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Encapsulated Peppermint Oil for Anti-Microbial Fragrant Leather

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Abstract:

The leather industry is rapidly evolving to meet growing consumer demand for multifunctional and value-added materials. Traditional fragrant leathers primarily enhance aroma but often suffer from short fragrance retention, weak stability and lack of antimicrobial protection. Fungal growth on leather is a common issue in damp or sweat-exposed conditions, leading to stains, surface defects, roughness, and reduced mechanical strength, ultimately degrading product quality. Generally, biocides such as pentachlorophenol, dimethyl fumarate, 2-(thiocyanomethylthio)benzothiazole, etc., are used to protect the leather products from fungal growth. These chemicals pose a threat to human health and the environment, and are listed in the REACH regulation. To overcome this problem, antimicrobial/cleaning solutions are available, which are a temporary measure, and the leather is prone to getting contaminated again. On the other hand, conventional leather perfuming technology has limitations such as easy volatilization of the fragrance, poor thermal stability, and bad compatibility, affecting the product’s durability. There is a demand for environment-friendly fragrance products for making scented leather goods/ accessories without affecting their bulk properties. To address these limitations, this study focuses on developing a smart antimicrobial fragrant leather

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using essential oil nanoencapsulates using silica as wall material. In this work, peppermint-oil–silica nanocapsules were prepared via controlled hydrolysis and condensation reactions. Further, the synthesized nanocapsules were characterized using DLS (295.3±3.85 nm) & Zeta potential (5.34 mV, whereas oil has -2.93 mV), TGA (oil loading efficiency), ATRFTIR, SEM & TEM (75-150 nm). These nanocapsules were subsequently infused into leather during the posttanning and finishing and assessed its antimicrobial and fragrant nature. Overall, this study demonstrates a promising approach to develop multifunctional leather with improved fragrance retention and antimicrobial property.

Keywords: Scent infused leather, Antimicrobial leather, Essential oils, Silica encapsulation, Emulsion polymerization; Antifungal agents.

1 Introduction

The leather industry is undergoing a transformation driven by increasing consumer demand for multifunctional, valueadded, and sustainable materials. Fragrant and antimicrobial leathers are of particular interest for applications exposed to moisture and prolonged human contact, such as footwear, upholstery, and fashion accessories. While fragrance enhances sensory appeal, microbial resistance is essential to maintain hygiene, material integrity, and product longevity. However,

achieving durable fragrance retention and effective antimicrobial performance in leather remains challenging using conventional technologies1.

Traditional fragrant leathers suffer from rapid fragrance loss due to the high volatility, poor thermal stability, and limited compatibility of perfume compounds with the leather matrix. Simultaneously, fungal growth under humid or sweat-prone conditions causes surface defects, odor formation, mechanical degradation, and reduced service life. Although synthetic biocides such as pentachlorophenol, dimethyl fumarate, and benzothiazole derivatives are commonly used, they pose serious health and environmental risks and are restricted under REACH regulations. Available antimicrobial treatments often provide only temporary protection, leading to recurring contamination. Hence, there is a critical need for ecofriendly, durable solutions that combine fragrance retention with antimicrobial functionality without compromising leather properties2,3.

To address these limitations, the present study focuses on developing smart antimicrobial fragrant leather using silicabased nanoencapsulation of essential oils. Peppermint oil was encapsulated within silica nanocapsules via controlled hydrolysis and condensation reactions to enhance stability and controlled release. The nanocapsules were thoroughly characterized and subsequently incorporated into leather during post-tanning and finishing processes. The treated leather was evaluated for fragrance durability and antimicrobial performance, demonstrating the potential of silica-encapsulated essential oils as an effective and sustainable approach for multifunctional leather development.

Methodology Materials

Tetraethyl orthosilicate (TEOS, >99%, SRL), 3aminopropyl triethoxysilane (APTES, 99%, SRL), peppermint oil (35%, Himedia), aqueous ammonia (NH4OH 28 %, Rankem) and cetyltrimethyl ammonium bromide (CTAB, 99%, SRL) were used. Chrome tanned goat skins were used for post tanning trials.

Characterization

The peppermint oil encapsulated silica nanocapsules were visualized using high resolution transmission electron microscope (JEOL JEM 2100) and field emission scanning electron microscope was performed with Tescan-Clara. Dynamic light scattering and zeta potential were performed using Malvern Zeta-sizer nano ZS. Attenuated total reflectance infrared spectra for samples were measured in JASCO-FT/IR-6X Infrared spectrometer. Thermogravimetric analysis (TGA) for samples was performed using Q50 TA instrument from 25 to 9000C in nitrogen flow with a ramp of 100C per minute.

2.2 Encapsulation of Peppermint oil into silica capsules:

A modified Stober process was followed to encapsulation peppermint oil into silica capsules. In brief, to a 2000 mL beaker, 100 mL of 0.1 M CTAB and 900 mL water were added. To this, 5g of pepermint oil (0.918 g/mL) was added dropwise and stirred for 10 mins. To this emulsion, 10 mL of TEOS was added dropwise followed by addition of aqueous ammonia and stirred for 12 hours. To introduce amine terminal, 10 mL of APTES was added and stirred overnight.

3. Results And Discussion

Core–shell peppermint oil–encapsulated silica nanocapsules were synthesized using a modified Stöber process. Initially, the essential oil was introduced into a surfactant medium, resulting in the formation of a microemulsion. Upon the addition of tetraethyl orthosilicate (TEOS) and ammonia, hydrolysis and condensation reactions commenced, leading to the formation of a silica shell around the emulsion droplets and thereby encapsulating the peppermint oil within silica nanocapsules.

The synthesized nanocapsules were examined using FESEM and HR-TEM. SEM images revealed that the silica nanocapsules were spherical in morphology with an average particle size of approximately 150 nm. TEM images further confirmed the spherical structure, showing

a distinct core–shell architecture characterized by a darker core and a lighter shell, corresponding to the peppermint oil core and the silica shell, respectively. The oil core was approximately 70 nm in diameter and was enclosed by a silica shell of about 20 nm thickness.

Encapsulation of peppermint oil within the silica matrix was further confirmed by ATR-FTIR analysis. Characteristic functional groups of peppermint oil, such as C–H, C–O–C, C=O, and –OH stretching vibrations, were observed and found to be consistent with reported literature. The FTIR spectrum of the encapsulated system exhibited these characteristic peaks along with additional bands in the range of 1020–1100 cm-1, attributed to Si–O–Si stretching vibrations, confirming the formation of the silica shell. Furthermore, the stretching band observed around 3000–3200 cm-1

indicated the presence of free amine terminal groups on the surface of the silica nanocapsules.

These findings were further supported by DLS and TGA analyses. DLS measurements showed that peppermint oil exhibited a larger hydrodynamic size, while encapsulation within silica resulted in a shift toward a smaller and

more uniform hydrodynamic diameter, indicating successful encapsulation. Additionally, the zeta potential shifted from a negative value for the oil (-2.93 mV) to a positive value for the nanocapsules (5.34 mV), confirming surface modification due to the presence of amine groups on the silica shell. TGA analysis revealed that peppermint oil underwent rapid thermal degradation owing to its organic nature. In contrast, the encapsulated oil demonstrated enhanced thermal stability, attributed to the protective effect of the silica shell. The encapsulation efficiency, as determined from TGA, was found to be 69%.

Following material characterization, the nanocapsules were applied to leather during the post-tanning stage to develop antifungal aromatic leather. Chrome-tanned leather was selected due to its widespread industrial use. The leather was neutralized to a pH range of approximately 5.5–6.5 using sodium bicarbonate. The oil-loaded nanocapsules were then added and drummed for 1 hour, followed by

fatliquoring for 1 hour and fixation for 30 minutes using a 3% formic acid solution. The silica nanocapsules also functioned as a retanning agent by forming hydrogen bonding interactions with free –NH, and –COOH groups present in the leather matrix.

Over time, the silica shell enabled the prolonged release of peppermint oil, imparting softening, sustained fragrance, and antifungal properties to the leather. The controlled aroma release helped mask the characteristic leather odor, providing a luxurious scented feel. Antifungal studies demonstrated that peppermint oil exhibited effective antifungal activity against five fungal strains, namely Aspergillus niger, Aspergillus flavus, Aspergillus fumigatus, Paecilomyces variotii, and Penicillium citrinum.

From a sustainability perspective, the use of natural essential oil as an antifungal and fragrance agent offers a safer alternative to conventional toxic biocides such as pentachlorophenol, dimethyl fumarate, and 2-(thiocyanomethylthio)benzothiazole. This approach supports environmentally responsible leather processing and aligns with sustainable development goals by reducing the use of hazardous chemicals.

4. Conclusions

Peppermint oil–loaded silica nanocapsules were successfully synthesized and confirmed through detailed physicochemical characterization, demonstrating effective core–shell formation, improved thermal stability, and controlled release behavior. The nanocapsules were applied during the post-tanning stage of chrome-tanned leather without adversely affecting its bulk properties. The silica nanocapsules served a dual function by acting as a carrier for sustained peppermint oil release, imparting longlasting fragrance, improved softness, and effective antifungal activity to the leather. The treated leather showed significant antifungal performance against common fungal strains, highlighting its potential for hygienic and value-added leather applications. From a sustainability perspective, the use of naturally derived peppermint oil encapsulated within a silica matrix provides an eco-friendly

alternative to conventional synthetic fungicides. This approach avoids the use of toxic biocides restricted under REACH regulations and supports sustainable development goals by promoting safer chemical usage, enhanced product durability, and environmentally responsible leather processing. Overall, the study presents a promising strategy for developing multifunctional, sustainable, and high-performance scented antimicrobial leather materials.

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