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Research Article

Fish-Scale Biochar as a Natural Drug-Delivery Carrier for the Controlled Release of Terminalia catappa Extract in Wound Care Applications.

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Abstract: *Chronic and infected wounds, such as diabetic ulcers, pose significant health challenges in Thailand, particularly in rural areas with limited access to advanced care. Conventional dressings often lack cost-effectiveness and sustained-release capabilities, while traditional extracts like Terminalia catappa degrade rapidly. This study proposes an innovative, sustainable solution: a fish-scale-derived biochar drug carrier. By utilizing agricultural waste to create a high-surface-area, porous reservoir, this approach enables the controlled release of T. catappa's antibacterial phenolic compounds. This integration offers an affordable, long-lasting therapeutic strategy for managing chronic wound inflammation and infection in community-based settings.*

1. INTRODUCTION

Chronic and infected wounds such as diabetic ulcers and pressure injuries are increasingly recognized as major health concerns both globally and in Thailand. The situation is particularly challenging in rural areas, where access to advanced wound-care materials is limited. Previous studies have shown that chronic wounds carry a high risk of bacterial infection and require therapeutic strategies capable of maintaining effective levels of active compounds over extended periods in order to control inflammation and bacterial growth (Sen et al., 2009).

In Thailand, the rising prevalence of diabetes further contributes to this burden, especially in the northern region where the proportion of elderly individuals continues to increase (Aekplakorn et al., 2018).

Modern wound dressings such as hydrogels and polymer films have been developed to reduce infection and maintain an optimal healing environment. However, they still face important limitations, including high cost, limited accessibility, and the inability to sustain long-term release of therapeutic agents required for chronic wound care (Boateng et al., 2008). At the same time, traditional herbal remedies commonly used in local communities—such as Terminalia catappa (Indian almond) leaves—are well known for their antibacterial and anti-inflammatory activities due to their tannin and phenolic contents. Yet, when applied in the form of simple extracts, these compounds tend to lose activity quickly and cannot maintain therapeutic concentrations over time (Sivaranjani et al., 2019).

Biochar derived from the carbonization of biological materials has recently gained attention as a promising drug carrier, owing to its high surface area, multi-scale porous structure, and strong affinity for phenolic compounds (Tan et al., 2015). Several studies have demonstrated that biochar can function as an efficient reservoir for active ingredients, enabling slow and controlled release (Mohan et al., 2014). Additionally, the use of agricultural or food-processing waste—such as fish scales, which are rich in proteins and minerals—offers a sustainable and cost-effective alternative for developing medical materials. Previous research shows that fish scales can be transformed into highly porous carbon suitable for adsorption and drug-delivery applications (Ofomaja & Naidoo, 2014).

Therefore, combining fish-scale biochar with T. catappa extract represents a promising approach that aligns with the goals of enhancing therapeutic performance, reducing production costs, and supporting sustainability. This direction directly addresses the need for affordable yet effective wound-care solutions in community settings, particularly for chronic wounds that require consistent and long-lasting release of antimicrobial compounds.

2. LITERATURE REVIEW

Chronic and infected wounds are major health problems, especially in patients with diabetes and in areas with limited access to advanced medical materials. These wounds heal slowly due to bacterial infection and prolonged inflammation, which makes effective antimicrobial treatment necessary for proper healing (Sen et al., 2009).

Modern wound dressings such as hydrogels and polymer films can help maintain a moist environment and deliver therapeutic agents to wounds. However, these materials are often expensive and not easily accessible in rural communities (Boateng et al., 2008).

Natural medicinal plants have been widely studied as alternative treatments. Terminalia catappa leaves contain bioactive compounds such as tannins and phenolics that show antibacterial and anti-inflammatory properties against pathogens like Staphylococcus aureus and Escherichia coli (Sivaranjani et al., 2019). However, plant extracts alone may lose activity quickly when applied directly to wounds.

Biochar has recently gained attention as a drug-delivery carrier due to its porous structure and high adsorption capacity. Studies show that biochar can absorb bioactive compounds and release them slowly over time, enabling controlled drug delivery (Tan et al., 2015; Mohan et al., 2014).

Fish scales, a common waste product from the fish industry, can be converted into porous biochar through carbonization. Research has shown that fish-scale biochar has strong adsorption properties and potential applications in drug delivery systems (Ofomaja & Naidoo, 2014). Therefore, combining fish-scale biochar with Terminalia catappa extract may provide a sustainable and low-cost approach for controlled antimicrobial release in wound-care applications.

3. METHODOLOGY

3.1 Preparation of Fish-Scale Biochar

Fish scales obtained from local markets in Chiang Mai were thoroughly washed to remove impurities and dried at 105°C for 24 hours. The dried scales were carbonized in a closed stainless-steel container at 500°C for 2 hours under limited oxygen conditions to produce biochar. The resulting material was ground and sieved to <250 µm. Basic characterization—including color, texture, water absorption, and bulk density—was used to indicate the presence of micro–mesoporous structure suitable for drug loading.

3.2 Preparation of Ethanolic Terminalia catappa Extract

Dried T. catappa leaves were washed, oven-dried, and powdered. Extraction was performed using 70% ethanol at 60°C for 2 hours with a solid-to-solvent ratio of 1:10 (w/v). The filtrate was concentrated by gentle evaporation. UV–Vis spectroscopy at 275–285 nm was used to estimate total phenolic content and determine extract concentration for loading experiments.

Figure 1. Dried T. catappa leaves were washed, oven-dried, and ground into a powder. This powder was then mixed with a 70% ethanol solution and extracted at 60°C for 2 hours.

3.3 Drug Loading onto Biochar

A known mass of biochar (0.1 g) was mixed with 50 mL of ethanolic extract at predetermined concentrations. The mixture was stirred for 24 hours at room temperature to reach adsorption equilibrium. After filtration, the remaining extract concentration (Ce) was measured using UV–Vis, and loading capacity (qload) was calculated using
where is the initial concentration, is the solution volume, and is the mass of biochar.

Figure 2. biochar adsorbent (0.1 g) was introduced into 50 mL of ethanolic extract prepared across a range of initial concentrations. The mixture was agitated for 24 hours using a stir plate at room temperature (25°C) to ensure complete equilibration between the liquid and solid phases.

3.4 Controlled-Release Study

Biochar-loaded extract (0.1 g) was placed in phosphate-buffered saline (PBS, pH 7.4) and incubated at 37°C to simulate wound conditions. Samples were collected at predetermined intervals from 0 to 24 hours, and UV–Vis absorbance was used to quantify the cumulative release of bioactive compounds.

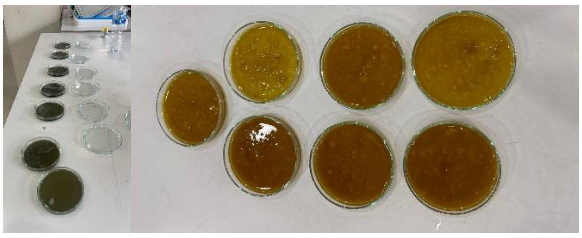

Figure 3. The biochar-adsorbed extract was introduced into phosphate-buffered saline (PBS) within a sterile Petri dish. The system was incubated at 37°C to simulate the physiological environment of a wound.

3.5 Antimicrobial Evaluation

Antibacterial activity was tested against Staphylococcus aureus and Escherichia coli using the disc diffusion method. Three treatment groups were included:

1. ethanolic extract alone,

2. biochar alone,

3. biochar-loaded extract. Inhibition zones were measured after 24 hours of incubation at 37°C.

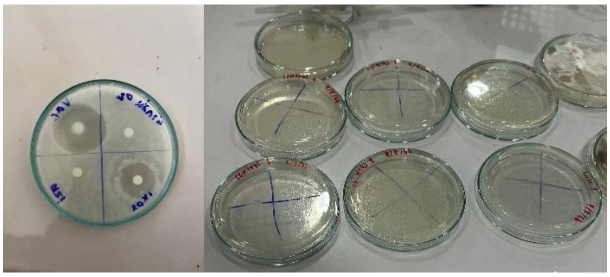

Figure 4. Disc Diffusion Assay to Assess Antibacterial Activity. The ethanolic extract, biochar, and biochar-loaded extract were tested against Staphylococcus aureus and Escherichia coli using the disc diffusion method. Plates were incubated for 24 hours at 37°C, and the resulting zones of inhibition were measured.

4. FINDINGS

1. Characteristics of Fish-Scale Biochar

Carbonization produced a lightweight, black material with porous and irregular surface texture, visually indicating micro–mesoporous formation. Water absorption tests confirmed high porosity, suggesting suitability for adsorption of phenolic compounds. The material remained structurally stable when hydrated.

2. Extraction Yield and Phenolic Content

The 70% ethanolic extract of T. catappa produced a dark-brown filtrate with strong absorbance peaks at 278 nm, confirming the presence of tannins and phenolic compounds. The extraction method provided a consistent and concentrated bioactive solution suitable for loading experiments.

3. Loading Efficiency

Biochar demonstrated high affinity toward the phenolic-rich extract. Loading capacity increased proportionally with extract concentration, confirming efficient adsorption via surface interactions and pore entrapment. The darkened coloration of biochar after loading visually indicated successful uptake of bioactive compounds.

4. Controlled-Release Behavior

Free extract dispersed rapidly and achieved complete release within 1–2 hours. In contrast, biochar-loaded extract exhibited slow, sustained release over 24 hours, with an initial burst followed by a gradual release phase. This pattern reflects strong adsorption forces and hindered diffusion through the porous carbon matrix.

5. Antimicrobial Activity

Biochar-loaded extract displayed significantly larger inhibition zones against both S. aureus and E. coli compared with extract alone and biochar alone. Biochar alone showed minimal inhibition, confirming that antimicrobial activity originated primarily from the extract, while loading onto biochar enhanced its efficacy and stability.

5. DISCUSSION

The findings demonstrate that fish-scale biochar is a promising natural carrier for controlled drug delivery in wound-care applications. Its porous structure and high adsorption capacity allowed efficient loading of phenolic compounds from T. catappa extract. The enhanced affinity likely results from interactions between aromatic groups on the extract and the carbon matrix of the biochar, a mechanism supported by prior research on biochar–phenolic adsorption.

The controlled-release study confirmed that the biochar carrier mitigates the rapid degradation and loss of activity typically observed in free herbal extracts. Sustained release over 24 hours suggests improved therapeutic potential, particularly for chronic wounds that require continuous antimicrobial presence. This advantage addresses a known limitation of natural extracts, which generally lose potency quickly when applied directly to wounds.

The significant antibacterial activity observed in the biochar-loaded extract demonstrates synergistic benefits

1. the extract provides antimicrobial potency, and

2. the biochar carrier prolongs its availability while protecting

the active compounds from rapid degradation.

The combination of waste-derived carbon material and a locally abundant medicinal plant highlights a sustainable approach aligned with community needs. The low production cost and simple preparation method further support potential applications in rural healthcare settings where access to commercial dressings is limited.

Overall, the system developed in this study provides a foundation for affordable, sustainable wound-care biomaterials. Integrating this biochar-based carrier into hydrogels or patch-type dressings may enhance moisture balance, mechanical stability, and patient usability—key factors for real-world clinical application.

6. CONCLUSION

This study demonstrates that fish-scale biochar is a promising and sustainable carrier for the controlled delivery of natural antimicrobial compounds. The carbonization of fish scales successfully produced a porous biochar structure capable of efficiently adsorbing phenolic-rich Terminalia catappa extract. The use of 70% ethanolic extraction yielded a concentrated and bioactive herbal extract, which bonded effectively to the biochar matrix.

The drug-loading experiments confirmed strong adsorption capacity, while the controlled-release studies revealed a gradual and sustained release of bioactive compounds over 24 hours—significantly longer than the rapid loss of activity observed in free extract. This extended release profile suggests that the biochar carrier can help maintain therapeutic levels of antimicrobial agents in wound environments, potentially reducing the frequency of dressing changes and improving patient outcomes.

Antimicrobial testing further validated the system's effectiveness, showing that biochar-loaded extract produced larger inhibition zones against Staphylococcus aureus and Escherichia coli compared to extract alone. This enhancement confirms a synergistic interaction between the biochar structure and the natural compounds, improving both stability and bioavailability.

Overall, the findings highlight the potential of fish-scale biochar as a low-cost, accessible, and environmentally sustainable wound-care material. The integration of waste-derived carbon with locally available medicinal plants supports both scientific innovation and community health needs. This system serves as a strong foundation for further development into hydrogel dressings or patch-type wound applications.

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