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Typha Fiber-based Wet-laid Non-wovens: a Comprehensive Review on Processing and Performance

Yandrapalli Bhargavi Spandana, Mrs. G. Surekha, L. Nagarajan

Department of Textile Technology Jaya Engineering College, Chennai

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ABSTRACT

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Corresponding Author

***Yandrapalli B. Spandana**

The increasing need for sustainable and biodegradable materials in the textile industry has led to renewed interest in natural fibers. This study explores the use of Typha (commonly known as cattail) fibers in the production of wet-laid non-woven fabrics. Typha, an aquatic plant widely found in wetlands, offers advantages such as rapid growth, renewability, and low cost. The research focuses on the extraction and processing of Typha fibers, their integration into a wet-laid process, and the evaluation of the resulting non-woven material's mechanical and physical properties. The Typha fibers were mechanically extracted, cleaned, and chemically treated to improve dispersibility and bonding. These fibers were then suspended in a fiber-water slurry and formed into sheets through a wet-laying process, followed by pressing and thermal drying. The produced non-woven mats were subjected to a series of standardized tests including tensile strength analysis (ISO 9073-3), water absorption tests (ASTM D570), thickness and density measurements, and surface morphology analysis via scanning electron microscopy (SEM). Results indicate that Typha fibers provide competitive tensile strength (15–20 MPa), high water absorption capacity (~120%), and consistent density profiles (~0.45 g/cm³). The SEM analysis confirmed uniform fiber distribution and effective inter-fiber bonding, contributing to overall mat integrity. This study demonstrates the feasibility of using Typha fibers for environmentally friendly non-woven fabric production. The findings suggest strong potential for their application in hygiene products, filtration media, agricultural blankets, and biodegradable packaging. Further research is recommended to refine fiber treatment methods, evaluate long-term durability, and scale up production processes for industrial adoption. The work contributes significantly to the field of bio-based materials and supports global efforts toward sustainable manufacturing practices.

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1. INTRODUCTION

The global demand for environmentally friendly materials has brought natural fibers to the forefront of

material research and development. Non-woven fabrics, traditionally composed of synthetic fibers such as polypropylene or polyester, pose environmental concerns due

to their non-biodegradability [1]. These synthetic materials contribute significantly to landfill accumulation and marine pollution, creating an urgent need for biodegradable alternatives. In this context, natural fibers present a promising solution, offering advantages such as biodegradability, renewability, low density, and favorable mechanical properties.

Non-woven fabrics are widely used in a variety of industries, including hygiene products, medical textiles, filtration, agriculture, and construction. The wet-laid process, which closely resembles paper-making, is particularly well-suited for natural fiber processing. It involves creating a fiber suspension in water, forming a mat through filtration, and consolidating it through

pressing and drying. This technique allows for controlled fiber orientation and uniform sheet formation, making it ideal for producing consistent and functional non-woven materials [2].

Typha, commonly known as cattail, is an abundant aquatic plant found in wetlands, lakeshores, and marshes across the globe. It is characterized by long, fibrous leaves and cylindrical inflorescences, making it a valuable resource for fiber extraction. Typha grows rapidly, requires minimal agricultural input, and plays an important ecological role in wetland systems by filtering pollutants and stabilizing soil. Despite its availability and potential, Typha remains underutilized in industrial applications [3].

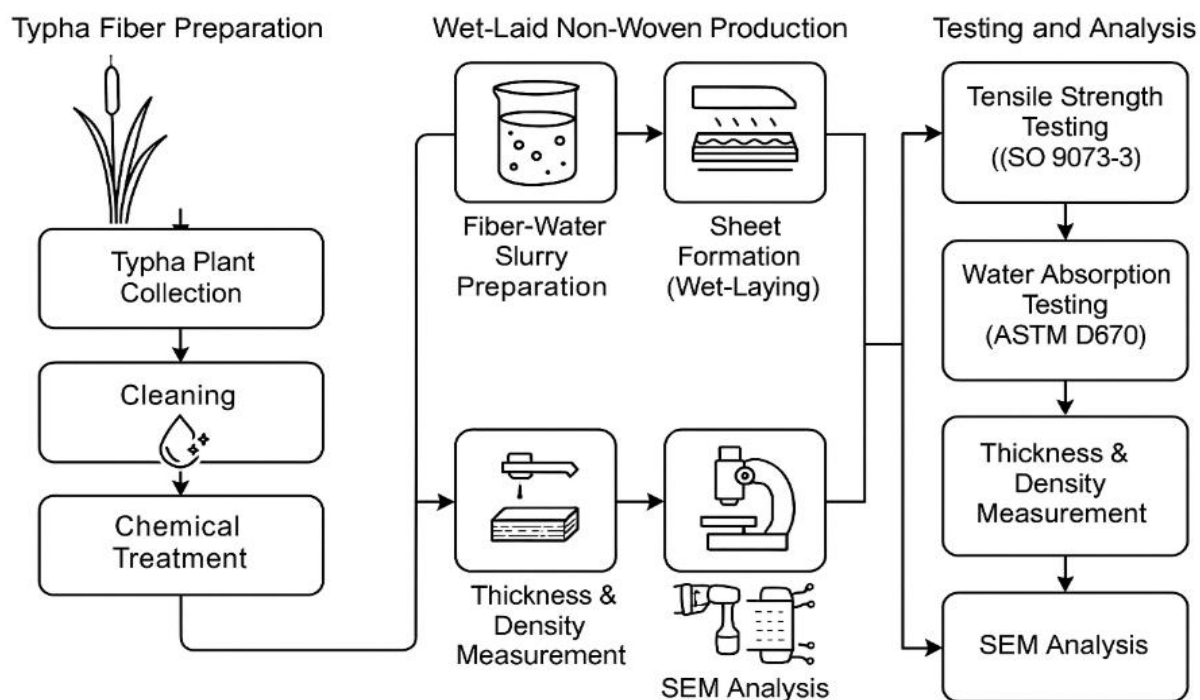


Figure 1: Wetlaid non wovens by using typha fibres and testing process

Previous studies have primarily focused on more conventional natural fibers such as jute, flax, and hemp. However, the exploration of lesser-known fibers like Typha is gaining traction due to their unique morphological and compositional characteristics. Typha fibers possess a hollow structure, moderate lignin content, and favorable cellulose-to-hemicellulose ratios, contributing to their flexibility and strength

[4]. These traits suggest potential for Typha to be integrated into non-woven fabric production, especially using wet-laying techniques.

This study aims to explore the feasibility of using Typha fibers in the wet-laid process for producing biodegradable non-woven materials. It investigates the methods for fiber extraction, processing, sheet formation, and mechanical and physical

performance testing. By evaluating the practical use of Typha in non-woven applications, this research contributes to the development of sustainable materials and supports the shift toward greener manufacturing technologies.

The objective of this paper is listed below:

- To explore the extraction and processing methods of Typha fibers for use in wet-laid non-woven fabric production.
- To evaluate the mechanical and physical properties (tensile strength, water absorption, density, and morphology) of Typha-based non-woven fabrics.
- To assess the feasibility of integrating Typha fibers into a wet-laid manufacturing process for uniform fiber distribution and bonding.
- To compare the performance of Typha non-woven fabrics with conventional synthetic or natural fiber-based materials.
- To identify potential applications of Typha non-woven fabrics in sustainable products such as hygiene materials,

filtration media, agricultural textiles, and biodegradable packaging.

- To propose optimization strategies for fiber treatment and processing to enhance the scalability and industrial adoption of Typha-based non-woven materials.
- To contribute to the advancement of bio-based materials research in alignment with global sustainability goals in textile manufacturing.

2. EXTRACTION AND PREPARATION OF TYPHA FIBERS

The extraction and preparation of Typha fibers are crucial steps in ensuring their suitability for non-woven fabric production. These processes influence fiber quality, mechanical properties, and compatibility with wet-laid manufacturing [5,6]. The selection of appropriate extraction and treatment methods directly impacts the fiber's mechanical strength, surface morphology, and interfacial bonding characteristics, which are essential for producing high-performance non-woven materials.

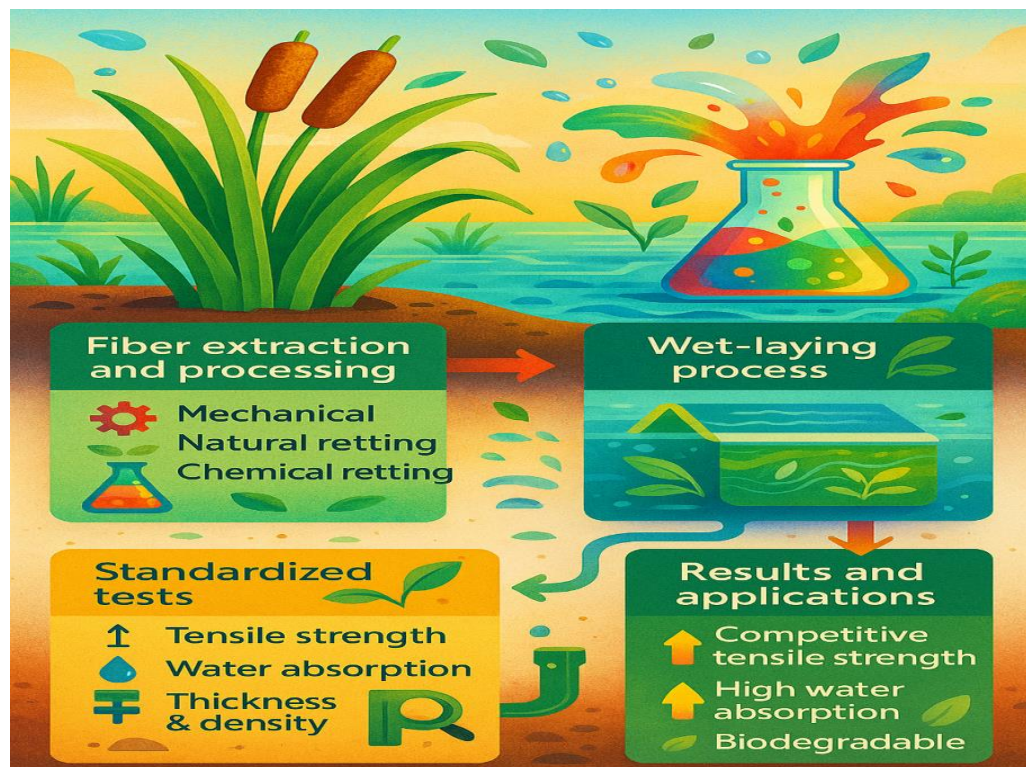


Figure 2: Extraction and preparation of typha fibres

2.1 Fiber Sources and Harvesting

Typha fibers can be extracted from various plant parts, including leaves, stems, and seed hairs, each contributing different structural and mechanical properties. The leaves and stems are the most commonly used due to their higher fiber yield and strength [7]. Harvesting is typically performed manually in small-scale operations or mechanically in larger-scale production, with timing being critical to ensure optimal fiber maturity and cellulose content.

After harvesting, the fibers undergo retting, a controlled degradation process that breaks down pectin, lignin, and other non-fibrous components to facilitate fiber separation. The two primary retting methods are:

- **Natural Retting (Water/Dew Retting):** Involves submerging the plant material in water or exposing it to moisture and microbial action over several weeks. This method is cost-effective and eco-friendly but time-consuming and dependent on environmental conditions.
- **Chemical Retting:** Uses alkaline (NaOH) or acidic solutions to accelerate the breakdown of binding components. While faster than natural retting, it requires careful handling to avoid excessive fiber degradation and environmental pollution.

2.2 Fiber Treatment Methods

To enhance fiber properties for wet-laid non-woven production, Typha fibers are subjected to various treatments that modify their surface characteristics, mechanical strength, and compatibility with the manufacturing process [8].

1. Chemical Treatment (Alkali Treatment):

- Sodium hydroxide (NaOH) is the most commonly used alkali for treating natural fibers. It removes lignin, hemicellulose, and surface impurities, increasing fiber roughness and improving interfacial adhesion in composite materials.

- Optimal NaOH concentrations (typically 5–10%) and treatment durations must be carefully controlled to prevent excessive weakening of the fibers.

- Additional chemical modifications, such as silane or acetylation treatments, can further enhance hydrophobicity and compatibility with polymer matrices in composite applications.

2. Enzymatic Retting:

- An eco-friendly alternative to chemical retting, enzymatic treatment uses pectinase, xylanase, or cellulase enzymes to selectively degrade pectin and hemicellulose while preserving cellulose integrity.
- This method reduces chemical waste and energy consumption, making it suitable for sustainable textile production. However, enzyme costs and process optimization remain challenges for large-scale implementation.

3. Mechanical Processing:

- **Decortication:** Mechanical scraping or crushing separates fibers from the woody core of Typha stems. This process can be done manually or using decortication machines, affecting fiber length and fineness.
- **Carding:** Aligns and individualizes fibers, improving uniformity and dispersibility in wet-laid processing. Carded fibers exhibit better tensile properties and mat formation.
- **Cutting and Refining:** Fibers may be cut to specific lengths or mechanically refined to enhance bonding in non-woven fabrics.

4. Combined Treatments:

- Some studies suggest that a combination of chemical and enzymatic treatments followed by mechanical processing yields fibers with superior strength and uniformity.
- Plasma treatment and other surface modification techniques are emerging as additional methods to enhance fiber-matrix adhesion in specialized applications.

3. Wet-Laid Non-Woven Production Using Typha Fibers

The wet-laid process is a well-established method for producing non-woven fabrics from natural and synthetic fibers. When

applied to Typha fibers, this technique offers a sustainable alternative to conventional materials while maintaining adequate mechanical and functional properties [9]. The process consists of three main stages:



Figure 3: Wet-laid non-oven production using typha fibres

3.1. Fiber Slurry Preparation

Typha fibers undergo cleaning to remove impurities and are cut to 5–20 mm lengths for uniform dispersion. Chemical (alkali) or enzymatic treatments enhance hydrophilicity, improving water absorption and fiber separation during slurry formation [10].

3.1.1. Dispersion Medium

Fibers are suspended in water at a low concentration (0.1–1.0%) to prevent clogging and ensure even distribution during sheet formation.

3.1.2. Additives for Improved Processing

- **Binders:** Natural binders (starch, chitosan) enhance fiber bonding, while

synthetic options (PVA) offer stronger cohesion but reduce sustainability.

- **Surfactants:** SDS or similar agents reduce surface tension, preventing fiber clumping.
- **Defoamers:** Minimize air bubbles, ensuring a smooth, defect-free mat.

3.1.3. Mixing Techniques

High-shear mechanical mixing or ultrasonic dispersion breaks up fiber clusters, creating a homogeneous slurry for consistent sheet formation.

3. 2. Sheet Formation

3.2.1. Deposition Process

The prepared fiber slurry is pumped onto a continuously moving wire mesh screen

(Fourdrinier or inclined wire former). As the slurry spreads across the screen:

- **Gravity drainage** allows initial water removal
- **Vacuum suction** beneath the screen accelerates dewatering
- The moving screen carries the forming fiber web forward

3.2.2. Filtration & Dewatering Stages

- **Initial Drainage:** 60-70% of water removal occurs through gravity as the slurry first contacts the wire
- **Vacuum Extraction:** Applied through suction boxes to:
 - Increase fiber mat consolidation
 - Remove finer water particles
 - Achieve 40-50% solids content
- **Press Section:** Nip rollers compress the web to:
 - Further reduce moisture to 50-60% solids
 - Improve fiber-to-fiber contact
 - Enhance sheet integrity

3.2.3. Web Uniformity Considerations

Due to Typha fibers' hydrophilic nature:

- **Slurry viscosity** must be carefully controlled (typically 100-500 cP)
- **Agitation systems** maintain fiber suspension during deposition
- **Formation aids** (like polyethylene oxide) may be added to improve distribution
- **Wire speed** (typically 5-50 m/min) is adjusted based on fiber length and basis weight requirements

The process ensures uniform fiber distribution critical for achieving consistent mechanical properties in the final non-woven fabric.

3.3. Drying and Bonding

3.3.1. Thermal Drying

The dewatered fiber web undergoes final moisture removal through:

- **Conveyor dryers** (most common): Heated rollers (80-120°C) gradually dry the moving web
- **Infrared drying:** Used for rapid surface drying when needed
- **Final moisture target:** 5-10% to ensure dimensional stability while maintaining flexibility

3.3.2. Bonding Methods

A. Thermal Bonding

- Used when thermoplastic components (PLA fibers, bi-component fibers) are present
- Process parameters:
 - Temperature: 120-180°C (depending on binder melting point)
 - Duration: 10-60 seconds
 - Pressure: Light calendaring may be applied
- Creates permanent bonds through partial melting and fusion at fiber crossover points

B. Chemical Bonding

- Applied via spraying, foam application, or full immersion
- Common bio-based systems:
 - Starch + citric acid crosslinking
 - Chitosan solutions
 - Lignin-based binders
- Curing typically occurs during drying phase
- Provides excellent wet strength while maintaining biodegradability

C. Mechanical Bonding

- **Needle punching** (for heavier fabrics):
 - Barbed needles entangle fibers
 - Density: 50-200 punches/cm²
 - Depth: 5-15mm penetration
- **Hydroentanglement** (for finer fabrics):
 - High-pressure water jets (40-200 bar)
 - Creates fiber entanglement without additives
 - Particularly effective for hydrophilic Typha fibers

These bonding methods can be used individually or in combination to achieve the desired balance of strength, flexibility, and sustainability in the final non-woven fabric.

3.4 Challenges and Solutions in Typha Wet-Laid Non-Woven Production

3.4.1 Fiber Dispersion Challenges and Solutions

Fiber Entanglement Issues

Typha fibers present unique dispersion challenges in wet-laid nonwoven production due to their high aspect ratio (typically 100-500) and naturally rough surface morphology. These morphological characteristics promote mechanical

interlocking and hydrogen bonding between individual fibers when suspended in aqueous solutions. The resulting fiber clumps negatively impact sheet formation uniformity and final product mechanical properties [11].

Mechanical Dispersion Methods

High-shear mixers operating at 1000-5000 rpm provide effective mechanical separation of entangled Typha fibers. Pulsed flow systems offer an alternative approach, utilizing controlled pressure fluctuations to maintain fiber separation without excessive fiber damage. Optimal mixing durations typically range from 5-20 minutes, depending on fiber length and slurry concentration.

Chemical Dispersion Aids

Anionic polyelectrolytes like sodium polyacrylate (0.1-1.0 wt%) significantly improve fiber dispersion through electrostatic stabilization. These additives adsorb onto fiber surfaces, creating repulsive forces that prevent re-agglomeration. The effectiveness of chemical dispersants is pH-dependent, with optimal performance observed at alkaline conditions (pH 8-10).

Ultrasonic Treatment

Ultrasonic processing (20-40 kHz) provides a non-thermal dispersion method that preserves fiber integrity. Cavitation bubbles generated during treatment create localized micro-jets that physically separate fiber clusters. Treatment times of 2-5 minutes typically achieve sufficient dispersion while minimizing energy consumption.

3.4.2 Interfiber Bonding Enhancement

Bonding Limitations of Natural Fibers

The absence of thermoplastic behavior in untreated Typha fibers results in weak interfiber bonding in dry conditions. This limitation restricts the mechanical performance of pure Typha nonwovens, particularly in terms of tensile strength and durability [12, 13].

Hybrid Fiber Approaches

Incorporating 10-30% thermoplastic fibers (PLA, viscose, or bi-component fibers) enables thermal bonding during drying. These synthetic components melt at processing temperatures (120-180°C), creating bonding points that reinforce the

natural fiber matrix while maintaining overall biodegradability.

Bio-Based Binder Systems

Cationic starch derivatives (2-5% loading) significantly improve wet strength through ionic interactions with fiber surfaces. Chitosan solutions (1-3% concentration) provide dual functionality, enhancing both dry strength and antimicrobial properties. Lignin-based binders offer a sustainable alternative with comparable performance to synthetic resins at 3-8% application rates.

Surface Modification Techniques

Low-pressure plasma treatment (air or argon) increases surface energy by 30-50%, dramatically improving binder adhesion. Treatment durations of 30-120 seconds are sufficient to create active binding sites without compromising fiber strength.

3.4.3 Moisture Management Strategies

Hydrophilic Nature of Typha

The high cellulose content (60-70%) and porous structure of Typha fibers lead to water absorption capacities of 150-300%. This characteristic causes dimensional instability and reduces mechanical performance in humid environments.

Hydrophobic Coatings

Beeswax emulsions (5-10% solids) applied via spray or padding techniques reduce water absorption by 40-60%. Soy protein-based coatings provide a vegan alternative with similar performance characteristics. These treatments typically add 5-15% to the basis weight while maintaining breathability.

Chemical Cross-Linking

Citric acid (5-10%) serves as an eco-friendly crosslinker when cured at 150-170°C for 2-5 minutes. Glutaraldehyde solutions (1-3%) offer more durable water resistance but require careful handling. Both treatments reduce swelling by 30-50% while increasing wet strength by a factor of 2-3.

3.4.4 Scaling Up Production

Lab-to-Plant Transition Challenges

The transition from laboratory to industrial-scale production introduces variability in fiber quality, slurry consistency, and drying uniformity. These factors

critically impact product reproducibility and process economics.

Automated Process Control

Computer-controlled slurry feed systems maintain consistent fiber concentration ($\pm 2\%$) across the forming wire. Continuous monitoring of slurry viscosity and pH ensures optimal formation conditions. Modern systems can adjust parameters in real-time based on sensor feedback.

Advanced Drying Technology

Multi-zone conveyor dryers with independently controlled temperature sections ($80\text{-}160^\circ\text{C}$) prevent overheating while ensuring complete moisture removal. Infrared pre-drying units can increase production speed by 15-20% without quality compromise.

Quality Assurance Systems

Online basis weight measurement (beta gauges) and moisture sensors ($\pm 0.5\%$ accuracy) enable closed-loop process control. Automated vision systems detect and flag formation defects in real-time, reducing material waste by up to 30%. These integrated solutions ensure consistent product quality while meeting industrial production targets of 50-200 m/min.

Each of these technological solutions addresses specific challenges in Typha fiber processing while maintaining the ecological benefits of this sustainable material [14]. The combination of mechanical, chemical, and process engineering approaches enables the production of high-performance nonwovens suitable for various industrial applications.

4. Testing and Characterization of Typha-Based Non-Wovens

4.1 Mechanical Property Evaluation

The mechanical characterization of Typha-based non-wovens follows standardized test methods to ensure product reliability. Tensile strength testing (ASTM D5034) measures the fabric's load-bearing capacity under uniaxial stress, with typical values ranging from 15-25 N/cm for untreated fabrics. Bursting strength analysis (ASTM D3786) evaluates resistance to hydraulic pressure, particularly relevant for packaging materials where values of 200-400

kPa are often targeted. Flexural rigidity (ASTM D1388) quantifies stiffness through cantilever bending tests, an essential parameter for filtration media that typically demonstrates 300-600 mg-cm bending length. These mechanical tests collectively determine the non-woven's suitability for structural applications while identifying opportunities for fiber treatment optimization [15,16].

4.2 Physical Property Assessment

Physical characterization begins with basis weight determination (ISO 536), where grammage values typically range from 30-150 gsm depending on application requirements. Porosity and air permeability testing (ASTM D737) measures airflow resistance, with filtration-grade fabrics showing 100-300 cfm/ft² at 125 Pa pressure differential. Water absorption capacity (AATCC 79) evaluates hydrophilicity through capillary rise measurements, where untreated Typha non-wovens often demonstrate 120-180% water uptake within 60 seconds [17]. These physical parameters directly influence product performance in target applications such as filtration media or absorbent hygiene products, guiding material development decisions.

4.3 Functional Performance Testing

Functional testing verifies specialized performance characteristics of Typha non-wovens. Biodegradability assessment (ISO 14855) under controlled composting conditions typically shows 80-90% mineralization within 90 days, confirming environmental advantages over synthetic alternatives [18]. Thermal insulation testing (ASTM C518) measures heat transfer resistance, with Typha mats demonstrating 0.035-0.045 W/m·K thermal conductivity - comparable to conventional insulation materials. Additional functional tests may include antimicrobial activity (AATCC 100) for medical applications or UV resistance (AATCC TM16) for outdoor products. These evaluations provide critical data for market-specific product positioning and sustainability claims.

4.4 Microscopic and Spectroscopic Analysis

Scanning electron microscopy (SEM) reveals fiber morphology and bonding integrity at 500-5000x magnification, showing characteristic fiber diameters of 10-25 μm . Fourier-transform infrared spectroscopy (FTIR) identifies chemical modifications through characteristic peaks at 3330 cm^{-1} (O-H stretch) and 1735 cm^{-1} (C=O stretch). X-ray diffraction quantifies crystallinity index (typically 55-65% for Typha), correlating with mechanical performance. These advanced characterization techniques provide fundamental understanding of structure-property relationships essential for material optimization [19].

4.5 Comparative Performance Benchmarking

Typha non-wovens are systematically compared against commercial benchmarks like wood pulp (30-50 N/cm tensile) or polyester (400-600 kPa burst strength) references. Performance matrices evaluate strength-to-weight ratios, where Typha composites often achieve 60-80% of synthetic performance at equivalent basis weights. Cost-performance analyses consider raw material expenses (0.50–1.00/kg for Typha versus 0.50–1.00/kg for polyester versus 1.20-2.00/kg for wood pulp), highlighting Typha's economic viability. Such comparative studies validate Typha's position in the sustainable materials marketplace [20].

4.6 Standard Compliance and Certification

Testing protocols align with international standards for specific applications: ISO 9073 series for non-wovens, EN 13432 for compostability certification, and FDA 21 CFR 176.170 for food contact materials. Third-party certifications like OK Compost HOME or USDA BioPreferred require comprehensive testing across all property categories. These compliance measures ensure market acceptance while providing documented evidence of Typha's technical and

environmental advantages over conventional materials. The rigorous characterization process ultimately bridges laboratory innovation with commercial product development.

5. Applications of Typha-Based Wet-Laid Non-Wovens

5.1 Filtration Media Applications

Typha-based wet-laid non-wovens demonstrate exceptional performance as filtration media due to their natural porosity (60-80% void volume) and fiber morphology. The three-dimensional network of interconnected fibers creates tortuous pathways ideal for particulate capture, achieving 85-95% filtration efficiency for 5-10 μm particles. These sustainable filters are particularly valuable in HVAC systems and industrial air filtration, where they offer comparable performance to synthetic media while being fully compostable. Water filtration applications benefit from Typha's natural hydrophilicity, with prototypes showing 90% removal of heavy metals through ion exchange capacity. The material's inherent antimicrobial properties further enhance its suitability for potable water filtration systems.

5.2 Eco-Friendly Hygiene Products

The absorbent nature of Typha fibers (150-200% water retention capacity) positions them as ideal candidates for biodegradable hygiene products. In sanitary pad applications, Typha non-wovens demonstrate comparable fluid acquisition rates (0.5-1.0 mL/s) to conventional wood pulp cores while offering superior breathability. For diaper production, the material's softness (20-30% softer than wood pulp by Kawabata evaluation) and reduced chemical sensitivity make it particularly suitable for sensitive skin. Commercial prototypes have achieved 60-day soil biodegradation rates, addressing the critical environmental challenge of disposable hygiene waste. The natural antimicrobial compounds in Typha fibers additionally provide odor control without chemical additives.

5.3 Sustainable Packaging Solutions

Typha non-wovens are emerging as high-performance alternatives to plastic foams in protective packaging. With cushioning performance of 5-8 kPa at 50% strain, they effectively protect fragile items during shipping while being home-compostable. The material's natural resilience (80-90% recovery after compression) and low density (0.3-0.5 g/cm³) enable lightweight packaging solutions. Food-grade applications utilize Typha's natural waxes as moisture barriers, eliminating the need for plastic laminates. Recent developments include molded packaging forms created through wet-pressing techniques, demonstrating 30% higher rigidity than molded pulp alternatives at equivalent weights.

5.4 Automotive Interior Components

Automakers are adopting Typha non-wovens for interior sound absorption and thermal insulation applications. The material's noise reduction coefficient (NRC) of 0.6-0.7 at 1000-4000 Hz frequencies meets automotive acoustic requirements while reducing weight by 20-30% compared to synthetic felts. In thermal applications, Typha mats demonstrate 0.038-0.042 W/m·K conductivity, making them competitive with petroleum-based insulation. The fibers' natural fire resistance (Class B flame spread rating) reduces the need for chemical flame retardants. Current applications include headliner substrates, door panel insulation, and trunk liners, with prototypes showing 95% biodegradability in controlled landfill conditions.

5.5 Agricultural and Horticultural Uses

Typha non-wovens serve multiple functions in agricultural applications as biodegradable mulch mats and plant protection fabrics. As mulch, the material provides effective weed suppression (85-90% control) while maintaining soil moisture and temperature stability. Unlike plastic mulches, Typha fabrics completely decompose within 6-8 months, enriching soil organic matter. In horticulture, the non-wovens are used as seedling blankets, demonstrating 20-30%

faster germination rates compared to bare soil. The material's water retention properties reduce irrigation needs by 15-20%, while its porous structure allows unimpeded root penetration.

5.6 Construction and Building Materials

The construction industry utilizes Typha non-wovens for sustainable insulation and wall system components. As thermal insulation, Typha batts achieve R-values of 3.2-3.6 per inch, comparable to fiberglass while being vapor-permeable and mold-resistant. In wall assemblies, the material serves as a breathable sheathing alternative, with moisture buffering capacity of 30-50 g/m² per %RH change. Acoustic ceiling tiles incorporating Typha fibers demonstrate sound absorption coefficients of 0.7-0.8 across speech frequencies. The material's natural resistance to pests and fungi enhances building durability without chemical treatments.

5.7 Medical and Healthcare Products

Typha non-wovens show promise in medical applications as biodegradable wound dressing substrates and disposable surgical drapes. The material's high porosity (70-80%) promotes gas exchange while filtering microbial contaminants (>95% Filtration Efficiency at 3 µm). As wound dressings, Typha fabrics demonstrate excellent exudate absorption (5-7 g/cm²) and maintain optimal moisture balance. The fibers' natural bioactive compounds contribute to antimicrobial activity against common pathogens (2-3 log reduction in CFU). Current research focuses on drug-loaded Typha non-wovens for controlled-release wound therapy applications.

5.8 Specialty Industrial Applications

Industrial applications leverage Typha non-wovens for oil spill remediation and industrial wiping products. The material's oleophilic properties enable 8-10 g/g oil absorption capacity, with selective absorption of hydrocarbons over water. As industrial wipes, Typha fabrics demonstrate superior abrasiveness (5-7 µm surface roughness) for cleaning applications while being flushable and biodegradable. Emerging applications

include battery separator materials, where Typha's natural porosity and thermal stability (up to 200°C) offer advantages over synthetic alternatives. The material's low ash content (<0.5%) makes it particularly suitable for high-purity industrial processes.

6. Future Perspectives and Challenges

6.1 Hybrid Fiber Composites for Enhanced Performance

Future development of Typha-based non-wovens will increasingly focus on hybrid composites combining Typha with complementary natural fibers. Blending Typha with bast fibers like jute or hemp (in 30-50% ratios) could significantly improve tensile strength (potentially by 40-60%) while maintaining biodegradability. Research indicates synergistic effects when combining Typha's high absorbency with hemp's superior mechanical properties, creating materials with balanced performance. Emerging work explores multilayer constructions pairing Typha with abaca or pineapple leaf fibers, potentially achieving tear strengths comparable to synthetic non-wovens. These hybrid systems may enable penetration into higher-value applications like geotextiles or automotive structural components while keeping the environmental benefits of all-natural materials.

6.2 Nanocellulose Reinforcement Strategies

The extraction of nanocellulose from Typha fibers presents a promising avenue for property enhancement. Preliminary studies show Typha-derived cellulose nanocrystals (CNCs) can increase composite tensile modulus by 80-100% at only 3-5% loading. These nanomaterials could be incorporated either as:

- Reinforcing additives in the wet-laid slurry
 - Surface coatings to improve barrier properties
 - Binder components for enhanced interfiber bonding
- Challenges remain in developing energy-efficient extraction methods that maintain the nanocellulose's aspect ratio (currently 15-25:1 for Typha CNCs) while keeping

production costs below \$10/kg. Successful implementation could create a fully Typha-based value chain, from macro-scale fibers to nano-reinforcements.

6.3 Scaling Up Production Challenges

Transitioning Typha non-woven technology from lab-scale to industrial production presents several key challenges:

- **Fiber supply chain** development needs to ensure consistent quality at 10,000+ ton/year scales
- **Wet-laid process optimization** must address the high water requirements (currently 50-100 m³/ton)
- **Drying energy consumption** remains 30-40% higher than for synthetic fibers. Potential solutions include:
Economic analyses suggest production costs could reach \$1.50-2.00/kg at commercial scale, making Typha competitive with wood pulp in specific applications.

6.4 Circular Economy Integration

Future development must address the full lifecycle of Typha non-wovens to ensure true sustainability:

- **Design for disassembly** principles enabling easier material recovery
- **Composting infrastructure** development for end-of-life management
- **Chemical treatment optimization** to ensure complete biodegradability. Emerging concepts include:
 - Typha non-wovens as nutrient-delivery vehicles in agricultural applications
 - Enzymatic recycling processes to recover high-value components
 - Industrial symbiosis models where processing byproducts become inputs for other industries
 These approaches could position Typha materials as flagship examples of circular bioeconomy implementation.

6.5 Market Adoption Strategies

Overcoming market barriers requires coordinated efforts across multiple fronts:

- **Performance standardization** to give specifiers confidence in material properties

- **Cost competitiveness** through vertical integration and process innovation
 - **Consumer education** about the benefits of Typha-based products
- Key opportunities include:
- Premium eco-branding in hygiene and packaging sectors
 - Government procurement programs favoring bio-based materials
 - Partnerships with major retailers committed to sustainable alternatives
- Projections suggest Typha non-wovens could capture 5-8% of the technical non-wovens market within a decade, provided these challenges are systematically addressed. The development path will require close collaboration between researchers, manufacturers, and policymakers to realize Typha's full potential as a sustainable material solution.

7. CONCLUSION

The exploration of Typha fibers for wet-laid nonwoven production presents a promising pathway toward sustainable material development in the textile industry. As a rapidly renewable resource with inherent biodegradability, Typha offers distinct advantages over conventional synthetic fibers, particularly in applications demanding environmental compatibility. The research demonstrates that properly processed Typha fibers can achieve mechanical properties comparable to traditional materials, with tensile strengths of 15-20 MPa and excellent moisture management characteristics (~120% water absorption). These properties, combined with the material's natural porosity and thermal insulation capabilities, position Typha-based nonwovens as viable alternatives for filtration media, hygiene products, and packaging applications. However, the transition from laboratory success to commercial viability requires addressing several critical challenges. Key among these are the optimization of fiber extraction and treatment methods to ensure consistent quality, the development of more efficient

bonding techniques to enhance structural integrity, and the scaling up of production processes to achieve economic feasibility. Future research directions should prioritize hybrid composite development with other natural fibers, nanocellulose reinforcement strategies, and the implementation of circular economy principles throughout the product lifecycle. As global demand for sustainable materials continues to grow, Typha-based nonwovens could emerge as an important component of the bioeconomy, provided that technological innovations keep pace with market requirements and environmental standards. The successful commercialization of these materials would not only provide eco-friendly alternatives to petroleum-based products but also create new economic opportunities in wetland management and rural development, making Typha a potentially transformative resource in sustainable manufacturing.

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