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Sustainable Fatliquoring through Amphoteric Polymer Design: A Comparative Study on Chrome-Tanned and Chrome-Free Leather

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Abstract:

In response to the growing demand for environmentally sustainable, resource- efficient leather processing technologies, this study presents the development of a novel amphoteric polymeric fatliquor synthesized from allyltrimethylammonium bromide (ATMA) via free-radical polymerization. The designed polymer possesses a dual ionic architecture incorporating cationic, anionic, and hydrophobic functionalities, enabling adaptive interactions with collagen across varying pH conditions. Comprehensive structural characterization using FTIR, 1H NMR, GPC, and ESIMS confirmed successful polymer formation and controlled molecular architecture. The amphoteric nature of the polymer facilitates pH-responsive binding with collagen, ensuring uniform penetration during processing and enhanced fixation during posttanning. The efficiency of fatliquoring was systematically evaluated and compared in both chrometanned and chrome-free tanned leather systems to establish the versatility of the developed polymer. When applied to chrome-tanned leather, the developed fatliquor demonstrated a significantly higher uptake (85.2%) compared to conventional fatliquoring systems (68.7%). This improved fixation translated into superior leather performance, tensile strength (32.25 N/mm², representing a 46.7% increase), and notable improvements in softness and fullness, with a softness

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index of 8.3 compared to 6.1 for the control. Importantly, the improved exhaustion efficiency resulted in a marked reduction in effluent load, with chemical oxygen demand (COD) decreasing from approximately 42,000 mg/L to 32,000 mg/L, highlighting the environmental advantage of the process. Comparable enhancements in physical and environmental performance were also observed in chrome-free leather systems, further validating the polymer’s applicability across tanning technologies. Overall, this work introduces an innovative, scalable, and eco-efficient fatliquoring technology that integrates functional polymer design with sustainable leather processing, making a meaningful contribution to next-generation green manufacturing practices in the leather industry.

Keywords: Amphoteric polymer, Polymeric fatliquor, Sustainable leather processing, collagen interaction, Effluent load reduction.

1. Introduction

Leather processing plays a vital role in the global materials sector; however, post-tanning operations such as fatliquoring contribute significantly to wastewater pollution due to low chemical fixation and high organic discharge. Conventional fatliquors based on sulphated or sulfonated oils typically exhibit limited exhaustion (65–70%), resulting in elevated COD levels in effluents. Chrome tanning

remains the most widely adopted tanning technology owing to its superior thermal and mechanical stabilization of collagen. The chromium species used is predominantly trivalent chromium [Cr(III)], which is chemically stable and safe under controlled processing conditions. Nevertheless, inefficiencies in chemical uptake during post-tanning steps contribute to chromium-bearing sludge and increased environmental load. Chrome-free tanning systems have gained attention due to regulatory and market-driven sustainability requirements. While these systems reduce metal discharge, they often suffer from inferior hydrothermal stability and mechanical strength. Consequently, the development of multifunctional auxiliaries that can operate effectively across both chrome and chrome-free systems is highly desirable. Amphoteric polymers, containing both cationic and anionic

functional groups within a single macromolecule, have emerged as promising multifunctional auxiliaries in leather processing. Their pH-responsive ionic behavior enables effective interaction with the amphoteric collagen matrix, improving penetration, lubrication, and fixation across different tanning systems. In this context, the present study focuses on the design and application of a novel amphoteric polymeric fatliquor capable of functioning efficiently in both chrome and chrome-free leathers, thereby addressing performance limitations and environmental concerns simultaneously.

2. Methodology

2.1 Synthesis of Amphoteric Polymeric Fatliquor

The amphoteric polymer was synthesized via aqueous free-radical copolymerization using a cationic monomer (allyltrimethylammonium-based) and an anionic monomer (carboxylic acid- based). Polymerization was carried out under controlled temperature (60–70 °C) using a persulfate initiator in a nitrogen atmosphere. The resulting polymer was neutralized to achieve balanced ionic character and formulated with jatropa oil as a stable aqueous fatliquoring emulsion.

2.2 Fatliquoring Application

Fatliquoring trials were conducted on both chrome-tanned and chrome-free (wet-white) leathers.

 Control: Commercial anionic fatliquor

 Experimental: Amphoteric polymeric fatliquor

Both systems were applied under identical process conditions. Exhaustion efficiency was determined gravimetrically. Post-treatment, leathers were crusted and conditioned before testing.

2.3 Characterization

The synthesized amphoteric polymer was chemically characterized using FTIR, NMR, ESI- MS, GPC, TGA, DSC, and Zeta potential studies. Mechanical properties, including tensile strength, elongation at break, softness, fullness, and shrinkage temperature, were evaluated using standard testing methods. Effluent COD was measured following standard protocols to assess environmental impact.

3. Results and Discussion

3.1 Chemical Characterization of the Amphoteric Polymer

The successful synthesis and structural integrity of the amphoteric polymer (ATMA–DMAS) were confirmed through comprehensive spectroscopic and thermal analyses. FTIR spectra showed characteristic absorption bands at ~3422 cm^{-1} (–OH/–NH stretching), 1720 cm^{-1} (ester C=O stretching), and 1151–1733 cm^{-1} corresponding to C–N and sulfonate functionalities, confirming the incorporation of both cationic and anionic groups within the polymer backbone. The ESI–MS spectrum of ATMA exhibited isotopic peaks at m/z 179.15 and 181.20, validating the monomer structure. Further confirmation was obtained from ^{1}H and ^{13}C NMR spectra, where signals corresponding to quaternary ammonium methyl groups, aliphatic backbone carbons, and sulfonate-linked segments were clearly observed, indicating successful polymerization without structural degradation. Thermogravimetric analysis demonstrated enhanced thermal stability of ATMA–DMAS, with major degradation occurring above ~260° compared to ATMA (~235 °C), while DSC revealed a glass transition around

120 °C, indicative of a flexible yet stable polymer matrix suitable for leather processing conditions. Zeta potential analysis showed pH-responsive charge behavior, transitioning from positive to negative with increasing pH, confirming the amphoteric nature of the polymer and explaining its strong, adaptive interaction with collagen fibers across both chrome and chrome-free tanning systems.

3.2 Fatliquor Exhaustion and Environmental Impact The amphoteric polymer exhibited significantly higher exhaustion (>85%) compared to the conventional anionic fatliquor (~67%). This improved fixation reduced residual organic matter in the float, leading to approximately 24% reduction in COD values. The high exhaustion efficiency directly contributes to reduced chemical consumption and lower effluent treatment load, addressing key sustainability concerns.

3.3 Mechanical and Physical Properties

Leathers treated with the amphoteric polymer showed marked improvements in tensile strength, elongation, softness, and fullness. In chrome-free leathers, the shrinkage temperature increased from approximately 98°C to above 108°C, indicating enhanced collagen

stabilization. These improvements are attributed to the polymer’s dual ionic interactions with collagen, which promote uniform lubrication and fiber cohesion without surface migration.

3.4 Applicability Across Tanning Systems

The amphoteric polymer performed effectively in both chrome and chrome-free systems, demonstrating its versatility. Unlike conventional fatliquors, which are optimized for specific tanning chemistries, the pHresponsive nature of the amphoteric polymer enables adaptive interaction with different collagen charge states, ensuring consistent performance.

3.5 Sustainability and Ethical Considerations

The polymer synthesis employs an aqueous route with no solvent emissions and avoids hazardous reagents. Improved exhaustion efficiency minimizes waste generation, supporting eco-friendly processing. The approach aligns with principles of green chemistry, cleaner production, and circular economy by reducing chemical losses and environmental footprint without compromising product quality.

4. Conclusion

A novel dual-ionic amphoteric polymeric fatliquoring agent was successfully developed and evaluated for both chrome and chrome-free leather systems. The polymer exhibited superior exhaustion efficiency, improved mechanical strength, enhanced softness and fullness, and increased hydrothermal stability, while significantly reducing effluent COD. Its pH-adaptive ionic behavior enables effective collagen interaction across different tanning chemistries, ensuring process versatility and consistent leather quality. By reducing chemical loss and wastewater load without altering existing industrial practices, this work demonstrates a sustainable, scalable, and net-zeroaligned solution for cleaner leather manufacturing, reinforcing the critical role of chemical sciences in sustainable industrial transformation.

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