the cattail plants grow on natural wetlands which provide abundant biomass but lead to inconsistent fibre qualities, or are cultivated in managed plantations allowing controlled harvesting, consistent qualities, and optimized fibre yields (Johnston, 1988; Shadhin et al., 2022). Controlled cultivation of cattail fits well in circular economy models, as it enables planned use of marginal or wetlands to produce renewable biomass especially for fibre production while minimizing waste and environmental impact (Bansal et al., 2019; Brinksma et al., 2022).

Conventional harvesting methods for the cattail plant involves manual cutting and bundling or use of mechanized mowers adapted from reed and bamboo harvesting systems (Lishawa et al., 2017). Manual harvesting is labour intensive and is common for small-scale operations or in places where mechanized equipment cannot access. Mechanized harvesters are used for larger scale operations and are designed operate in wetlands and swampy areas to cut and collect the cattails (Grosshans and Grieger, 2015). After harvesting, the usual post-harvest practices follow which include drying, shredding, and baling. These activities require careful control as they influence fibre extractability and quality (Jara-Vinueza et al., 2024).

As much as cultivation of the cattail plant shows agronomic promise, uncertainties still remain with regard to upscaling production and the existence of potential risks such as ecological trade-offs, invasive spread, and competition with conservation priorities (de Jong et al., 2021; Haldan et al., 2022). Thus, before larger scale adoption and cultivation of cattails, there should be establishment of clear governance frameworks. These should include proper land-use and environmental regulation, recognition of cultivation systems within agricultural policy, mechanisms for stakeholder participation, cross-sectoral coordination, and adaptive management to manage ecological risks such as invasive spread and conservation trade-offs (Dia et al., 2020; Williams et al., 2021).

4. Cattail fibre extraction and processing

Cattail fibre processing typically begins after harvesting and involves systematic steps (Fig. 3) which must be carefully managed to maintain fibre quality and ensure efficient extraction (Hasan et al., 2022). Extraction of leaf/stem fibres from the cattail plant is broadly similar to the conventional bast fibre extraction methods where fibres are

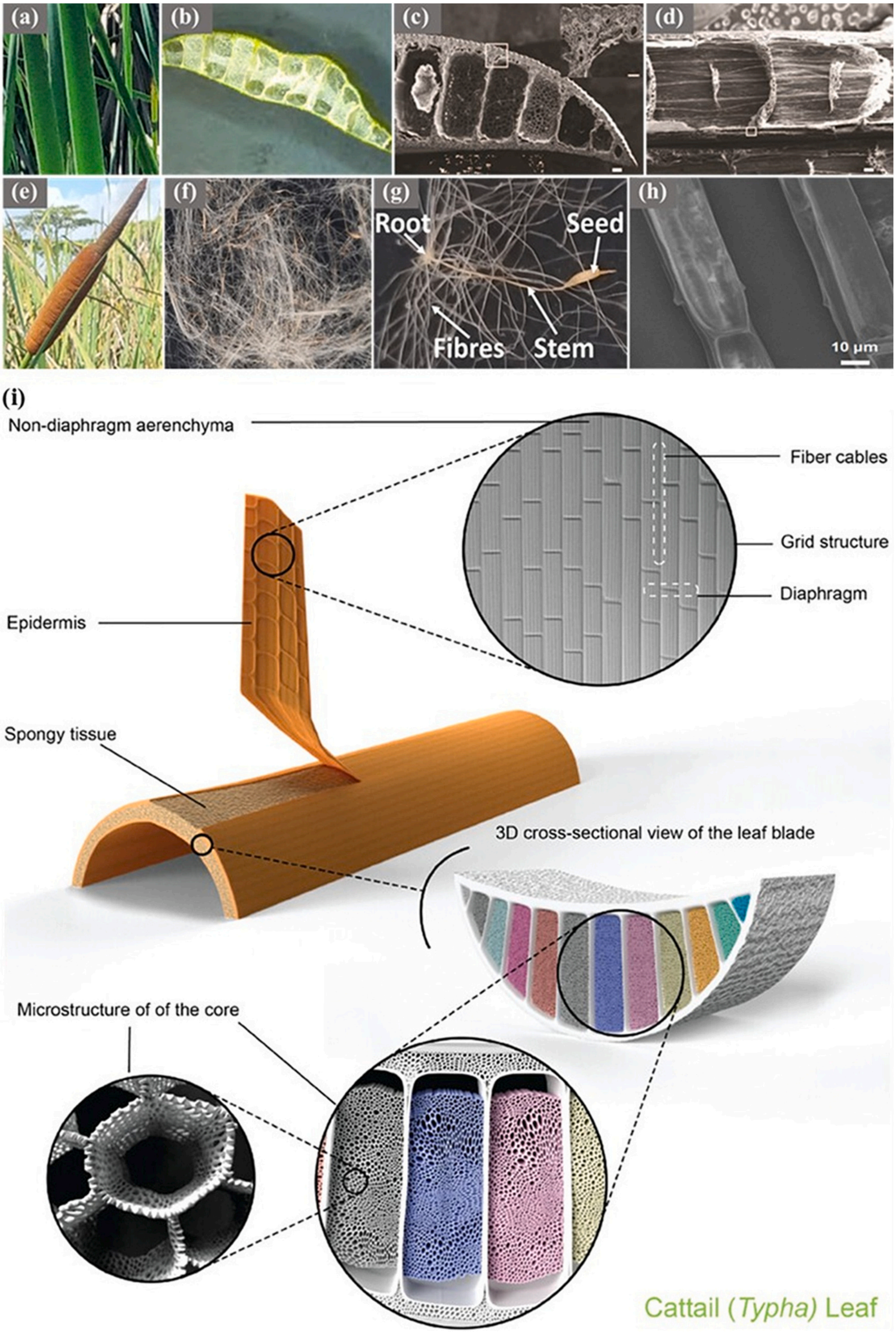

Fig. 2. Photo images of (a) cattail leaves, and (b) leaf cross-section (adapted from (Bansal et al., 2019), unrestricted use). SEM images of cattail leaf (c) cross-section, and (d) longitudinal section (c & d: adapted from (Liu et al., 2017), unrestricted use). Photo images of cattail (e) fruit structure, (f) seed fibre tufts, and (g) tuft fibre structure. (h) SEM image of cattail seed fibre (reproduced from (Wang et al., 2022), unrestricted use). (i) Structural model of the cattail leaf (reproduced from (Parvin et al., 2025), unrestricted use).

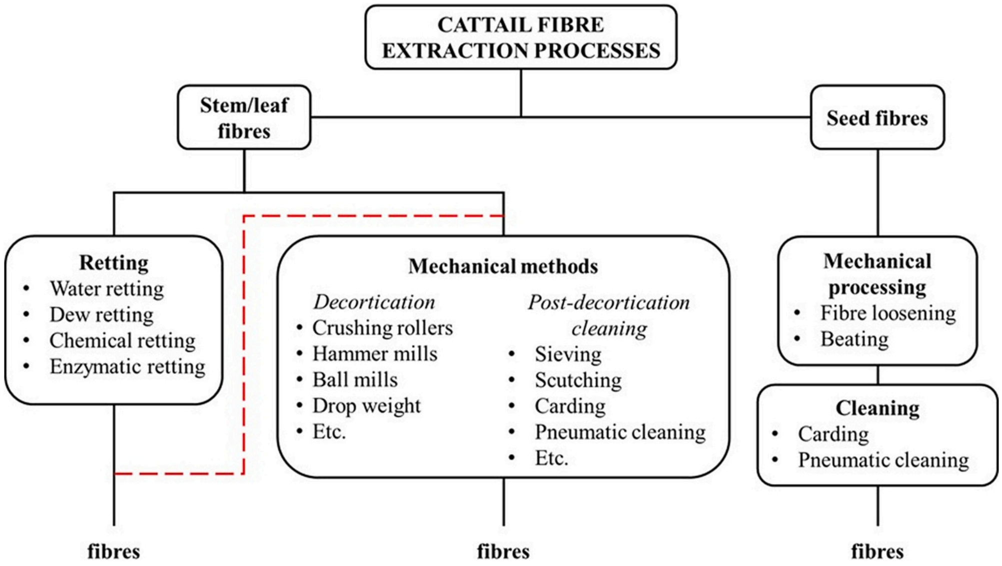

Fig. 3. Cattail fibre extraction routes (Sadrmanesh and Chen, 2019).

liberated by separating the cellulose bundles from surrounding tissues (Sadrmanesh and Chen, 2019). However, cattail's anatomical differences such as high aerenchyma and lower bast bundle density influence the technique choice and yield (Parvin et al., 2025). Common methods include water retting, chemical retting (alkaline, oxidative, or combined), enzymatic retting, mechanical decortication, and hybrid processes (Khan, 2021). For seed fibres, mechanical separation of fibres from the dense fibrous fruit structure is sufficient, often followed by cleaning and surface treatments (Oliveira et al., 2024).

4.1. Water retting

Water retting (biological degumming) is a traditional technique which relies on microbial decay of pectin to release the fibre bundles. It is done by submerging the cattail stem/leaves in ponds or tanks to soften the middle lamella via microbial pectinase activity, hence freeing the fibre bundles from parenchymal tissue (Lee et al., 2020). Cattail's aquatic habitat makes water retting feasible but may yield inconsistent fibre qualities if the retting conditions are not controlled. While effective, it consumes significant amounts of water and generates high-BOD effluent (Parvin et al., 2025). Dew retting, a field variation of water retting, involves leaving plants in the field after harvesting so that they can absorb dew, allowing for microbial growth. This is a relatively inexpensive technique which requires lower water input but is dependent on climatic conditions and may lead to variable fibre qualities (Sadrmanesh and Chen, 2019).

4.2. Chemical retting

Modern fibre extraction processes often use chemical retting which preferentially removes pectin, hemicellulose and waxy impurities (Cui et al., 2021; Kishor et al., 2024; Mbeche and Omara, 2020; Wu et al., 2024). Common chemicals include alkalis, mild acids, and certain salts, which not only extract fibres but also modify their surfaces. Alkali treatment is the most widely reported technique for cattail fibres, primarily due to its effectiveness in removing non-cellulosic components. Multiple studies report the use of NaOH concentrations between 2 and 10 wt%, at varying bath temperatures for treatment durations ranging from 1 to 12 h, resulting in cleaner fibre surfaces and improved fibre-matrix compatibility in composite applications (Hasan et al., 2022; Ikramullah et al., 2018; Shadhin et al., 2021). Alkali treatment disrupts intermolecular hydrogen bonding within the fibre bundles, improving fibrillation and cellulose exposure to produce finer fibres with enhanced surface roughness (Shadhin et al., 2021). Before treatment, harvested cattail leaves are usually dried and cut to short lengths to hasten the process (Fig. 4a-g).

Key factors that influence the fibre extraction efficiency and the major fibre properties include concentration of chemical, exposure time, and temperature (Fig. 5a-g), all of which must be adequately controlled to attain optimum fibre quality while avoiding incomplete processing or fibre degradation (Hasan et al., 2022). Alkali retting of cattail fibres with base concentration up to 5 wt% and temperature up to 80 °C for several hours has been shown to effectively remove pectin, hemicellulose, and portions of lignin to enhance fibre purity, cellulose content and crystallinity (Ikramullah et al., 2018).

Oxidative treatment, e.g., using hydrogen peroxide and/or acetic acid, can lead to further purification of the fibres, but risks fibre embrittlement if overtreated. Hybrid alkaline-oxidative sequences often provide a better trade-off between yield, purity and mechanical properties of the resultant fibres (Chattopadhyay et al., 2022; Islam et al., 2025a; Wu et al., 2024).

Fourier Transform Infrared (FTIR) spectroscopy studies (Fig. S2) confirm the chemical modifications induced by alkali treatment of cattail fibres (Ke et al., 2023). Untreated fibres exhibit a broad O—H stretching band at 3300–3400 cm^{-1}, C—H stretching near 2920 cm^{-1}, and a distinct peak at 1730–1745 cm^{-1} attributed to hemicellulose ester and acetyl groups, along with lignin-related bands at 1240–1260 cm^{-1} (Hasan et al., 2022; Ikramullah et al., 2018; Manimaran et al., 2022). After alkali treatment, marked reduction of the ~1730 cm^{-1} peak and attenuation of lignin bands indicate effective removal of hemicellulose and partial delignification, while enhanced cellulose-related peaks at 1030–1050 cm^{-1} reflect increased cellulose exposure (Cui et al., 2021; Ikramullah et al., 2018; Parvin et al., 2025).

4.3. Enzymatic retting

Enzymatic retting is an effective fibre extraction method which selectively hydrolyses the bast matrix to release fibre bundles in plant stems or leaves (Sadrmanesh and Chen, 2019). Enzymatic retting methods using pectinase, xylanase, and cellulase cocktails have been explored for selective removal of pectin and hemicellulose in various lignocellulosic fibres, and have potential for improving cattail fibre extraction with minimal cellulose degradation (Lee et al., 2020). Studies on flax and hemp fibres have demonstrated that tailored enzyme

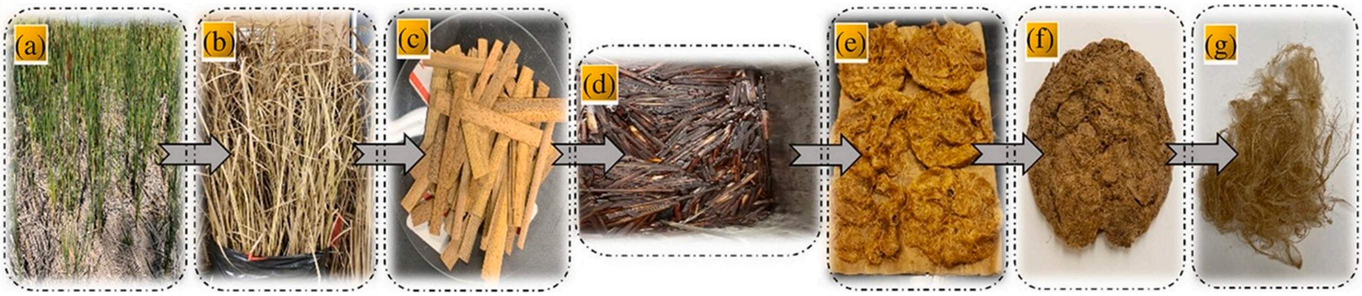

Fig. 4. Extraction of fibres from cattail leaves; (a) cattail plants, (b) collected and dried cattail leaves, (c) chopped leaves ready for retting, (d) chopped cattail leaves immersed in alkali, (e) retted and neutralized fibres, (f) dried retted fibres, and (g) individualized cattail leaf fibres. (reproduced from (Shadhin et al., 2024) as per the CC BY-NC-ND license).

cocktails can significantly reduce retting time from several days to several hours, while improving fibre quality through selective degradation of non-cellulosic components (Angulu and Gusovius, 2024). Enzymatic retting is typically conducted at moderate temperatures ranging between 30 and 50 °C, and at near neutral pH conditions (Wang and Salmon, 2025). To enhance enzyme efficiency, chelating agents such as ethylenediaminetetraacetic acid (EDTA) are often added (De Prez et al., 2018). After enzymatic retting, fibres should be subjected to thorough rinsing or enzyme inactivation to prevent over-degradation and maintain fibre integrity (Angulu and Gusovius, 2024). In some cases, additional treatments such as mild mechanical processing or use of chemical agents may further clean and prepare the fibres for subsequent applications (Akin et al., 2001; Foulk et al., 2011). In general, enzymatic retting produces cleaner fibres of consistent quality and minimal structural damage. It also generates milder effluents compared to conventional chemical methods. However, the process is expensive and requires precise control to achieve optimal results (Wang and Salmon, 2025).

4.4. Mechanical extraction

Mechanical extraction of fibres typically involves the use of decorticators, hammer mills, ball mills, blade crushers, and roller crushers (Fig. 6a-d) to release fibre bundles from dried leaves/stems of the cattail plant. It is particularly effective when combined with pre-softening steps such as spraying with steam or an alkali (Eleutério et al., 2025). Decortication breaks the outer leaf-sheath, allowing fibres to be pulled out. This mechanical extraction process is attractive for its low chemical footprint, but it often results in broken fibres with reduced tensile performance due to the high shear and compressive forces involved (Hobson et al., 2001). Usually after retting, the partially freed fibre bundles can further be refined through a mechanical carding process which aligns and separates the fibres to produce a wool-like web that can further be processed through light-medium pressing to produce a nonwoven fabric (Shadhin et al., 2021; Zimniewska, 2022).

Compared to bast fibres such as flax or hemp, cattail fibres are finer and more brittle, making them more susceptible to damage during aggressive mechanical extraction. This necessitates optimization of rotor speeds, feed rates, and pressure in decorticators or mills to balance fibre yield and quality (Diouf and Gning, 2024).

4.5. Hybrid processes

Hybrid extraction methods, which combine mechanical, chemical, enzymatic, or physical treatments in sequence or simultaneously, have gained attention for their ability to yield cleaner fibres with improved fineness, strength, and surface characteristics (Eleutério et al., 2025). These methods often begin with a mild mechanical disruption to break the outer layers and partially free fibre bundles. This is typically followed by chemical or enzymatic treatments to further remove lignin, hemicellulose, and pectin (Elanthikkal et al., 2010; Shadhin et al., 2021). Alternatively, mechano-enzymatic approaches, where fibres are subjected to simultaneous mechanical mixing and enzymatic hydrolysis, have shown promising results in increasing fibre accessibility and porosity while minimizing structural damage (Rahikainen et al., 2020).

Physical activation techniques such as ultrasound or microwave-assisted alkali pretreatments have also demonstrated effectiveness in loosening fibre structures and enhancing chemical penetration (Xia et al., 2024). For instance, ultrasound-assisted alkaline extraction achieved significantly higher delignification under milder conditions than alkali treatment alone (Wu et al., 2017), while microwave-assisted processes improved fibre swelling and reduced processing time (Liu et al., 2021). Such treatments are particularly beneficial in preserving fibre length and minimizing microstructural damage, which are essential for applications in composites and textiles (Rahikainen et al., 2020).

The efficiency of hybrid methods is highly dependent on process parameters such as chemical concentration, treatment time, and temperature. Overly harsh conditions may lead to fibre embrittlement or shortening, impacting on their suitability for structural applications. Therefore, optimization is important to balance fibre quality, environmental impact, and processing costs (Eleutério et al., 2025).

4.6. Extraction of cattail seed fibres

Cattail seed fibres differ fundamentally from the structural fibres obtained from the leaves and stems, thus, their extraction is much different. Extraction of seed fibres is mainly a mechanical process involving breaking open the fruit structure, and then separating the fibres from the seeds. The process begins with the collection of the mature fruit heads which are then air-dried in a ventilated environment to prevent microbial growth and promote fibre loosening (Pandey et al., 2022). After drying, fibre separation can be done manually by hand-rubbing or gentle beating to detach the fluffy seed hairs. The fibres come off still attached to their seeds, necessitating a seed removal step, which can be challenging due to the extremely low mass and aerodynamic properties of the seeds (Wall and Macdonald, 2009).

Seed separation and trash removal can be performed using fibre stripping machines equipped with rotating suction cylinders. These systems strip the fibres from the seeds, allowing seeds and debris to fall away while collecting the detached fibres as a lightweight web. However, complete seed removal is difficult, and trace amounts often remain embedded within the fibre mass. These fibres are largely used without further treatment to preserve their natural hydrophobicity which is especially important for oil sorption (Cao et al., 2016; Gorbachev et al., 2025). For purposes of cellulose extraction, cleaned cattail fibres can undergo chemical treatment, usually using an alkali followed by an oxidative treatment to remove non-cellulosic components. Table 2 gives a summary of the extraction techniques for cattail fibres.

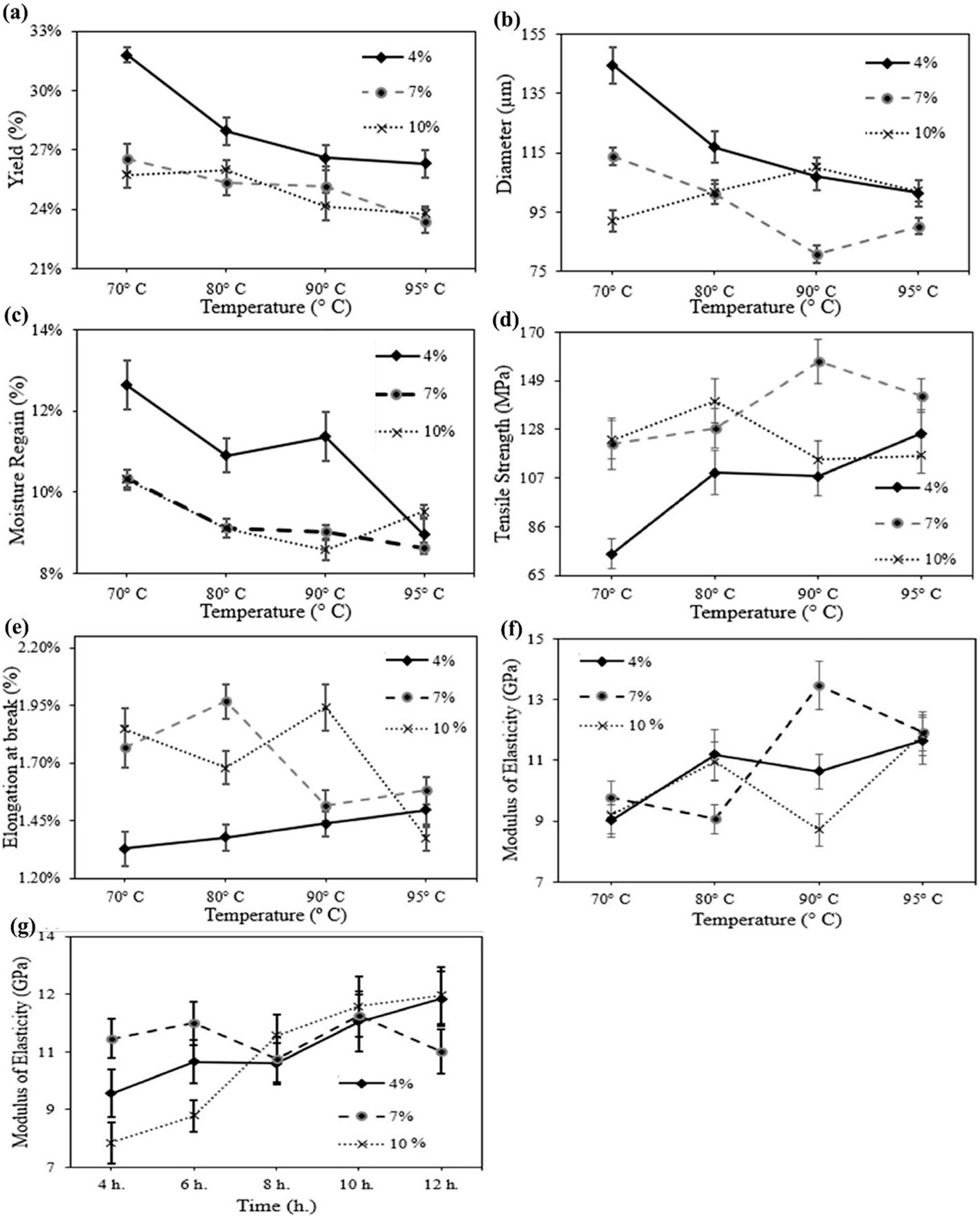

Fig. 5. The effects of interaction of temperature and NaOH concentration on (a) yield, (b) diameter, (c) moisture regain, (d) tensile strength, (e) elongation at break, and (f) modulus of elasticity of extracted fibres. (g) Interaction effects of time and alkali concentration on fibres' modulus of elasticity. (Adapted from (Hasan et al., 2022), unrestricted use).

5. Cattail fibre properties

5.1. Chemical composition

Cattail fibres are lignocellulosic in nature (Fig. 7), comprising cellulose, lignin, hemicellulose, pectin, and minor components such as waxes and ash (Hafez et al., 2025). Like many natural plant fibres such as flax and jute, the biochemical composition of cattail fibres can vary considerably depending on species, environmental conditions, plant maturity, and processing method (Hossain et al., 2024; Pandey et al., 2022; Parvin et al., 2025).

In their untreated form, stem and leaf fibres can contain approximately 38–48 wt% cellulose, 12–22 wt% lignin, and up to 23 wt%, hemicellulose. The presence of pectin and surface-bound waxes contributes to inter-fibre adhesion in the raw plant structure and imparts hydrophobicity, particularly in aerial parts of the plant (Admas and Assefa, 2025; Hafez et al., 2025). Retting and chemical treatments selectively degrade and remove the non-cellulosic components to

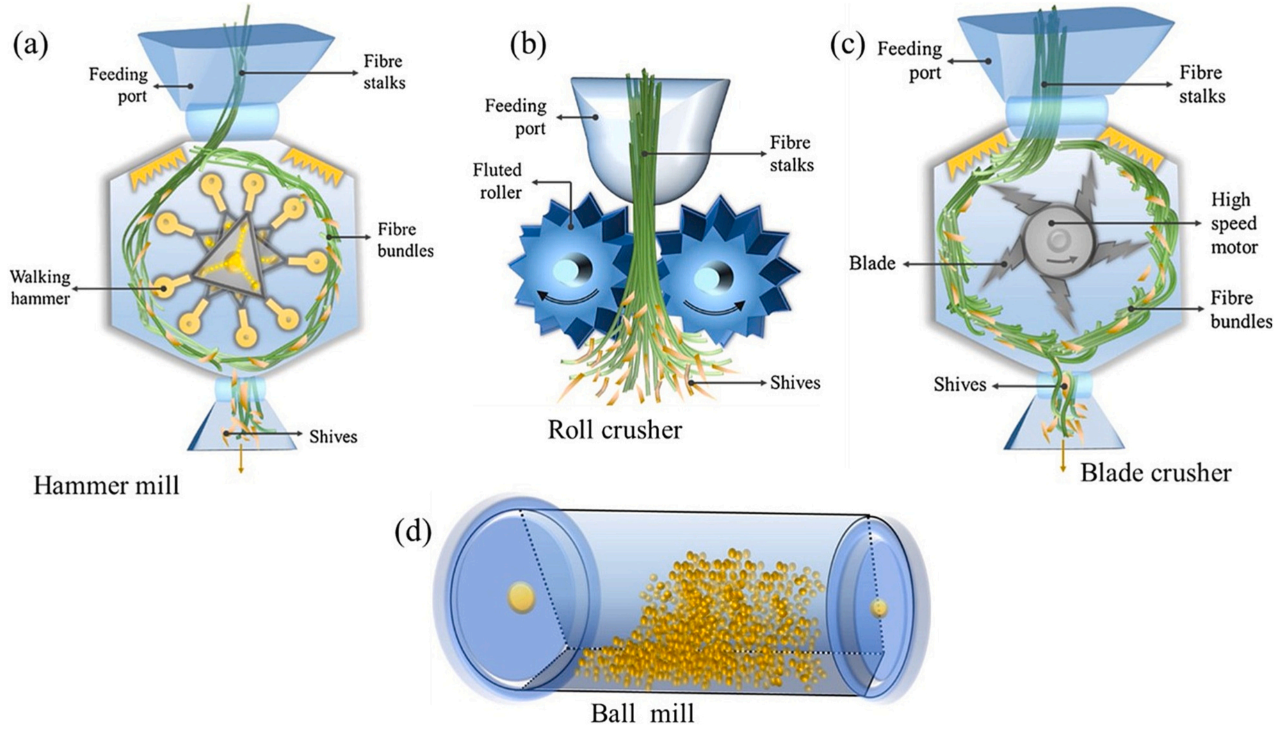

Fig. 6. Schematic representations of (a) hammer crusher, (b) roll crusher, (c) blade crusher, and (d) ball mill used in mechanical bast fibres extraction. Adapted from (Lyu et al., 2021) with permission from Elsevier © 2021).

Table 2
Summary of extraction methods for cattail fibres.

Method	Extraction parameters	Fibre yield (%)	Cellulose content (%)	Tensile strength (MPa)	References
Water retting	7–15 days ~20°C	~9	63–73	~245–370	(Admas and Assefa, 2025; Diouf and Gning, 2024; Pandey et al., 2022)
Mechanical decortication		~12–22	~50–60	~100–500	(Admas and Assefa, 2025; Diouf and Gning, 2024)
Chemical retting	NaOH, KOH, LiOH (2–10%) 2–12 h @ 50–120 °C	~18–50	~56–72%	~9–1100	(Hasan, 2019; Ikramullah et al., 2018; Kamali Moghaddam, 2022; Parvin et al., 2025; Rahman et al., 2021; Shadhin et al., 2022; Shadhin et al., 2021)
Hybrid (alkali + oxidative)	7% NaOH @ 80 °C for 3 h (repeat 2–3 times) + Immersion in H_2O_2 for 3 h @ 45 °C.		~78%	–	(El Amri et al., 2023)
Hybrid (microwave + alkali)	1–4% NaOH/KOH; > 10 min	~26–35	–	259–529	(Jahan, 2023)

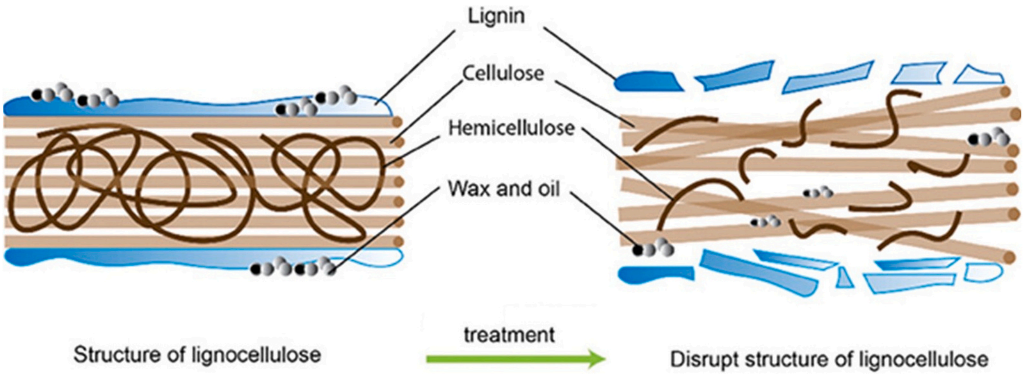

Fig. 7. Lignocellulosic biomass structural composition (adapted from (Parvin et al., 2025), unrestricted use).

increase the relative cellulose content and crystallinity index of cattail fibres. This modification enhances surface morphology, mechanical strength, and thermal stability, which are critical for improving fibre-matrix adhesion and performance in composite materials (Luamkanchanaphan et al., 2012; Shadhin et al., 2021). Retted cattail stem and leaf fibres have shown cellulose contents increasing to over 65 wt%, with corresponding reductions in lignin and hemicellulose (Manimaran et al., 2022; Parvin et al., 2025).

Cattail seed fibres are unicellular and highly porous, with a thin cell wall structure and significant internal lumen volume. Their surface is coated with epicuticular waxes and lipids, typically exceeding 10 wt%, giving rise to their well-documented hydrophobicity and low wettability (Dong et al., 2015). The fibres also contain cellulose at about 42 wt% content before treatment and up to ~90 wt%, after a number of chemical treatments (Cui et al., 2021). The lignin content in seed fibres is reportedly relatively low (~9 wt%) compared to structural fibres, likely contributing to their softer texture and lighter colouration (Pandey et al., 2022).

5.2. Morphological and physical properties of cattail fibres

Microscopy studies have revealed cattail stem and leaf fibres to be multicellular bundles (Fig. 8a) with a central lumen, walls of varying thickness, and relatively low microfibrillar angles compared to traditional bast fibres (Witztum and Wayne, 2014). Cattail fibres and stalks have high porosity with large cavities which reduce their bulk density. This has made them excellent for applications such as insulations boards which are reported to have low thermal conductivities (Jara-Vinueza et al., 2024; Luamkanchanaphan et al., 2012; Wu et al., 2021). Scanning electron microscopy studies (Shadhin et al., 2022; Shadhin et al., 2021) have shown that cattail fibres extracted via alkali retting lose surface impurities, exhibit pit formation and surface roughening, which are likely to expose internal surfaces and increase surface area for better bonding in polymer composites. Fibre diameters reported are in the range ~ 13–143 μm, while fibre lengths depend on the cut leaf/stem length and extraction technique (Shadhin et al., 2024; Shadhin et al., 2021).

Moisture regain values of cattail leaf fibres under ambient conditions are comparable to those of other cellulosic fibres (Hasan et al., 2022; Rahman et al., 2021). Extraction conditions have a significant effect on moisture regain. For instance, in fibres extracted under alkali treatment, moisture regain has been demonstrated to decrease with increase in treatment time, temperature, and alkali concentration (Hasan et al., 2022).

Cattail seed fibres are very fine (Fig. 8b) with diameters of about 10–37.5 μm, lengths of ~8–15 mm, and a hollow-like structure with a hydrophobic wax coating over their lignocellulosic skeleton. Microscopy studies show single fibres to have a unique cross-section with a sunken centre and "winged" sides (Fig. 8c, d) (Cui et al., 2014; Dong et al., 2015; Wu et al., 2021; Xu et al., 2020). Untreated seed fibres usually exhibit a generally smooth surface, which become foldy and expose the xylem vessels upon dewaxing treatments (Fig. 8e). Alkali treatments make the fibre surfaces rough (Fig. 8f) due to the removal of most non-cellulosic components. Further treatment processes such as bleaching results in significant distortion of the fibre surfaces (Fig. 8 g) indicating fibrils separation due to removal of residual binding lignin (Cui et al., 2021). The fibres' extremely low density, fine diameter, and unique cross-section make them valuable for low-weight fillings, insulation, and sorption media. However, their tensile strength and spinnability remain limited due to short fibre length and fragile morphology. The presence of epicuticular waxes makes cattail seed fibres highly water-repellent with water contact angles exceeding 130° (Cao et al., 2016; Srisuk et al., 2024). This hydrophobicity can reduce the absorption of water-borne dyes in case of textile applications or lessen adhesion to polymer matrices when used in composites unless the surface is modified.

One major advantage of cattail fibres is their low thermal conductivity. Boards or woven mats made from stem or leaf-derived fibres have been shown to have conductivity values in the range of ~0.04–0.07 W/m·K, comparable to those of mineral wool and hemp-based insulating materials (Jara-Vinueza et al., 2024; Luamkanchanaphan et al., 2012). Cattail seed fibres could potentially yield lower conductivities due to their fluffy nature, and high porosity.

Regarding thermal stability of cattail fibres, studies have revealed untreated fibres to exhibit a major degradation between approximately 220 and 300 °C attributed to hemicellulose decomposition (Luamkanchanaphan et al., 2012; Mbeche and Omara, 2020). The principal cellulose degradation occurs between 300 and 370 °C, while lignin degradation extends over a broader temperature range above 400 °C. Alkali-treated cattail fibres show a modest increase in the onset degradation temperature and a shift of the main decomposition to higher temperatures, reflecting improved thermal stability (Mbeche and Omara, 2020). This enhancement is attributed to the removal of thermally unstable hemicellulose and an increase in relative cellulose content. These findings indicate that alkali-treated cattail fibres are thermally stable enough for processing with biodegradable polymers and conventional thermoplastics below 220 °C (Neto et al., 2021).

5.3. Mechanical properties

The mechanical properties of cattail stem and leaf fibres vary widely and are highly sensitive to fibre origin, microstructural characteristics, moisture content, extraction method, and testing conditions (Admas and

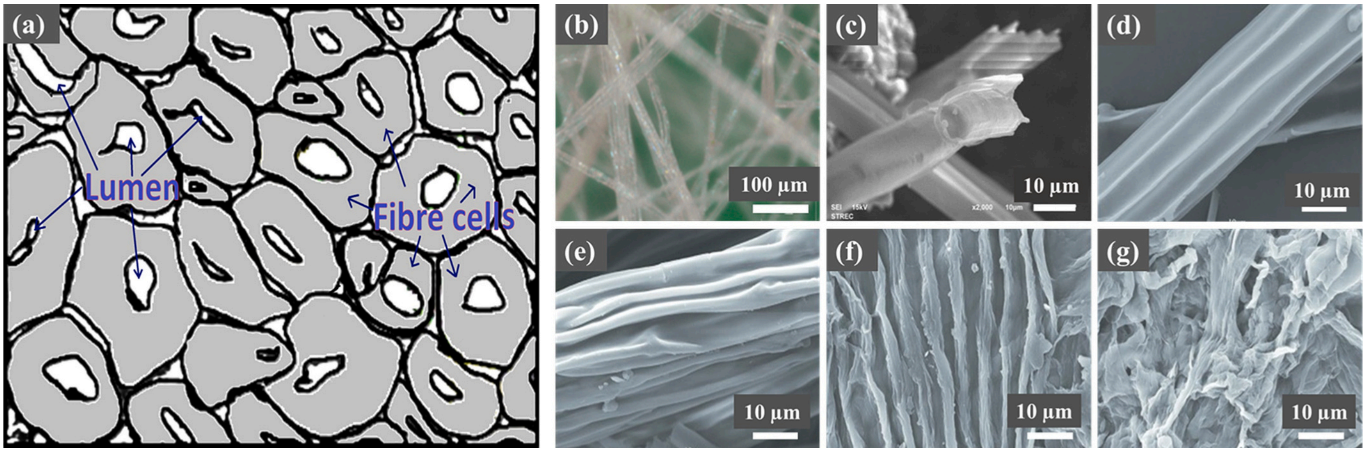

Fig. 8. (a) schematic cross-section of the cattail leaf fibre showing various lumen shapes and wall thicknesses (Witztum and Wayne, 2014). (b) Optical image of cattail seed fibre surfaces, and SEM micrographs of their (c) cross-section, (adapted from (Srisuk et al., 2024), unrestricted use) (d) longitudinal section, (e) dewaxed surface, (f) alkali treated surface, and (g) bleached surface (d, e, f, & g: adapted from (Cui et al., 2021) with permission from Elsevier © 2021).

Assefa, 2025; Hossain et al., 2024; Shadhin et al., 2021). Studies have shown that pristine cattail fibres can have tensile strengths ranging between 9 and 365 MPa with Young's modulus values of about 3 to 40 GPa (Parvin et al., 2025; Shadhin et al., 2021). These relatively modest but broadly ranging values are primarily attributed to differences in fibre maturity, fibre diameter, lumen size, and interfacial bonding between the cellulose microfibrils (Witztum and Wayne, 2014). Cattail's mechanical properties have been reported to improve under favourable extraction treatments (Hasan et al., 2022), reduced fibre size, and moderate relative humidity, where limited moisture plasticization enhances stress transfer without excessive swelling (Pavlovic et al., 2025). Under such optimized conditions, cattail fibres' tensile strength can exceed 1100 MPa with tensile modulus values in the range of 48–75 GPa (Hossain et al., 2024; Rahman et al., 2021; Shadhin et al., 2022).

Alkali-treated fibres with reduced diameter and increased cellulose crystallinity consistently exhibit higher strength and modulus due to the partial removal of amorphous hemicellulose and lignin, resulting in better microfibril alignment and load sharing (Parvin et al., 2025). However, excessive treatment, as has been reported for other lignocellulosic fibres, can lead to fibrillation damage, cellulose degradation, and embrittlement, highlighting the importance of process optimization (Kurien et al., 2023b; Pattnaik et al., 2025). Compared to flax and jute, optimized cattail fibres exhibit comparable specific strength but greater scatter, largely due to cattail's unique morphology, fibre diameter variability, and sensitivity to extraction conditions (Parvin et al., 2025; Shadhin, 2021). This scatter is further exacerbated by differences in gauge length, fibre selection, humidity conditioning, and whether measurements are conducted on single fibres or fibre bundles.

For cattail-based hybrid composite materials, improvements achieved at the fibre level translate into enhanced composite performance, particularly in flexural strength, impact resistance, and damage tolerance. When used as partial or full reinforcement, cattail fibres generally outperform cereal straw-based composites and show comparable or superior toughness to sisal-reinforced systems, especially under impact and bending loads (Bajwa et al., 2015; Mbeche and Omara, 2020). Composite panels incorporating alkali-treated cattail fibres have demonstrated tensile strength increases of approximately 20–30% relative to untreated counterparts, indicating improved fibre-matrix adhesion and more efficient stress transfer (Hasan et al., 2022; Shadhin et al., 2021). Compared with composites reinforced with flax or hemp, cattail-based composites typically exhibit lower absolute tensile and flexural stiffness, but comparable specific properties due to the inherently lower density and unique morphology of cattail fibres (Shadhin et al., 2021). Similar trends have been reported for other low-density plant fibre composites, where reduced stiffness is offset by improved energy absorption and impact performance (Faruk et al., 2012). As a result, cattail-based composites are particularly attractive for lightweight and functional applications where stiffness requirements are moderate and weight efficiency or damping capacity is prioritized over maximum load-bearing performance. Nonetheless, the greater scatter in the mechanical properties of cattail-based composites emphasizes the need for optimized fibre surface treatments and hybridization strategies to achieve performance consistency comparable to established bast-fibre composite systems (Pickering et al., 2016; Shadhin, 2021). Environmental exposure studies on similar lignocellulosic fibre composites indicate that moisture uptake, fibre swelling, and progressive interfacial degradation are significant contributors to mechanical property decline and long-term reliability concerns for outdoor applications (Pattnaik et al., 2025).

As for cattail seed fibres, reliable data on mechanical properties remains scarce, likely because standardized single-fibre testing is challenging due to their short lengths, low density, and bundled morphology. A study on the mechanical properties of the cattail trunk/stem fibre bundle attached to the seed (Fig. S3) reported a tensile strength of approximately 107 MPa, a Young's modulus of about 6.2 GPa, and an elongation at break of around 3.9% (Wu et al., 2021). While these values are lower than those of optimized leaf fibres, they are comparable and may exceed those of other seed-derived fibres such as cotton linters.

At the bulk scale, cattail seed fibres exhibit excellent compressive resilience and recovery under low-to-moderate loads, attributable to their highly porous, fluffy architecture (Cao et al., 2016). This behaviour can particularly be advantageous for insulation, cushioning, and padding applications, where energy absorption, resilience, and low density are more critical than tensile strength.

5.4. *Water absorption*

Cattail leaf and stem fibres exhibit high moisture affinity due to their lignocellulosic composition and porous internal structure. Some studies have reported that untreated cattail fibres absorb water rapidly during the initial immersion period, followed by a saturation stage, a behaviour primarily driven by the presence of hemicellulose and accessible hydroxyl groups (Hasan et al., 2022; Rahman et al., 2021). Alkali treatment significantly reduces water absorption by removing hemicellulose and surface impurities, resulting in fewer hydrophilic sites and a more compact fibre structure. Reductions in water uptake ranging from 10 to 35% have been reported depending on alkali concentration and treatment duration (Hasan et al., 2022; Shadhin et al., 2022). When incorporated into composites, alkali-treated cattail fibres contribute to reduced thickness swelling and improved dimensional stability (Rizal et al., 2019).

The water absorption behaviour of cattail fibres and their lignocellulosic nature make them fully biodegradable, where microbial degradation preferentially targets amorphous regions. Alkali-treated fibres may exhibit slightly reduced biodegradation rates due to lower amorphous content, but remain environmentally degradable and compatible with composting systems (Cui et al., 2021; Kamali Moghaddam, 2022).

5.5. *Factors affecting properties of cattail fibres*

The properties of cattail fibres are highly variable and influenced by a range of biological, environmental, and processing factors. A key factor is the stage of growth at harvest. As the plant matures, the chemical composition and microstructure of the fibres change. Studies have shown that fibres harvested at different phenological stages exhibit significant variation in tensile strength and modulus, with tensile stress ranging from approximately 400 MPa up to 1500 MPa depending on the growth stage (Hossain et al., 2024). These changes are closely tied to the changes in the fibre's internal composition, with higher cellulose content generally contributing to higher tensile strength and stiffness. Hemicellulose and pectin have a positive correlation with failure strain and specific strength, while lignin impacts negatively on tensile strength and stiffness (Komuraiah et al., 2014). The high surface wax content on cattail seed fibres makes them naturally hydrophobic and oleophilic (Cui et al., 2014; Gorbachev et al., 2025). Internally, the microfibril angle and cell wall thickness affect mechanical behaviour, with smaller angles correlating with better strength and stiffness (Hossain et al., 2024; Komuraiah et al., 2014). As well, the variation in porosity with maturity of cattail fibres contributes to low density and high insulation capacity while introducing variability in strength due to potential structural defects. Moreover, fibres from different parts of the plant i.e., leaves versus stem or outer leaves versus inner leaves, can vary in diameter, strength, and chemical content (Hossain et al., 2024; Pandey et al., 2022; Witztum and Wayne, 2016). This variation can further be compounded by natural defects in the fibres, such as irregular cross-sections, which create stress concentrations and reduce mechanical reliability.

The processing techniques, particularly fibre extraction and chemical treatments, considerably impact fibre quality. Processing parameters, such as time, temperature, and chemical concentration, influence the fibre attributes and require a delicate balance to attain the desired properties and maximum fibre yield (Parvin et al., 2025). For instance, while alkali and oxidative treatments remove non-cellulosic materials leading to an enhancement in fibre stiffness and reduced moisture uptake, poorly controlled or excessive treatments may lead to degraded fibres and diminished fibre yield (Hasan et al., 2022; Rahman et al., 2021).

6. Applications of cattail fibres

6.1. Textiles

Historically, the leaves of cattails have been used to weave mats, baskets, and for thatch (Mitich, 2000). Modern use of cattail has extended this to textile substrates where the cellulosic fibre bundles are extracted via mechanical or chemical means and then blended with other natural or synthetic fibres for fabric use (Chakma et al., 2017; Khan, 2021). The processing of cattail leaf-based fibres towards textile applications has revealed them to have moisture regain, mean diameter, and thermal resistance comparable to wool and cotton, a dye exhaustion similar to that of cotton, and colour fastness meeting industry standards. Their fibre stiffness, is however quite high making them difficult to process in conventional spinning equipment (Liu et al., 2011; Rahman et al., 2021). In woven and knit constructions, blends containing cattail leaf fibres may exhibit reduced yarn evenness and lower tenacity, compared to when using pure cotton for instance, because of fibre coarseness and variability. While leaf fibre coarseness limits use in fine apparel, blends for rustic textiles, accessories, and home upholstery are feasible at low cattail fractions (≤30 wt%) or in nonwoven structures where bulk and warmth outweigh fibre fineness requirements (Kumar and Saxena, 2025). Non-woven fabric formation is the most versatile route for transforming cattail fibres to usable textiles through common techniques such as stitch-bonding, air-laying, etc. (Moghaddam et al., 2016; Parvin et al., 2025; Srisuk et al., 2024). In particular, the seed fibres provide exceptional bulk and resilience in nonwovens processed through hot-press or bicomponent-binder approaches to yield disposable, hydrophobic flexible laminates and padding materials (Srisuk et al., 2024). Owing to their waxy cuticle and structure, finished webs made of cattail seed fibres show fast oil uptake but slow wettability which is advantageous for disposable absorbent technical textile layers where water repellence is desired (Dong et al., 2015; Khan, 2021). In common home use, the cattail seed fibres can potentially substitute conventional down fibres in pillows and jackets where biodegradability and cost are key drivers. The usefulness of the fluffy seed fibres from cattail has been demonstrated in prototypes such as Finland's "Fluff Stuff" shown to compete with down in filling, due to its bulk, resilience, and hydrophobic surface (Minna et al., 2022).

6.2. Polymer composites

Cattail leaf/stem fibres function as lightweight reinforcement in unsaturated polyester, epoxy, and PLA matrices (Mbeche et al., 2022; Parvin et al., 2025; Saravanan et al., 2020). Alkali and silane surface treatments are commonly used to remove pectin and hemicellulose and to expose cellulose, improving fibre wettability and interfacial bonding with polymer matrices (Alao et al., 2021; Rizal et al., 2018). These treatments often improve the composite's tensile strength and modulus, with the improvement dependent on matrix-fibre ratio, treatment conditions, fibre type and matrix chemistry (Rizal et al., 2019; Shadhin et al., 2021). In thermoplastic matrices, malleated polyolefins and other coupling agents are established routes to enhance the interfacial shear strength by reacting with fibre surface hydroxyls and compatibilizing with the polymer phase (Djafari Petroudy et al., 2023; Keener et al., 2004). However, it should be noted that careful moisture control and selection of processing temperatures are critical because the natural fibre components can undergo thermal decomposition and property loss if exposed to excessive temperatures or retained moisture during processing (Neto et al., 2021; Pavlovic et al., 2025). Hybridization with higher-performance natural fibres such as flax, or the addition of microfibrillated cellulose are key to tailoring stiffness-toughness tradeoffs while still maintaining low composite density (Ismail et al., 2022).

6.3. Building and insulation products

Many studies demonstrate that cattail leaf fibres are increasingly being incorporated into construction materials (Brinksma et al., 2022; Jara-Vinueza et al., 2024). Boards produced from cattail leaf mass together with mineral binders exhibit low thermal conductivities and structural stability, making them promising as load-bearing insulation panels (Krus et al., 2015; Luamkanchanaphan et al., 2012; Parvin et al., 2025). Panels containing cattail fibres have been shown to offer structural properties that approach those of conventional wood-based boards, with the added benefit of low density (Krus et al., 2014). Recent studies show that composites of cattail with clay or gypsum enhance thermal, mechanical, and acoustic performance in wall systems with performance comparable or exceeding those of commercial options (Coulibaly et al., 2025; Dieye, 2019; Muntongkaw et al., 2021). A range of binder systems including mineral binders and resins have been explored, with initial findings suggesting good resistance to fire and moisture, though quantitative durability data under moisture cycling remain limited (Krus et al., 2015; Parvin et al., 2025). Because cattail-based boards leverage low density and renewable biomass, they hold promise for sustainable lightweight core, cavity-insulation and interior acoustic panels (Moghaddam et al., 2016). An aspect of these materials still requiring attention is their durability which remains largely underexplored. It has been highlighted that cattail-based construction materials may undergo performance degradation under cyclic climatic or moisture exposure. For instance, a cattail-based geotextile exhibited statistically significant tensile strength loss after outdoor exposure, with the strength-loss moderated by waterproof coatings (Holanda et al., 2024a). Although dedicated long-term moisture cycling and ageing studies of cattail-based structural boards are scarce, some evidence suggests vulnerability to hygrothermal effects which are sensitive to fibre morphology and proportion (Niang et al., 2018).

6.4. Filtration and environmental remediation

Beyond construction applications, cattail, especially its seed-derived fibres, have been demonstrated as strong biosorbents for oil spills and aqueous pollutants (Dong et al., 2015; Gorbachev et al., 2025; Nguyen et al., 2022). Cattail-based sorbents leverage high porosity, hierarchical pores, and tailored surface chemistry, positioning them as low-cost, biodegradable options. Raw or minimally cleaned seed fibres show rapid and selective uptake of hydrocarbons with reported oil sorption capacities ranging from 11 to 31 g/g, depending on sorbent packing density, structure, oil type, and temperature (Cao et al., 2016; Cui et al., 2014; Dong et al., 2015; Xu et al., 2020). The sorbents often retain over 90% of absorbed oil over 24 h with the mechanism of sorption understood to involve the highly hydrophobic wax-coated fibre surface, low density, hollow lumens and capillary action (Cui et al., 2014). Cellulose extracted from cattail seed fibres has been used to fabricate composite aerogels that can adsorb antibiotics at a capacity exceeding 172 mg/g alongside other micropollutants, while retaining mechanical integrity after repeated use (Cui et al., 2021). Carboxylated cattail fibres have been shown to possess excellent sorption capacity for fluoroquinolone residues in water, with high reproducibility and reusability and extraction efficiencies that could exceed 80% (Zhang et al., 2022). As well, cattail leaf fibres have demonstrated excellent potential as sorbents for heavy metals such as Cd and Pb from water with up to 95% removal efficiency (Phaenark et al., 2023).

Cattail fibres have also been widely investigated for soil and sediment remediation through biodegradable geotextiles and bioengineering systems, where they contribute to erosion control, slope stabilization, and enhanced vegetation establishment (Holanda et al., 2008; Holanda et al., 2024a; Ijaz et al., 2016). Their high cellulose content, intrinsic permeability, and favourable tensile behaviour enable effective short-to-medium-term mechanical reinforcement, while avoiding the long-term environmental burdens associated with synthetic geosynthetics. Although cattail fibres are inherently biodegradable, surface treatments such as alkali modification have been shown to delay degradation, improve interfacial interactions, and extend functional service life, making cattail-based materials particularly attractive for erosion-prone landscapes and ecological restoration initiatives (Holanda et al., 2024b). Overall, cattail fibres represent an economical and environmentally benign substrate that can be used either in native form or with simple chemical modifications for both aquatic and terrestrial environmental remediation.

6.5. *Energy devices and functional materials*

Degummed cattail fibres have been carbonized to produce porous, conductive carbon materials suitable for energy-storage devices. For example, cattail-based cellulose microfibres converted into carbon aerogels and anchored with polypyrrole, to make a binder-free supercapacitor has been shown to attain an areal capacitance of 419 mF/cm^2 with excellent cycling stability (Yu et al., 2018). Other works have demonstrated cattail-derived activated porous carbon achieving high charge-discharge capacity (~815 mAh/g) retained over 400 cycles as the anode for Li-ion batteries (Li et al., 2023). Carbonized cattail-based gas sensors have demonstrated real-time detection, quick response and recovery, and selectivity for target gases with performance stability sustained over several weeks (Yang et al., 2022). This leveraged on the porous structure and defect-rich carbon of degummed cattail fibres to enable rapid toxic gas detection. In situ functionalisation of cattail fibre-based substrates, with conductive polymers for instance, have been shown to yield flexible device architectures, applicable for wearable sensors or energy storage devices (Xiao et al., 2020).

As a sustainable fuel source, cattail biomass can be processed into pellets, briquettes, and bioethanol, though efficiency and logistics remain significant bottlenecks. Past work have shown that cattail-based pellets can attain a gross calorific values comparable to those of commercial wood pellets (Grosshans and Grieger, 2015; Svedarsky et al., 2019). Studies of anaerobic digestion and hydrothermal carbonization of cattail have confirmed their convertibility to methane and hydrochar further anchoring cattail's potential as a sustainable energy resource (Zhang et al., 2020).

6.6. *Biomedical and healthcare applications*

Biodegradable nonwovens based on cattail leaf or seed fibres blended with biopolymers such as PLA have been proposed as sustainable alternatives for single-use medical textiles including surgical gowns, drapes and absorbent dressings (Srisuk et al., 2024). It has been demonstrated that blends of PLA bicomponent fibres with natural fibres such as cattail can produce composite webs with the permeability and handling characteristics suitable for medical nonwovens (Parvin et al., 2025; Srisuk et al., 2024). The attainable mechanical and barrier properties depend on the fibre content and processing route (Šajn Gorjanc and Kostajnšek, 2024). For cattail-based biomedical and healthcare textiles, antimicrobial surface finishing remains an attractive strategy, especially with the use of biobased compounds such as chitosan-based coatings, tannins, or plant-based polyphenols which possess proven biocompatibility and antimicrobial capability, (Aliabadi et al., 2021) potentially augmenting the intrinsic phenolic chemistry of certain cattail types (Alzagameem et al., 2019; Ivanov and Godjevargova, 2024; Parvin et al., 2025).

7. Sustainability, circularity, and techno-economic viability of cattail fibre production

The development of cattail fibres into commercially viable materials depends not only on their technical performance but also on cost competitiveness, scalability, and environmental sustainability. A multi-criteria assessment that integrates techno-economic analysis (TEA) and life cycle assessment (LCA) is critical to inform investment and policy decisions. Sustainability metrics especially with regard to fibre extraction may include water consumption, effluent load, chemical usage, and energy demand (Table 3). Traditional water retting processes generate effluents with high biochemical oxygen demand (BOD), posing significant environmental concerns (Parvin et al., 2025). Mitigation strategies include on-site wastewater treatment such as aeration or anaerobic digestion, or transitioning to alternative retting methods, including enzymatic and dew retting, or controlled alkaline processes. Enzymatic methods, though, may face cost constraints if enzyme reuse systems are not integrated (Hasan et al., 2022; Parvin et al., 2025). Chemical retting systems can also be designed as closed-loop processes that enable alkali recovery, enhancing both sustainability and process efficiency. While alkaline-oxidative hybrid systems balance quality and throughput, they require robust effluent treatment. In contrast, dry mechanical processing produces minimal liquid effluent but may necessitate dust management measures and often results in lower fibre quality unless supplemented by mild wet finishing techniques (Chakma et al., 2017; Shadhin et al., 2021). The LCA profiles for production of cattail fibres via mechanical or enzymatic extraction are comparable to those for conventional bast fibres when optimized extraction is used (Georgiev et al., 2013). When embedded in circular-economy frameworks, their environmental footprint can be further reduced (Brinksma et al., 2022).

In the context of resource and land utilization, cattail stands tend to occur in dense populations that can become invasive across wetland ecosystems (Bansal et al., 2019). Therefore, harvesting of this biomass should be strategic, integrating it into invasive species control and wetland management frameworks, while providing a feedstock for fibre production (Dia et al., 2020; Parvin et al., 2025). However, harvesting practices must be carefully managed to preserve critical ecological functions, including habitat provision e.g., for nesting birds, as well as maintain water quality standards (Bansal et al., 2019; Dia et al., 2020; Lishawa et al., 2020). Implementing rotational harvesting schedules has been shown to optimize both fibre quality and ecological sustainability (Pijlman et al., 2019).

Prior to processing, the primary cost components associated with cattail biomass as a raw material include harvesting (cutting/bundling), on-site collection, and transportation (Grosshans and Grieger, 2015). Utilization of simple mechanized harvesters such as those commonly employed for reed harvesting, combined with field-based pre-drying can significantly reduce the mass of material to be transported, thereby lowering logistical expenses (Grosshans and Grieger, 2015; Svedarsky et al., 2019).

Application-wise, for composites for low stress applications, cattail fibres can achieve cost competitiveness with conventional materials such glass fibres at moderate loadings (15–30 wt%) due to density-related material savings (Parvin et al., 2025; Shadhin et al., 2021). In nonwoven and sorbent applications, cattail seed fibres offer a compelling alternative to synthetic options like polypropylene pads, owing to their low cost and high sorption capacity per unit mass, particularly in single-use scenarios (Chelst et al., 2017; Cui et al., 2021; Dong et al., 2015; Gorbachev et al., 2025).

The capital expenditure (Capex) and operating expenditure (Opex) outlooks for various cattail-based product pathways are summarized in Table 4. Low-Capex, low-Opex applications, such as seed fibre-based oil sorbents, rustic textiles, and fibrous nonwovens present viable near-term commercial opportunities (Cui et al., 2014; Moghaddam et al., 2016; Xu et al., 2020). In contrast, more advanced applications, including aerogel sorbents and carbonized fibres for sensor and energy technologies, entail

Table 3
Environmental and process considerations for extraction routes of cattail fibres.

Method	Water requirement and effluent load	Energy	Chemicals	Advantages	Processing considerations
Water retting	High water use, high BOD effluent	Low-to-moderate	Minimal	Good fibre quality	Odour control, effluent treatment needed, permit requirements for ponds
Dew retting	Minimal	Very low	None	Low inputs	Weather variability, variable fibre quality, large land requirement
Mechanical	Minimal	Low-to-moderate	None (dry)	Low effluent	Generation of dust, fibre losses, cleaning step requirement
Alkaline	Moderate	Moderate (heat requirement)	NaOH/KOH; recovery advisable	High cleanliness	Alkali chemical handling, risk of corrosion
Oxidative	Moderate	Moderate	H_2O_2/peracetic, neutralization	High purity fibres	Handling of oxidants, risk of fibre embrittlement
Enzymatic	Low-to-moderate	Low (40–50 °C)	Enzymes, pH buffers	Selective degumming, mild effluent	Enzyme cost, enzyme activity control
Hybrid	Moderate	Moderate	Mixed	Tuneable outcomes, balanced quality	Integration complexity

(Kamali Moghaddam, 2022; Parvin et al., 2025; Shadhin et al., 2023; Shadhin et al., 2021).

Table 4
Indicative cost and risk matrix for selected cattail product pathways.

Product pathway	Relative Capex	Relative Opex	Key risks	Mitigations	Near-term viability
Textiles (apparel)	High	High	Inconsistent fibre quality, short fibres; high cost for fine processing, market acceptance.	Blend with fine fibres e.g., cotton/hemp, optimize pretreatment, target niche eco-fashion market.	Low
Textiles (healthcare)	Medium-to-high	Medium	Inconsistent technical performance, reproducibility, durability.	Blend with synthetic biopolymers.	Medium
Textiles (rustic)	Low-to-medium	Low-to-medium	Rot susceptibility, seasonal supply.	Local sourcing, low-tech processing, target niche markets, eco-branding	High
Oil sorbents (seed fibre)	Low	Low	Seasonal supply, quality variability.	Local sourcing, simple cleaning lines	High
Nonwovens (Thermoplastic-bonded)	Low-to-medium	Low-to-medium	Limited binder compatibility, thermal processing limits.	PLA bicomponent filaments, moisture control, coupling agents	High
Thermoset composites	Medium	Medium	Moisture sensitivity, poor adhesion.	Alkali/silane treatment, sizing, pre-drying steps	Medium
Aerogel sorbents (seed fibre cellulose)	Medium-to-high	Medium	Chemical handling, high additive and processing costs.	Green solvents, recyclability plans	Medium
Carbonized fibre for sensors	Medium	Low –medium	Consistency of carbon microstructure	Controlled pyrolysis, activation	Medium

(Bai et al., 2023; Cui et al., 2021; Cui et al., 2014; Li et al., 2023; Moghaddam et al., 2016; Srisuk et al., 2024; Xu et al., 2020; Yang et al., 2022)

higher capital investment but may access niche, high-value markets (Bai et al., 2023; Cui et al., 2021; Li et al., 2023; Yang et al., 2022). The key economic advantage, though, lies in the low cost of the cattail feedstock, as it typically grows on marginal land with minimal agricultural input.

With regard to end-of-life options, cattail-derived fibre products are compatible with industrial composting systems, offering a biodegradable end-of-life pathway. The degradability of cattail-based composites is largely influenced by the choice of matrix material. In applications such as oil spill remediation, energy recovery through controlled incineration presents a practical disposal option. In systems incorporating advanced functional fillers such as graphene oxide or metal-organic frameworks, end-of-life strategies must account for the recovery or safe immobilization of these additives so that the overall environmental benefit is preserved (Cui et al., 2021).

8. Perspectives

A core bottleneck in cattail fibre studies is the absence of specific harmonized testing protocols. Important parameters that should be reported, but often are not, include fibre length/diameter distributions, gauge length, humidity history, and Weibull parameters for single-fibre tests, alongside composite interfacial shear strength and dynamic mechanical analysis under controlled relative humidity (Parvin et al., 2025; Shadhin et al., 2022; Shadhin et al., 2023; Shadhin et al., 2021).

With regard to fibre extraction scalability and green chemistry, enzymatic and low-alkali hybrid routes show promise but remain constrained by enzyme cost and recovery challenges. Integrating enzyme immobilization, recycling systems, or alkali recovery loops makes these approaches more viable for industrial use. Comparative pilot-scale studies contrasting field-based dew retting with controlled alkaline extraction would clarify optimal routes for different cattail types and regional conditions (Parvin et al., 2025).

In composite applications, improved interfacial compatibility remains a priority. Cattail fibre surface modification strategies including silane coupling, acetylation, and plasma treatments can enhance fibre-matrix adhesion while improving moisture resistance (Alao et al., 2021; Pavlovic et al., 2025; Seisa et al., 2022). Mechanical durability under moisture cycling, creep, and fatigue conditions also requires systematic evaluation. Biobased coupling agents derived from lignin, tannins or other plant polyphenols may offer a sustainable pathway to balance adhesion strength with biodegradability in cattail fibre-reinforced composites (Fazeli et al., 2024; Tilouche-Guerdelli et al., 2024). For thermoplastic-cattail composites, low-melting point biodegradable matrices and reactive extrusion strategies may unlock thermal processing windows compatible with cattail fibres.

As for cattail seed fibres, their properties enable them to serve beyond oil sorption, and can be particularly beneficial as platforms for catalytic and antimicrobial functions (Jarernboon et al., 2018). Additionally, emerging areas such as flexible electronics, energy storage, and water purification can benefit from the high surface area and unique morphology of cattail fibre-derived carbons and aerogels (Achayalingam et al., 2024; Yu et al., 2018). Cattail seed fibre-based aerogels for water treatment, in particular, warrant further kinetic and regeneration studies under real-water conditions (Cui et al., 2021).

9. Conclusion

This review explored the potential of cattail fibres as low-cost, renewable, and multifunctional materials for sustainable systems. It highlighted how fibre origin, extraction methods, chemical composition, and microstructural characteristics collectively influence the mechanical, physical, and functional performance of cattail fibres as well as their suitability for different applications. Cattail leaf and stem fibres exhibit mechanical properties ranging from modest values in untreated form to values approaching those of established bast fibres when optimized extraction and surface modification are employed. Alkali, enzymatic, and hybrid chemical-mechanical treatments effectively reduce non-cellulosic components, refine fibre morphology, and improve cellulose exposure, thereby enhancing strength, interfacial bonding, and composite performance. While optimized cattail fibres show competitive specific properties relative to other bast fibres, their greater variability remains a key constraint. In composite systems, cattail fibres contribute effectively as lightweight reinforcements, offering improved tensile, flexural, and impact performance when appropriate fibre treatments are applied. Cattail seed fibres, exhibit exceptional bulk resilience, low density, and hydrophobic-oleophilic behaviour, despite limited tensile capacity and short fibre length. These characteristics underpin their suitability for insulation, cushioning, filtration, and oil-sorption applications. From a sustainability perspective, cattail offers distinct advantages, including rapid growth on marginal land, minimal agricultural inputs, and the potential for integration into ecosystem management initiatives such as invasive species control and phytoremediation. The comprehensive utilization of leaf, stem, and seed fibres further supports circular economy principles through efficient biomass valorisation.

CRediT authorship contribution statement

Bethwel Kipchirchir Tarus: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tusekile Said Alfredy:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Josphat Igadwa Mwasiagi:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Yusufu Abeid Chande Jande:** Writing – review & editing, Visualization, Validation, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

References

Achayalingam, R., Basu, S., Rao, P.K., Pandey, J., Selvaraj, N., Selvam, J., Hudson, M.S.L., 2024. Electrochemical capacitance and hydrogen adsorption behavior of activated carbon derived from cattail fiber. Energy Storage 6 (1), e579.

Admas, A., Assefa, A., 2025. Extraction and characterization of natural fibre from Ethiopian Typha latifolia leaf plant. AUTEX Research Journal 25 (1).

Adriano, D.C., Fulenwider, A., Sharitz, R.R., Ciravolo, T.G., Hoyt, G.D., 1980. Growth and Mineral Nutrition of Cattail (Typha) as Influenced by thermal Alteration. J. Environ. Qual. 9 (4), 649–653.

Akin, D.E., Foulk, J.A., Dodd, R.B., McAlister 3rd., D.D., 2001. Enzyme-retting of flax and characterization of processed fibers. J. Biotechnol. 89 (2–3), 193–203.

Alao, P.F., Marrot, L., Burnard, M.D., Lavrič, G., Saarna, M., Kers, J., 2021. Impact of Alkali and Silane Treatment on Hemp/PLA Composites' Performance: from Micro to Macro Scale. Polymers (Basel) 13 (6).

Aliabadi, M., Chee, B.S., Matos, M., Cortese, Y.J., Nugent, M.J.D., de Lima, T.A.M., Magalhães, W.L.E., de Lima, G.G., Firouzabadi, M.D., 2021. Microfibrillated cellulose films containing chitosan and tannic acid for wound healing applications. J. Mater. Sci. Mater. Med. 32 (6), 67.

Alufasi, R., Parawira, W., Stefanakis, A.I., Lebea, P., Chakauya, E., Chingwaru, W., 2022. Internalisation of Salmonella spp. by Typha latifolia and Cyperus papyrus in vitro and implications for pathogen removal in Constructed Wetlands. Environ. Technol. 43 (7), 949–961.

Alzagameem, A., Klein, S.E., Bergs, M., Do, X.T., Korte, I., Dohlen, S., Hüwe, C., Kreyenschmidt, J., Kamm, B., Larkins, M., Schulze, M., 2019. Antimicrobial activity of Lignin and Lignin-Derived Cellulose and Chitosan Composites against selected Pathogenic and Spoilage Microorganisms. Polymers 11 (4), 670.

Angulu, M., Gusovius, H.-J., 2024. Retting of Bast Fiber Crops like Hemp and Flax—A Review for Classification of Procedures. Fibers 12 (3), 28.

Bai, J., Li, D., Tang, W., Wang, J., Shi, C., Cui, Y., Liu, Q., 2023. Carbonized biomass cattail for flexible pressure sensor. Mater. Today Commun. 35, 105561.

Bajwa, D.S., Sitz, E.D., Bajwa, S.G., Barnick, A.R., 2015. Evaluation of cattail (Typha spp.) for manufacturing composite panels. Ind. Crop. Prod. 75, 195–199.

Bansal, S., Lishawa, S.C., Newman, S., Tangen, B.A., Wilcox, D., Albert, D., Anteau, M.J., Chimney, M.J., Cressey, R.L., DeKeyser, E., Elgersma, K.J., Finkelstein, S.A., Freeland, J., Grosshans, R., Klug, P.E., Larkin, D.J., Lawrence, B.A., Linz, G., Marburger, J., Noe, G., Otto, C., Reo, N., Richards, J., Richardson, C., Rodgers, L., Schrank, A.J., Svedarsky, D., Travis, S., Tuchman, N., Windham-Myers, L., 2019. Typha (Cattail) Invasion in north American Wetlands: Biology, Regional Problems, Impacts, Ecosystem Services, and Management. Wetlands 39 (4), 645–684.

Behera, D., Pattnaik, S.S., Manna, S., Das, N., Behera, A.K., 2025a. Sustainable valorization of lignocellulosic biomass into green composites: recent advances, applications, and future perspectives. Sustain. Mater. Technol. 46, e01748.

Behera, D., Pattnaik, S.S., Nanda, D., Mishra, P.P., Manna, S., Behera, A.K., 2025b. A review on bamboo fiber reinforced composites and their potential applications. Emerg. Mater. 8 (1), 157–172.

Behera, D., Pattnaik, S.S., Patra, S.S., Barick, A.K., Pradhan, J., Behera, A.K., 2025c. Development and characterization of water hyacinth reinforced thermoplastic starch as sustainable biocomposites. RSC Sustainability 3 (4), 1807–1818.

Berry, P., Yassin, F., Grosshans, R., Lindenschmidt, K.E., 2017. Surface water retention systems for cattail production as a biofuel. J. Environ. Manag. 203 (Pt 1), 500–509.

Brinksma, H., van der Stelt, M.J.C., Oostra, M., 2022. Typha as a circular building material. IOP Conf. Ser. Earth Environ. Sci. 1122 (1), 012039.

Cao, S., Dong, T., Xu, G., Wang, F., 2016. Study on structure and wetting characteristic of cattail fibers as natural materials for oil sorption. Environ. Technol. 37 (24), 3193–3199.

Carhuancho, F., Aguado, P., Curt, M., 2022. The energy potential of different biomass fractions of Typha dominguensis grown in green floating filters. 30th European Biomass Conference and Exhibition 72–78.

Chakma, K., Cicek, N., Rahman, M., 2017. Fiber extraction efficiency, quality and characterization of cattail fibres for textile applications. In: Proceedings of the Canadian Society for Bioengineering Conference (CSBE). Canada, Winnipeg.

Chattopadhyay, S.N., Pan, N.C., Roy, A.N., Samanta, K.K., Khan, A., 2022. Two-step Bleaching of jute Yarn and fabric using Hydrogen Peroxide and Peracetic Acid. Journal of Natural Fibers 19 (3), 1159–1167.

Chelst, S., Delaine-Facey, B., Hull, S., Jordan, D., Monsaint-Queeney, V., Patel, M., Thapa, A., Wall, J., Yee, D., 2017. Evaluating the Efficacy of Cattail (Typha spp.) Fiber for Oil Sorption.

Clements, D., 2022. *Typha latifolia* (Broadleaf Cattail). CABI Compendium.

Corrêa, F.F., Madail, R.H., Barbosa, S., Pereira, M.P., Castro, E.M., Soriano, C.T.G., Pereira, F.J., 2015. Anatomy and physiology of Cattail as related to different population densities. 33 (1), 01–12.

Coulibaly, D., Diallo, O., Traore, Y., Diouf, M., Bal, H.M., Gaye, S., 2025. Physico-mechanical characterisation of the composite of clay and grown typha fiber. Int. J. Innov. Appl. Stud. 45 (1), 56–67.

Cui, F., Li, H., Chen, C., Wang, Z., Liu, X., Jiang, G., Cheng, T., Bai, R., Song, L., 2021. Cattail fibers as source of cellulose to prepare a novel type of composite aerogel adsorbent for the removal of enrofloxacin in wastewater. Int. J. Biol. Macromol. 191, 171–181.

Cui, Y., Xu, G., Liu, Y., 2014. Oil sorption mechanism and capability of cattail fiber assembly. J. Ind. Text. 43 (3), 330–337.

da Cunha Cruz, Y., Martins Scarpa, A.L., Pereira, M.P., Mauro de Castro, E., Pereira, F.J., 2020. Root anatomy and nutrient uptake of the cattail Typha domingensis Pers. (Typhaceae) grown under drought condition. *Rhizosphere* 16, 100253.

da Cunha Cruz, Y., Scarpa, A.L.M., Díaz, A.S., Pereira, M.P., de Castro, E.M., Pereira, F.J., 2023. Influence of seasonal variation to the population growth and ecophysiology of Typha domingensis (Typhaceae). J. Plant Res. 136 (5), 665–678.

de Jong, M., van Hal, O., Pijlman, J., van Eekeren, N., Junginger, M., 2021. Paludiculture as paludifuture on Dutch peatlands: an environmental and economic analysis of Typha cultivation and insulation production. Sci. Total Environ. 792, 148161.

De Prez, J., Van Vuure, A.W., Ivens, J., Aerts, G., Van de Voorde, I., 2018. Enzymatic treatment of flax for use in composites. Biotechnol. Rep. (Amst.) 20, e00294.

Dia, B.M., Diagne, M.L., Goudiaby, M.S., 2020. Optimal control of invasive species with economic benefits: Application to the Typha proliferation. Nat. Resour. Model. 33 (2), e12268.

Dieye, Y., 2019. Thermomechanical Characterization of Particleboards from Powder Typha Leaves. Journal of Sustainable Construction Materials and Technologies 4 (1), 306–317.

Diouf, G., Gning, P.B., 2024. Influence of the Extraction Process on the Mechanical and Morphological Properties of Technical Fibers from Typha domingensis. Journal of Natural Fibers 21 (1), 2357744.

Djafari Petroudy, S.R., Shojaeiarani, J., Chabot, B., 2023. Recent advances in isolation, characterization, and potential applications of nanocellulose-based composites: A comprehensive review. Journal of Natural Fibers 20 (1), 2146830.

Dong, T., Xu, G., Wang, F., 2015. Oil spill cleanup by structured natural sorbents made from cattail fibers. Ind. Crop. Prod. 76, 25–33.

El Amri, A., Ouass, A., bensalah, j., Wardighi, Z., Zahra Bouhassane, F., Zarrouk, A., Habsaoui, A., Rifi, E.-H., Lebkiri, A., 2023. Extraction and characterization of cellulosic nanocrystals from stems of the reed plant large-leaved cattail (Typha latifolia). Mater. Today Proc. 72, 3609–3616.

Elanthikkal, S., Gopalakrishnapanicker, U., Varghese, S., Guthrie, J.T., 2010. Cellulose microfibres produced from banana plant wastes: Isolation and characterization. Carbohydr. Polym. 80 (3), 852–859.

Eleutério, T., Trota, M.J., Meirelles, M.G., Vasconcelos, H.C., 2025. A Review of Natural Fibers: Classification, Composition, Extraction, Treatments, and applications. Fibers 13 (9), 119.

Fan, X., Wang, Y., Zheng, M., Dunne, F., Liu, T., Fu, X., Kong, L., Pan, S., Zhong, W.-H., 2018. Morphology engineering of protein fabrics for advanced and sustainable filtration. J. Mater. Chem. A 6 (43), 21585–21595.

Faruk, O., Bledzki, A.K., Fink, H.-P., Sain, M., 2012. Biocomposites reinforced with natural fibers: 2000–2010. Prog. Polym. Sci. 37 (11), 1552–1596.

Fazeli, M., Mukherjee, S., Baniasadi, H., Abidnejad, R., Mujtaba, M., Lipponen, J., Seppälä, J., Rojas, O.J., 2024. Lignin beyond the status quo: recent and emerging composite applications. Green Chem. 26 (2), 593–630.

Foulk, J.A., Rho, D., Alcock, M.M., Ulven, C.A., Huo, S., 2011. Modifications Caused by Enzyme-Retting and their effect on Composite Performance. Adv. Mater. Sci. Eng. 2011 (1), 179023.

Gaye, A., Sene, N.A., Balland, P., Sambou, V., Gning, P.B., 2023. Extraction and physicomechanical characterisation of Typha Australis fibres: Sensitivity to a location in the plant. Journal of Natural Fibers 20 (1), 2164106.

Georgiev, G., Theuerkorn, W., Krus, M., Kilian, R., Grosskinsky, T., 2013. The potential role of cattail-reinforced clay plaster in sustainable building. Mires and Peat 13.

Geurts, J., Fritz, C., 2018. Paludiculture Pilots and Experiments with Focus on Cattail and Reed in the Netherlands-Technical Report-CINDERELLA Project FACCE-JPI ERA-NET Plus on Climate Smart Agriculture.

Gorbachev, S., Gorovykh, O.G., Mani, A., Dixit, A., Alzhanov, B.A., Yan, J., 2025. Biotechnological breakthrough to cattail fiber as an ultra-efficient natural oil sorbent. Sci. Rep. 15 (1), 24688.

Gotore, O., Mushayi, V., Tipnee, S., 2021. Evaluation of cattail characteristics as an invasive wetland plant and biomass usage management for biogas generation. Maejo International Journal of Energy and Environmental Communication 3 (2), 1–6.

Grosshans, R., 2014. Cattail (Typha spp.) Biomass Harvesting for Nutrient Capture and Sustainable Bioenergy for Integrated Watershed Management.

Grosshans, R., Grieger, L., 2015. Cattail Biomass to Energy: Commercial-Scale Harvesting of Cattail Biomass for Biocarbon and Solid Fuel.

Grosshans, R.E., Venema, H., Cicek, N., Goldsborough, G., 2011. Cattail farming for water quality: Harvesting cattails for nutrient removal and phosphorous recovery in the watershed. *Proceedings of WEF-IWA Nutrient Recovery and Management* 2011.

Hafez, R.M., Abdel-Rahman, T.M.A., Yahia, M.M., El-Gabry, K.I.M., Wahab, Y.M.M.A., 2025. Biochemical and cytological studies of Typha domingensis used for bioethanol production. Biomass Convers. Biorefinery 15 (10), 15361–15384.

Haldan, K., Köhn, N., Hornig, A., Wichmann, S., Kreyling, J., 2022. Typha for paludiculture—Suitable water table and nutrient conditions for potential biomass utilization explored in mesocosm gradient experiments. Ecol. Evol. 12 (8), e9191.

Hasan, M., 2019. Optimization of Typha Fibre Extraction and Properties for Composite Applications Using Desirability Function Analysis.

Hasan, M., Rahman, M., Chen, Y., Cicek, N., 2022. Optimization of Typha Fibre Extraction and Properties for Bio-Composite applications using Desirability Function Analysis. Polymers 14 (9), 1685.

Hobson, R.N., Hepworth, D.G., Bruce, D.M., 2001. PH—Postharvest Technology: Quality of Fibre Separated from Unretted Hemp Stems by Decortication. J. Agric. Eng. Res. 78 (2), 153–158.

Holanda, F.S., Rocha, I.P.d., Oliveira, V.S., 2008. Riverbank stabilization with soil bioengineering techniques at the lower São Francisco River. Revista Brasileira de Engenharia Agrícola e Ambiental 12, 570–575.

Holanda, F.S.R., Santos, L.D.V., Melo, J.C.R., Boge, G.M., Sussuchi, E.M., Nascimento, B. L., Santos, M., Oliveira, M.I.U., 2024a. Resistance of the fiber-derived geotextile from Typha domingensis submitted to field degradation. Sci. Rep. 14 (1), 8648.

Holanda, F.S.R., Vidal Santos, L.D., Melo, J.C.R., Pedrotti, A., Sussuchi, E.M., Griza, S., Filho, Araújo, R.N.d., Nascimento, B.L., 2024b. Influence of Sodium Hydroxide Treatment on Typha domingensis Fibers for Geotextile Manufacturing. ACS Omega 9 (52), 51040–51051.

Hossain, M.S., Rahman, M., Cicek, N., 2024. Tensile Properties of Cattail Fibres at various Phenological Development Stages. Polymers 16 (19), 2692.

Ijaz, A., Iqbal, Z., Afzal, M., 2016. Remediation of sewage and industrial effluent using bacterially assisted floating treatment wetlands vegetated with Typha domingensis. Water Sci. Technol. 74 (9), 2192–2201.

Ikramullah, Rizal, S., Thalib, S., Huzni, S., 2018. Hemicellulose and lignin removal on typha fiber by alkali treatment. IOP Conference Series: Materials Science and Engineering 352 (1), 012019.

Islam, M.M., Chowdhury, M.A., Talukder, A., Hossain, N., Rana, M.M., Patwary, M.A.I., Khan, R.A., 2025a. Effect of time, temperature and chemical concentration of peracetic acid treatment on enhancement of crystallinity of jute fibers. J. Ind. Text. 55, 15280837251321136.

Islam, M.Z., Sarker, M.E., Rahman, M.M., Islam, M.R., Ahmed, A.T.M.F., Mahmud, M.S., Syduzzaman, M., 2022. Green composites from natural fibers and biopolymers: A review on processing, properties, and applications. J. Reinf. Plast. Compos. 41 (13–14), 526–557.

Islam, T., Hossain, M.M., Covington, S.M., 2025b. Natural Fibers Towards Fashion Sustainability: A Review of Raw Materials, production, Application, and Perspective. Journal of Natural Fibers 22 (1), 2462218.

Ismail, S.O., Akpan, E., Dhakal, H.N., 2022. Review on natural plant fibres and their hybrid composites for structural applications: recent trends and future perspectives. Composites Part C: Open Access 9, 100322.

Ivanov, Y., Godjevargova, T., 2024. Antimicrobial Polymer Films with Grape seed and Skin Extracts for Food packaging. Microorganisms 12 (7), 1378.

Jahan, M., 2023. An Investigation of Treatments to Improve the Hand of Fibre Extracted from *Typha latifolia* Plants.

Jara-Vinueza, O., Pavon, W., Remache, A., 2024. Sustainable Construction with Cattail Fibers in Imbabura, Ecuador: Physical and Mechanical Properties, Research, and applications. Buildings 14 (6), 1703.

Jarernboon, W., Iamtipueng, P., Pimanpang, S., Amornkitbamrung, V., 2018. Preparation of the natural carbon fiber from narrow-leaved cattails (Typha angustifolia Linn.) flower for using as the cathode catalyst in the zinc-air fuel cell. Mater. Today Proc. 5 (6, Part 1), 14002–14008.

Johnston, C.A., 1988. Productivity of wet soils: Biomass of cultivated and natural vegetation. Oak Ridge National Lab., TN (USA); Johnston (Carol A.), Duluth, MN (USA).

Kadlec, R.H., Wallace, S., 2008. Treatment Wetlands. CRC press.

Kamali Moghaddam, M., 2022. Typha Leaves Fiber and its Composites: A Review. Journal of Natural Fibers 19 (13), 4993–5007.

Kannan, G., Kurien, R.A., Thangaraju, R., Shanmugam, V., Rajendran, S., Karupaiah, V., Ramasamy, S., Suttiruengwong, S., Rangappa, S.M., Siengchin, S., 2025a. Advances in cellulosic natural fibre-reinforced polymer composites: Properties, additive manufacturing and hybridisation – A review. Int. J. Biol. Macromol. 327, 147374.

Kannan, G., Thangaraju, R., Suttiruengwong, S., Shanmugam, V., Rangappa, S.M., Sumesh, K.R., Kurien, R.A., Siengchin, S., 2025b. Effect of drilling process parameters on agro-waste-based polymer composites reinforced with banana fiber and coconut shell filler. Biomass Convers. Biorefinery 15 (9), 13719–13732.

Karimah, A., Ridho, M.R., Munawar, S.S., Ismadi, Amin, Y., Damayanti, R., Lubis, M.A. R., Wulandari, A.P., Nurindah, Iswanto, A.H., Fudholi, A., Asrofi, M., Saedah, E., Sari, N.H., Pratama, B.R., Fatriasari, W., Nawawi, D.S., Rangappa, S.M., Siengchin, S., 2021. A Comprehensive Review on Natural Fibers: Technological and Socio-Economical Aspects. Polymers 13 (24), 4280.

Ke, G., Tan, S., Wang, Y., Chen, S., Liu, K., 2023. Extraction and characterization of cellulosic fibers from cattail leaves by aqueous sodium hydroxide/urea. Cellulose 30 (11), 6799–6810.

Keener, T.J., Stuart, R.K., Brown, T.K., 2004. Maleated coupling agents for natural fibre composites. Compos. A: Appl. Sci. Manuf. 35 (3), 357–362.

Khan, M.K.R., 2021. Cattail Textile fiber and its Research Trend. Bangladesh University of Business and Technology.

Khider, T.O., Omer, S., Taha, O., 2012. Alkaline pulping of Typha domingensis stems from Sudan. World Appl. Sci. J. 16 (3), 331–336.

Kishor, K., Singh, M.K., Chakraborty, S., 2024. Extraction and characterization of cattail fibre and lignin recovery from retting bath. Bioresour. Technol. Rep. 25, 101753.

Kõiv-Vainik, M., Ostonen, I., Kanu-Oji, C.O., Kasak, K., 2025. Assessment of nutrient storage and translocation in winter harvested Typha latifolia from free-water surface treatment wetland mitigating diffuse agricultural pollution. Sci. Total Environ. 962, 178424.

Komuraiah, A., Kumar, N.S., Prasad, B.D., 2014. Chemical Composition of Natural Fibers and its Influence on their Mechanical Properties. Mech. Compos. Mater. 50 (3), 359–376.

Kozłowski, R.M., Mackiewicz-Talarczyk, M., 2020. Introduction to natural textile fibres. In: Kozłowski, R.M., Mackiewicz-Talarczyk, M. (Eds.), Handbook of Natural Fibres (Second Edition). Publishing, Woodhead, pp. 1–13.

Krus, M., Theuerkorn, W., Großkinsky, T., Künzel, H., 2014. New sustainable and insulating building material made of cattail. Full papers NSB 156, 1252–1260.

Krus, M., Werner, T., Großkinsky, T., Georgiev, G., 2015. A new load-bearing insulation material made of cattail. Academic Journal of Civil Engineering 33 (2), 666–673.

Kumar, R., Saxena, A., 2025. A Study on thermal Comfort Properties in Knit Fabrics made from Cattail and Cotton Blends. Fibers and Polymers 26 (5), 2249–2255.

Kurien, R.A., Kannan, G., Suttiruengwong, S., 2026. Processing methods and techniques for eco-friendly fibers and polymers for the sustainable environment. In: Rangappa, S.M., Siengchin, S., Leao, A.L., Kozlowski, R.M. (Eds.), Eco-Friendly Fiber Reinforced Polymer Composite Materials. Publishing, Woodhead, pp. 77–107.

Kurien, R.A., Maria Anil, M., Sharan Mohan, S.L., Anna Thomas, J., 2023a. Natural fiber Composites as Sustainable Resources for Emerging Applications- a Review. Proceedings, Materials Today.

Kurien, R.A., Selvaraj, D.P., Sekar, M., Koshy, C.P., Paul, C., Palanisamy, S., Santulli, C., Kumar, P., 2023b. A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites. Cellulose 30 (14), 8643–8664.

Lee, C.H., Khalina, A., Lee, S.H., Liu, M., 2020. A Comprehensive Review on Bast Fibre Retting Process for Optimal Performance in Fibre-Reinforced Polymer Composites. Adv. Mater. Sci. Eng. 2020 (1), 6074063.

Li, H., Song, L., Huo, D., Yang, Y., Zhang, N., Liang, J., 2023. Cattail-Grass-Derived Porous Carbon as High-Capacity Anode Material for Li-Ion Batteries. Molecules 28 (11), 4427.

Li, S., Lissner, J., Mendelssohn, I.A., Brix, H., Lorenzen, B., McKee, K.L., Miao, S., 2010. Nutrient and growth responses of cattail (Typha domingensis) to redox intensity and phosphate availability. Ann. Bot. 105 (1), 175–184.

Lishawa, S.C., Carson, B.D., Brandt, J.S., Tallant, J.M., Reo, N.J., Albert, D.A., Monks, A.M., Lautenbach, J.M., Clark, E., 2017. Mechanical harvesting effectively controls young typha spp. invasion and unmanned aerial vehicle data enhances post-treatment monitoring. Frontiers in Plant Science Volume 8–2017.

Lishawa, S.C., Dunton, E.M., Pearsall, D.R., Monks, A.M., Himmler, K.B., Carson, B.D., Loges, B., Albert, D.A., 2020. Wetland Waterbird Food Resources increased by Harvesting Invasive Cattails. J. Wildl. Manag. 84 (7), 1326–1337.

Lishawa, S.C., Lawrence, B.A., Albert, D.A., Tuchman, N.C., 2015. Biomass harvest of invasive Typha promotes plant diversity in a Great Lakes coastal wetland. Restor. Ecol. 23 (3), 228–237.

Liu, J., Zhang, Z., Yu, Z., Liang, Y., Li, X., Ren, L., 2017. The Structure and Flexural Properties of Typha Leaves. Applied Bionics and Biomechanics 2017 (1), 1249870.

Liu, L.Y., Han, Y.L., Zhang, X.R., 2011. Research on the Spinnability of the Renewable Cattail Fiber. Adv. Mater. Res. 332-334, 192–195.

Liu, Q., He, W.Q., Aguedo, M., Xia, X., Bai, W.B., Dong, Y.Y., Song, J.Q., Richel, A., Goffin, D., 2021. Microwave-assisted alkali hydrolysis for cellulose isolation from wheat straw: Influence of reaction conditions and non-thermal effects of microwave. Carbohydr. Polym. 253, 117170.

Luamkanchanaphan, T., Chotikaprakhan, S., Jarusombati, S., 2012. A Study of Physical, Mechanical and thermal Properties for thermal Insulation from Narrow-leaved Cattail Fibers. APCBEE Proc. 1, 46–52.

Lyu, P., Zhang, Y., Wang, X., Hurren, C., 2021. Degumming methods for bast fibers—A mini review. Ind. Crop. Prod. 174, 114158.

Manimaran, P., Vignesh, V., Khan, A., Pillai, G.P., Nagarajan, K.J., Prithiviraj, M., Al-Romaizan, A.N., Hussein, M.A., Puttegowda, M., Asiri, A.M., 2022. Extraction and characterization of natural lignocellulosic fibres from Typha angustata grass. Int. J. Biol. Macromol. 222 (Pt B), 1840–1851.

Mbeche, S., Wambua, P., Njuguna, D., 2022. Thermal properties of sisal/cattail fiber reinforced polyester composites. In: Advances in Phytochemistry. CRC Press, Textile and Renewable Energy Research for Industrial Growth, pp. 121–124.

Mbeche, S.M., Omara, T., 2020. Effects of alkali treatment on the mechanical and thermal properties of sisal/cattail polyester commingled composites. PeerJ Materials Science 2, e5.

Mbeche, S.M., Wambua, P.M., Githinji, D.N., 2020. Mechanical Properties of Sisal/Cattail Hybrid-Reinforced Polyester Composites. Adv. Mater. Sci. Eng. 2020 (1), 6290480.

Minna, H., Annika, R., Anna, B., Anne, K., Mikko, R., Anna, B., 2022. An Eco-Filling to Replace Down, vol. 2025. Aalto University, Finland.

Mitich, L.M., 2000. Common Cattail. *Typha latifolia* L. *Weed Technology* 14 (2), 446–450.

Moghaddam, M.K., Safi, S., Hassanzadeh, S., Mortazavi, S.M., 2016. Sound absorption characteristics of needle-punched sustainable Typha /polypropylene non-woven. The Journal of The Textile Institute 107 (2), 145–153.

Mukherjee, C., Varghese, D., Krishna, J.S., Boominathan, T., Rakeshkumar, R., Dineshkumar, S., Brahmananda Rao, C.V.S., Sivaramakrishna, A., 2023. Recent advances in biodegradable polymers – Properties, applications and future prospects. Eur. Polym. J. 192, 112068.

Muntongkaw, S., Pianklang, S., Tangboriboon, N., 2021. Modifications to improve properties of gypsum ceiling composites as multifunctional construction by embedding Typha angustifolia fiber and natural rubber latex compound. Case Studies in Construction Materials 15, e00658.

Nagaraja, S., Anand, P.B., K, M.K., Ammarullah, M.I., 2024. Synergistic advances in natural fibre composites: a comprehensive review of the eco-friendly bio-composite development, its characterization and diverse applications. RSC Adv. 14 (25), 17594–17611.

Naveena Shri, C., Amsamani, S., 2024. Fiber extraction and characterization of Typha Domingensis Pers for the development of bio-composites: A renewable approach to minimize plastic usage in the field of agriculture. Polym. Bull. 81 (13), 11975–11996.

Neto, J.S.S., de Queiroz, H.F.M., Aguiar, R.A.A., Banea, M.D., 2021. A Review on the thermal Characterisation of Natural and Hybrid Fiber Composites. Polymers (Basel) 13 (24).

Nguyen, D.T.C., Tran, T.V., Kumar, P.S., Din, A.T.M., Jalil, A.A., Vo, D.N., 2022. Invasive plants as biosorbents for environmental remediation: A review. Environ. Chem. Lett. 20 (2), 1421–1451.

Niang, I., Maalouf, C., Moussa, T., Bliard, C., Samin, E., Thomachot-Schneider, C., Lachi, M., Pron, H., Mai, T.H., Gaye, S., 2018. Hygrothermal performance of various Typha–clay composite. J. Build. Phys. 42 (3), 316–335.

Oliveira, L.M.T.M., Fonseca, E.J.S., Bernardo, V.B., Zanta, C.L.P.S., Oliveira, L.F.A.M., Oliveira, J.N.S.R.d., Souza, S.T.d., Duarte, J.L.d.S., 2024. Modified Kapok Fibers (*Ceiba pentandra* (L.) Gaerth) for Oil Spill Remediation. Appl. Sci. **14** (24), 11995.

Pandey, R., Jose, S., Sinha, M.K., 2022. Fiber Extraction and Characterization from Typha Domingensis. Journal of Natural Fibers 19 (7), 2648–2659.

Parvin, M., Shadhin, M., Dulal, M., Rahman, M., 2025. Harnessing Cattail Biomass for Sustainable Fibers and Engineered Bioproducts: A Review. Global Chall. 9 (1), 2400183.

Pattnaik, S.S., Behera, D., Das, N., Dash, A.K., Behera, A.K., 2024. Fabrication and characterization of natural fiber reinforced cowpea resin-based green composites: an approach towards agro-waste valorization. RSC Adv. 14 (35), 25728–25739.

Pattnaik, S.S., Behera, D., Jali, P., Behera, A.K., 2025. Mechanical and biodegradation analysis under various environmental conditions of the waste vetiver root fiber reinforced soy composite. Polym. Int. 74 (10), 905–913.

Pavlovic, A., Valzania, L., Minak, G., 2025. Effects of Moisture Absorption on the Mechanical and Fatigue Properties of Natural Fiber Composites: A Review. Polymers (Basel) 17 (14).

Phaenark, C., Harn-asa, P., Paejaroen, P., Chunchob, S., Sawangproh, W., 2023. Removal of Pb(II) and Cd(II) by Biomass Derived from Broadleaf Cattail and Water Hyacinth. Journal of Water and Environment Technology 21 (4), 191–203.

Pickering, K.L., Efendy, M.G.A., Le, T.M., 2016. A review of recent developments in natural fibre composites and their mechanical performance. Compos. A: Appl. Sci. Manuf. 83, 98–112.

Pijlman, J., Geurts, J., Vroom, R., Bestman, M., Fritz, C., Van Eekeren, N., 2019. The effects of harvest date and frequency on the yield, nutritional value and mineral content of the paludiculture crop cattail (Typha latifolia L.) in the first year after planting. Mires and Peat 25, 04.

Prasad, V., Alliyankal Vijayakumar, A., Jose, T., George, S.C., 2024. A Comprehensive Review of Sustainability in Natural-Fiber-Reinforced Polymers. Sustainability 16 (3), 1223.

Pratt, D., Andrews, N., 1978. Cattails as an energy source. Minnesota Univ., Minneapolis (USA). Dept. of Botany.

Rahikainen, J., Mattila, O., Maloney, T., Lovikka, V., Kruus, K., Suurnäkki, A., Grönqvist, S., 2020. High consistency mechano-enzymatic pretreatment for Kraft fibres: effect of treatment consistency on fibre properties. Cellulose 27 (9), 5311–5322.

Rahman, M., Cicek, N., Chakma, K., 2021. The Optimum Parameters for Fibre Yield (%) and Characterization of Typha latifolia L. Fibres for Textile applications. Fibers and Polymers 22 (6), 1543–1555.

Raja, R., J, N., Kurien, R.A., Jannet, S., 2025. 3D printing of tailored polymer composites: enhancing sustainability with banana and pineapple fiber particle reinforcements. Engineering Research Express 7 (2), 025442.

Razaq, A., Asif, M.H., Kalsoom, R., Khan, A.F., Awan, M.S., Ishrat, S., Ramay, S.M., 2015. Conductive and electroactive composite paper reinforced by coating of polyaniline on lignocelluloses fibers. J. Appl. Polym. Sci. 132 (29).

Rezig, S., Jaouadi, M., El Oudiani Bessghaier, A., Msahli, S., 2025. Physical properties, morphology and crystallinity of Typha leaf fibers processed by different extraction treatments. The Journal of The Textile Institute 116 (1), 21–32.

Rizal, S., Gopakumar, D.A., Huzni, S., Thalib, S., Syakir, M., Owolabi, F., Aprilla, N., Paridah, M., Khalil, H., 2019. Tailoring the Effective Properties of Typha Fiber Reinforced Polymer Composite via Alkali Treatment. BioResources 14 (3).

Rizal, S., Gopakumar, D.A., Thalib, S., Huzni, S., Abdul Khalil, H.P.S., 2018. Interfacial Compatibility Evaluation on the Fiber Treatment in the Typha Fiber Reinforced Epoxy Composites and their effect on the Chemical and Mechanical Properties. Polymers (Basel) 10 (12).

Robles, M.E.L., Reyes, N.J.D., Choi, H., Jeon, M., Kim, L., 2023. Carbon Storage and Sequestration in Constructed Wetlands. A Systematic Review. *한국습지학회지* 25 (2), 132–144.

Sadrmanesh, V., Chen, Y., 2019. Bast fibres: Structure, processing, properties, and applications. Int. Mater. Rev. 64 (7), 381–406.

Šajn Gorjanc, D., Kostajnšek, K., 2024. Permeable Properties of Hygienic Nonwovens Bonded using Mechanical, Chemical, and thermal Techniques. Polymers 16 (8), 1132.

Sandoval-Herazo, M., Martínez-Reséndiz, G., Fernández Echeverria, E., Fernández-Lambert, G., Sandoval Herazo, L.C., 2021. Plant Biomass Production in Constructed Wetlands Treating Swine Wastewater in Tropical Climates. Fermentation 7 (4), 296.

Saravanan, M., Krishnamoorthi, S., Karthik, N., Kavin Kumar, S., Nikhil Krishnan, V., 2020. Evaluation of mechanical strength of combined natural fiber reinforced polymer composites. IOP Conference Series: Materials Science and Engineering 993 (1), 012021.

Schuck, L., 2023. Seeds of a Sustainable Transition? (Investigating the properties of cattail seed hair as textile fillings and their potential for peatland management shifts in Finland).

Seisa, K., Chinnasamy, V., Ude, A.U., 2022. Surface treatments of natural fibres in fibre reinforced composites: a review. Fibres & Textiles in Eastern *Europe*(2 (151), 82–89.

Shadhin, M., 2021. Comparative Evaluation of Flax, Cattail, and Hemp fiber Composites.

Shadhin, M., Jayaraman, R., Rahman, M., Mann, D., 2024. Effect of fiber surface treatment on mechanical, interfacial, and moisture absorption properties of cattail fiber-reinforced composites. J. Appl. Polym. Sci. 141 (1), e54765.

Shadhin, M., Mann, D., Rahman, M., 2022. Probabilistic model for cattail and canola fibers: effect of environmental conditions, structural parameters, fiber length, and estimators. Text. Res. J. 92 (13–14), 2513–2528.

Shadhin, M., Rahman, M., Jayaraman, R., Chen, Y., Mann, D., Zhong, W., 2023. Natural biomass & waste biomass fibers – Structures, environmental footprints, sustainability, degumming methods, & surface modifications. Ind. Crop. Prod. 204, 117252.

Shadhin, M., Rahman, M., Jayaraman, R., Mann, D., 2021. Novel cattail fiber composites: Converting waste biomass into reinforcement for composites. Bioresour. Bioprocess. 8 (1), 101.

Shanmugam, V., Babu, K., Garrison, T.F., Capezza, A.J., Olsson, R.T., Ramakrishna, S., Hedenqvist, M.S., Singha, S., Bartoli, M., Giorcelli, M., Sas, G., Försth, M., Das, O., Restás, Á., Berto, F., 2021. Potential natural polymer-based nanofibres for the development of facemasks in countering viral outbreaks. J. Appl. Polym. Sci. 138 (27), 50658.

Shih, J.G., Finkelstein, S.A., 2008. Range dynamics and invasive tendencies in Typha latifolia and Typha angustifolia in eastern North America derived from herbarium and pollen records. Wetlands 28 (1), 1–16.

Srisuk, T., Charoenlarp, K., Kampeerapappun, P., 2024. Utilization of Waste Natural Fibers mixed with Polylactic Acid (PLA) Bicomponent Fiber: Incorporating Kapok and Cattail Fibers for Nonwoven Medical Textile applications. Polymers 16 (1), 76.

Stewart, D., Hood, W.G., Martin, T.G., 2023. Undetected but Widespread: the Cryptic Invasion of Non-Native Cattail (Typha) in a Pacific Northwest Estuary. Estuar. Coasts 46 (3), 802–817.

Svedarsky, D., Grosshans, R., Venema, H.D., Ellis-Felege, S.N., Bruggman, J., Ostlund, A., Lewis, J., 2019. Integrated management of invasive cattails (Typha spp.) for wetland habitat and biofuel in the Northern Great Plains of the United States and Canada: A review. Mires and Peat 25, 1.

Tanner, C.C., 2001. Plants as ecosystem engineers in subsurface-flow treatment wetlands. Water Sci. Technol. 44 (11–12), 9–17.

Tilouche-Guerdelli, K., Lacoste, C., Perrin, D., Liotier, P.-J., Ouagne, P., Tirillò, J., Sarasini, F., Bergeret, A., 2024. Tannins as Biobased Molecules for Surface Treatments of Flax Wrapped Rovings for Epoxy/Flax Fabrics Biocomposites: Influence on Mechanical Properties through a Multi-Scale Approach. Journal of Composites Science 8 (2), 75.

van den Berg, M., Gremmen, T.M., Vroom, R.J.E., van Huissteden, J., Boonman, J., van Huissteden, C.J.A., van der Velde, Y., Smolders, A.J.P., van de Riet, B.P., 2024. A case study on topsoil removal and rewetting for paludiculture: effect on biogeochemistry and greenhouse gas emissions from Typha latifolia, Typha angustifolia, and Azolla filiculoides. Biogeosciences 21 (11), 2669–2690.

Wall, M., Macdonald, J., 2009. Processing Seeds of California Native Plants for Conservation, Storage, and Restoration. Rancho Santa Ana Botanic Garden.

Wang, L., Wei, J., Zhou, C., Yang, S., 2022. A simple and Efficient Solar Interfacial Evaporation device based on Carbonized Cattail and Agarose Hydrogel for Water Evaporation and Purification. Membranes 12 (11), 1076.

Wang, S., Salmon, S., 2025. Enzymatic degumming of hemp: A literature review. Cellulose 32 (13), 7501–7533.

Williams, F., Constantine, K.L., Ali, A.A., Karanja, T.W., Kibet, S., Lingeera, E.K., Muthike, G., Rwomushana, I., Godwin, J., Day, R., 2021. An assessment of the capacity and responsiveness of a national system to address the threat of invasive species: a systems approach. CABI Agric. Biosci. 2 (1), 42.

Witztum, A., Wayne, R., 2014. Fibre cables in the lacunae of Typha leaves contribute to a tensegrity structure. Ann. Bot. 113 (5), 789–797.

Witztum, A., Wayne, R., 2016. Lignified and nonlignified fiber cables in the lacunae of Typha angustifolia. Protoplasma 253 (6), 1589–1592.

Wu, H., Dai, X., Zhou, S.L., Gan, Y.Y., Xiong, Z.Y., Qin, Y.H., Ma, J., Yang, L., Wu, Z.K., Wang, T.L., Wang, W.G., Wang, C.W., 2017. Ultrasound-assisted alkaline pretreatment for enhancing the enzymatic hydrolysis of rice straw by using the heat energy dissipated from ultrasonication. Bioresour. Technol. 241, 70–74.

Wu, S., Zhang, J., Li, C., Wang, F., Shi, L., Tao, M., Weng, B., Yan, B., Guo, Y., Chen, Y., 2021. Characterization of potential cellulose fiber from cattail fiber: A study on micro/nano structure and other properties. Int. J. Biol. Macromol. 193, 27–37.

Wu, Y., Luo, C., Wang, T., Yang, Y., Sun, Y., Zhang, Y., Cui, L., Song, Z., Chen, X., Cao, X., Li, S., Cai, G., 2024. Extraction and characterization of nanocellulose from cattail leaves: Morphological, microstructural and thermal properties. Int. J. Biol. Macromol. 255, 128123.

Xia, W., Anwar, A., Wang, L., Cao, Z., Li, B., Nie, K., Zhou, C., Zhang, Y., Han, G., Jiang, W., Ben, H., Zhao, T., 2024. Microwave-assisted solid-state pretreatment for fabrication of hemp fibres using ethanolamine at low temperature. Carbohydr. Polym. 332, 121906.

Xiao, Y., Hao, J., Wu, X., Liu, T., Zhang, H., Tang, N., Wang, X., 2020. Facile synthesis of curly conductive polyaniline composite fibers using cattail fluff as substrate. Polym. Bull. 77 (6), 3101–3109.

Xu, Y., Shen, H., Xu, G., 2020. Evaluation of oil sorption kinetics behavior and wetting characteristic of cattail fiber. Cellulose 27 (3), 1531–1541.

Yang, X., Wu, Z., Qin, Z., Chen, F., Lv, C., Zhang, M., Zhong, F., Shaymurat, T., Duan, H., 2022. Highly selective and sensitive phenol sensor based on cattail carbon fibre operating at room temperature. Sensors Actuators A Phys. 341, 113593.

Yu, C.H., 2021. A Study on the Extraction Methods and Characterizations of Typha Leaf Fibers.

Yu, M., Han, Y., Li, Y., Li, J., Wang, L., 2018. Polypyrrole-anchored cattail biomass-derived carbon aerogels for high performance binder-free supercapacitors. Carbohydr. Polym. 199, 555–562.

Zhang, B., Joseph, G., Wang, L., Li, X., Shahbazi, A., 2020. Thermophilic anaerobic digestion of cattail and hydrothermal carbonization of the digestate for co-production of biomethane and hydrochar. J. Environ. Sci. Health A 55 (3), 230–238.

Zhang, J., Yan, X., Cao, S., Xu, G., 2018. Morphological characterization and properties of cattail fibers. Materiali in tehnologije 52 (5), 625–631.

Zhang, N., Gao, Y., Sheng, K., Jing, W., Xu, X., Bao, T., Wang, S., 2022. Effective extraction of fluoroquinolones from water using facile modified plant fibers. Journal of Pharmaceutical Analysis 12 (5), 791–800.

Zimniewska, M., 2022. Hemp Fibre Properties and Processing Target Textile: A Review. Materials 15 (5), 1901.

Zorai, A., Benzahi, K., Labed, B., Ouakouak, A., Serraoui, M., Bouhoreira, A., 2022. Performance of Canna indica and Typha latifolia in mono and mixed culture for secondary wastewater treatment in constructed wetlands with vertical flows under arid conditions (Touggourt, Algeria). Water Practice and Technology 18 (1), 53–67.