Sustainable Transformation of Goat Bone Osteo-Waste into a Multifunctional Adsorbent–Catalyst for Ibuprofen Removal and Biodiesel Production

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ABSTRACT

The valorization of biological residues into functional materials has emerged as a viable route toward sustainable environmental protection and resource conservation. In the present work, goat bone osteo-waste generated by the meat processing sector was converted into a dual-purpose material capable of acting as an adsorbent for pharmaceutical contaminants and as a heterogeneous catalyst for biodiesel production. Chemically activated goat bone powder exhibited strong affinity toward ibuprofen in aqueous solutions, achieving a maximum removal efficiency of 78.42% under optimized experimental conditions. In parallel, hydroxyapatite produced through thermal treatment of goat bone waste demonstrated excellent catalytic performance during the two-step transesterification of waste cooking oil, yielding a biodiesel conversion efficiency of 95.05%. The quality of the synthesized biodiesel was confirmed using UV–visible spectroscopy, flame combustion assessment, and boiling point determination. The combined application of goat bone waste in pharmaceutical wastewater remediation and renewable fuel generation represents an economical and environmentally responsible strategy aligned with circular economy principles. These findings highlight the potential of meat industry byproducts as sustainable, low-cost resources for environmental remediation and energy-related applications.

Keywords: Goat bone waste, Pharmaceutical adsorption, Ibuprofen removal, Heterogeneous catalyst, Biodiesel synthesis, Circular economy

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1. Introduction

The expansion of the global meat processing industry has resulted in the accumulation of large quantities of bone-derived waste, which presents serious environmental challenges due to its limited biodegradability. Although commonly treated as low-value refuse, animal bones are inherently rich in inorganic minerals such as calcium phosphate, making them suitable precursors for the development of advanced functional materials. Efficient reuse of osteo-waste offers a dual benefit by mitigating disposal-related issues while enabling the production of value-added materials for environmental and energy applications.[1,2] In recent years, increasing attention has been directed toward the contamination of aquatic systems by pharmaceutical compounds. Non-steroidal anti-inflammatory drugs, particularly ibuprofen, are frequently detected in surface water and wastewater streams as a consequence of widespread consumption and incomplete removal during conventional treatment processes. The continuous presence of these residues raises concerns regarding ecological imbalance and potential human health risks.[3,4] Among various remediation techniques, adsorption has proven to be an effective and economical approach, especially when low-cost and sustainable adsorbents are utilized. At the same time, diminishing fossil fuel reserves and escalating global energy demands have intensified interest in biodiesel as a renewable and environmentally benign alternative fuel. Waste cooking oil has gained prominence as an inexpensive and readily available feedstock; however, its elevated free fatty acid content often necessitates the use of efficient catalytic systems to achieve high conversion yields. In this context, heterogeneous solid catalysts derived from waste materials have attracted significant interest due to their reusability, ease of separation, and reduced environmental footprint.[5,6]Against this background, the present study adopts a waste-to-resource strategy by transforming goat bone osteo-waste into two functional materials: (i) a chemically activated adsorbent for ibuprofen removal from aqueous media and (ii) a thermally treated solid base catalyst for biodiesel production from waste cooking oil. Adsorption efficiency was assessed through systematic parameter optimization and kinetic analysis, while catalytic performance was evaluated based on biodiesel yield and physicochemical characterization. By integrating pharmaceutical wastewater treatment with renewable fuel generation, this work presents a sustainable and scalable pathway for animal bone waste valorization within a circular economy framework.[7,8]

2. Materials and Methods

2.1 Materials

Goat bone waste was sourced from local meat-processing facilities in Goa, India. Analytical-grade ibuprofen was obtained from an authorized pharmaceutical supplier. Waste cooking oil was collected from nearby food establishments. Methanol, sulfuric acid, potassium hydroxide, sodium hydroxide, hydrochloric acid, and other reagents used were of analytical grade and applied without further purification. Distilled water was used throughout all experimental procedures.[9,10]

2.2 Pre-treatment of Goat Bone Waste

Collected goat bones were thoroughly rinsed with tap water followed by distilled water to remove surface impurities and adhering organic matter. The cleaned bones were air-dried and subsequently oven-dried at 105 °C to eliminate residual moisture. The dried material was mechanically crushed and ground into a fine powder, sieved to obtain uniform particle size, and stored in airtight containers.[11,12]

2.3 Chemical Activation of Goat Bone Powder

Surface modification of the goat bone powder was achieved through alkaline activation using sodium hydroxide solution under controlled conditions with continuous stirring. The treated material was repeatedly washed with distilled water until neutral pH was attained, followed by oven drying for subsequent adsorption studies.[13]

2.4 Thermal Treatment for Catalyst Preparation

For catalyst synthesis, goat bone powder was calcined in a muffle furnace at elevated temperatures for a predetermined duration to induce the formation of hydroxyapatite-rich phases. The calcined material was cooled inside the furnace, gently ground, and stored in desiccators to prevent moisture absorption.[14]

2.5 Characterization

Functional group identification and confirmation of surface modification were performed using Fourier Transform Infrared (FTIR) spectroscopy.[15]

2.6 Preparation of Ibuprofen Solutions

A standard ibuprofen stock solution was prepared in distilled water, and required concentrations were obtained through appropriate dilution prior to adsorption experiments.[16]

2.7 Adsorption Experiments and Kinetic Analysis

Batch adsorption experiments were conducted using fixed adsorbent dosages under controlled agitation. The effects of contact time, adsorbent dosage, initial ibuprofen concentration, pH, and temperature were systematically evaluated. Residual ibuprofen concentration was quantified using UV–Visible spectrophotometry at 222 nm. Kinetic data were analyzed using pseudo-first-order and pseudo-second-order models.[17,18]

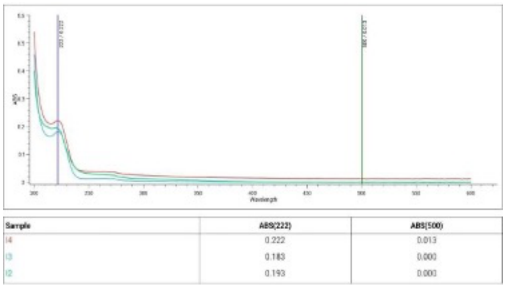
2.8 Biodiesel Production and Characterization

Waste cooking oil was filtered, dehydrated, and analyzed for acid value and free fatty acid content. A two-step transesterification process—acid-catalyzed esterification followed by base-catalyzed transesterification—was employed. The resulting biodiesel was purified and characterized using UV–Visible spectroscopy, flame combustion analysis, and boiling point determination.[19,20]

3. Results and Discussion

3.1 Characterization of Goat Bone-Derived Materials

FTIR analysis of the chemically activated goat bone adsorbent revealed the presence of characteristic functional groups responsible for adsorption activity. Prominent absorption bands corresponding to phosphate (PO_4^{3-}) groups confirmed the mineral composition of the bone matrix, while hydroxyl group vibrations indicated surface hydrophilicity, which plays a crucial role in pharmaceutical adsorption. Minor shifts in peak positions after activation suggested successful surface modification.



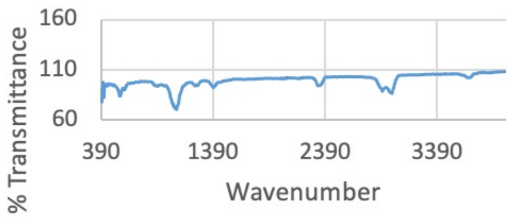


Fig 1 IR spectra of activated powdered osteo waste

3.2 UV–Visible Spectroscopy

The standard ibuprofen solution exhibited a maximum absorbance value of 0.496 at 222 nm, which corresponds to the reported λ_max of ibuprofen. The presence of a distinct and sharp absorption peak at this wavelength confirms the chemical purity of the prepared standard solution. These results also validate the selection of 222 nm as an appropriate wavelength for the quantitative determination of ibuprofen in subsequent adsorption studies.

Standard	Absorbance
Ibuprofen	0.496

Table 1: Standard Absorbance of Ibuprofen at 222 nm

3.3 Optimization of Adsorption Parameters for Ibuprofen Removal

3.3.1 Percentage Removal of Ibuprofen

The adsorption efficiency of ibuprofen using the prepared adsorbent was expressed in terms of percentage removal, calculated using the following equation:

$$\% \text{ Removal of Ibuprofen} = \frac{\text{Absorbance of standard} - \text{Absorbance of sample}}{\text{Absorbance of standard}} \times 100$$

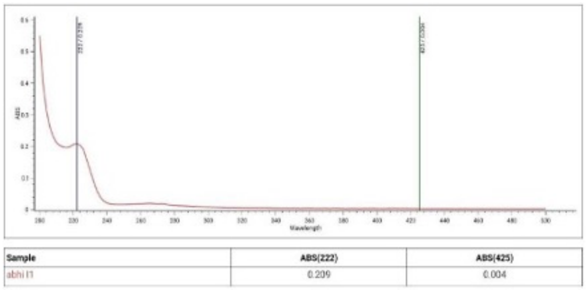


Fig. 2: **Absorbance profile of contaminated ibuprofen solution after treatment with prepared adsorbent**

Sample Name	Percentage Removal of Ibuprofen
I1	57.86%

Table 2: Percentage Removal of Ibuprofen to Assess Adsorptive Performance

3.4 Effect of pH on Ibuprofen Adsorption

The role of solution pH in governing ibuprofen adsorption was examined by performing experiments at pH 2.0, 3.0, 5.0, and 10.0 in order to determine the most suitable conditions for effective drug removal.

Fig. 3: Effect of pH (2.0, 3.0, 5.0) on ibuprofen

Fig. 4: Effect of pH (10.0) on ibuprofen adsorption adsorption

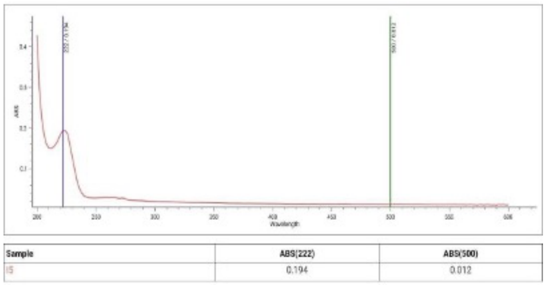


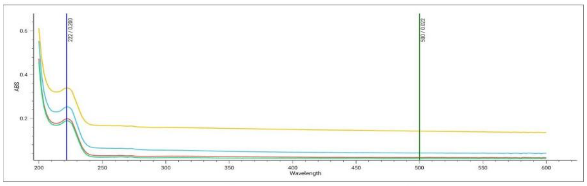
Table 3: Percentage Removal of Ibuprofen at Different pH Values

Sample Name	pH	Percentage Removal
I2	2.0	63.10%
I3	3.0	61.08%
I4	5.0	55.24%
I5	10.0	36.08%

The adsorption results demonstrated a strong dependence on pH, with the highest ibuprofen removal (63.10%) observed under acidic conditions at pH 2.0. As the pH increased toward neutral and alkaline values, a progressive decline in adsorption efficiency was recorded. This behavior is attributed to enhanced ionization of ibuprofen molecules and electrostatic repulsion between negatively charged drug species and the adsorbent surface at higher pH levels. Consequently, pH 2.0 was selected as the optimum pH and maintained for all subsequent experiments.

3.5 Effect of Adsorbent Dosage

The effect of adsorbent quantity on the removal of ibuprofen was investigated by varying the adsorbent mass from 0.05 g to 0.20 g.



Sample	ABS(222)	ABS(500)
I7	0.200	0.022
I8	0.254	0.042
I9	0.190	0.017
I10	0.340	0.143

Fig. 5: Effect of adsorbent dosage on ibuprofen removal

Sample Name	Adsorbent Dosage (g)	Percentage Removal
I10	0.05	31.45%
I8	0.10	48.79%
I7	0.15	59.67%
I9	0.20	61.69%

Table 4: Percentage Removal of Ibuprofen at Different Adsorbent Dosages

A progressive increase in ibuprofen removal was noted as the adsorbent quantity increased, primarily due to the presence of a higher number of accessible adsorption sites. The highest removal efficiency was recorded at an adsorbent dose of 0.20 g, which was therefore fixed as the optimum amount for all subsequent experimental studies.

3.6 Effect of Initial Ibuprofen Concentration

The role of the initial ibuprofen concentration in influencing adsorption efficiency was examined using solutions containing 2.5 mg/L, 3.5 mg/L, and 5 mg/L of the drug.

Sample Name	Initial Concentration	Percentage Removal
I16	2.5 mg/L	61.69%
I15	3.5 mg/L	62.09%
I14	5 mg/L	66.93%

Table 5: Percentage Removal at Different Initial Concentrations

Comparable adsorption efficiencies were observed across the tested concentration range, with the highest percentage removal occurring at 5 mg/L. Consequently, 5 mg/L was chosen as the standard initial ibuprofen concentration and used consistently in all further adsorption experiments.

3.7 Effect of Temperature

The influence of temperature on the adsorption behavior of ibuprofen was evaluated by conducting experiments at 30 °C, 40 °C, 50 °C, and 60 °C.

Sample Name	Temperature	Percentage Removal
I8	30 °C	58.46%
I9	40 °C	57.25%
I7	50 °C	47.98%
I10	60 °C	41.73%

Table 6: Percentage Removal of Ibuprofen at Different Temperatures

The results indicate that increasing temperature led to a decrease in adsorption efficiency, suggesting an exothermic adsorption process. Elevated temperatures weaken adsorbate–adsorbent interactions, resulting in reduced drug uptake. Optimal adsorption was observed at 30 °C, which was therefore selected for all further experiments.

3.8 Effect of Contact Time

The effect of exposure duration on ibuprofen adsorption was examined by varying the contact period between 1 and 5 hours.

Sample Name	Time	Percentage Removal
I23	1 hour	42.13%
I24	2 hours	42.94%
I25	3 hours	43.54%
I22	4 hours	44.15%
I21	5 hours	48.18%

Table 7: Percentage Removal of Ibuprofen at Different Contact Times

A gradual increase in ibuprofen removal was observed with increasing contact time, indicating enhanced adsorption due to prolonged interaction between the adsorbent and drug molecules. Maximum removal occurred at **5 hours**, which was selected as the optimum contact time.

3.9 Combined Optimization of Adsorption Parameters

Parameter	Optimized Value
pH	2.0
Adsorbent dosage	0.20 g
Initial concentration	5 mg
Time	5 hours
Temperature	30 °C

Table 8: Optimized Parameters for Application Study

Sample Name	Percentage Removal
I26	78.42%

Table 9: Percentage Removal under Optimized Conditions

The highest ibuprofen removal efficiency was achieved when all optimized parameters were applied simultaneously, confirming the synergistic contribution of each variable to adsorption performance.

3.10 Application to Ibuprofen-Contaminated Wastewater

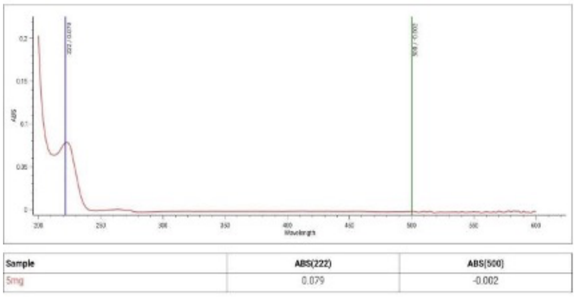


Fig. 6: Ibuprofen removal from contaminated wastewater

Sample	Percentage Removal
Ibuprofen (5 mg)	84.07%

Table 10: Percentage Removal in Wastewater

The results demonstrate effective ibuprofen removal in real wastewater samples, confirming the practical applicability of the adsorbent under optimized conditions.

3.11 COD Analysis

COD analysis revealed a reduction from 20 mg/L (before treatment) to 16 mg/L (after treatment), confirming a significant decrease in organic pollutant load following adsorption.

Sample	Initial Reading (mL)	Final Reading (mL)	Volume Used (mg/L)	COD (mg/L)
Blank	0 mL	1.4	1.4	20 mg
Polluted Water	0 mL	0.9	0.9	

Table 11: COD of collected sample before treating it with catalyst in adsorption process

Sample	Initial Reading (mL)	Final Reading (mL)	Volume Used (mg/L)	COD (mg/L)
Blank	0 mL	1.4	1.4	16 mg
Polluted Water	0 mL	1.0	1.0	

Table 12: COD of collected sample after treating it with catalyst in adsorption process

3.12 Reaction Order

The graph of $1/(C_0 - C_e)$ plotted against time produced a straight-line trend, confirming that the adsorption mechanism is governed by second-order kinetic behavior.

Co	Ce	Co-Ce	1/(Co-Ce)	Time (mins)
0.496	0.277	0.219	4.56	120
0.496	0.280	0.216	4.62	180
0.496	0.283	0.213	4.69	240
0.496	0.287	0.209	4.78	300

Table 13: Calculations for 1/(Co-Ce) vs time

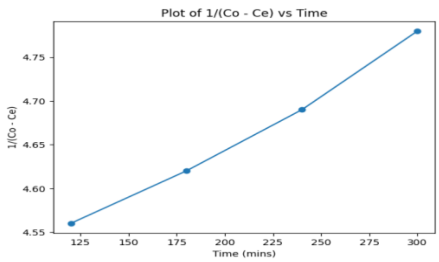


Fig 7: Graph of 1/(Co-Ce) vs time

3.13 IR Characterization of Goat Bone Catalyst

FTIR spectra confirmed the presence of characteristic PO_4^{3-} and OH^- functional groups, verifying hydroxyapatite formation. These functional groups act as active basic sites, facilitating methanol activation and promoting transesterification reactions.

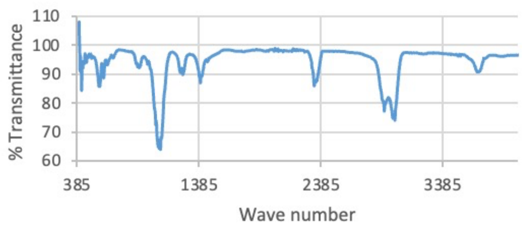


Fig 8: IR spectra of osteo waste catalyst for adsorption

3.14 Acid Value and Free Fatty Acid Content

Parameter	Value
Acid Value	7.47
Free Fatty Acid (%)	8.53

Table 14: Acid and Free Fatty Acid Values

The elevated FFA content necessitated pre-treatment prior to biodiesel synthesis.

3.15 UV–Visible Analysis of Biodiesel

Lower absorbance observed in purified biodiesel confirmed effective removal of impurities during washing.

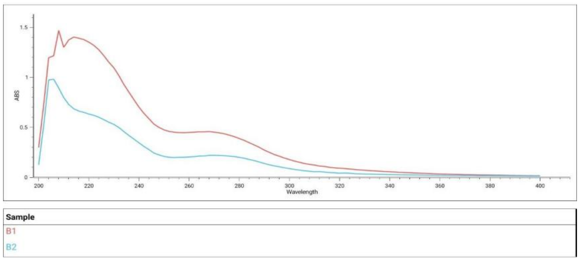


Fig 9: Absorbance of unpurified biodiesel and purified biodiesel

3.16 Biodiesel Conversion Efficiency

Acid Value (Raw)	Acid Value (Product)	Conversion (%)
7.47	0.37	95.05

Table 15: Percentage of converted biodiesel

3.17 Flame Test

The synthesized biodiesel exhibited a clean blue flame, confirming efficient combustion and improved fuel quality.

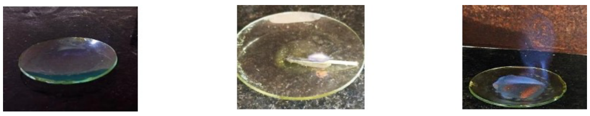


Fig 10: Comparative flame test of methanol, WCO and produced biodiesel

3.18 Boiling Point

The boiling point of the produced biodiesel was determined to be 222 °C, consistent with feedstock-dependent variability.

Conclusion

The outcomes of this study confirm the successful transformation of goat bone osteo-waste into multifunctional materials, presenting a sustainable waste-to-resource solution for both pharmaceutical wastewater remediation and biodiesel production. The chemically activated goat bone powder exhibited notable adsorption efficiency for ibuprofen, achieving a maximum removal of 78.42% under optimized laboratory conditions and 84.07% in real wastewater samples, thereby demonstrating its practical effectiveness. The adsorption process followed second-order kinetic behavior, and the observed decrease in chemical oxygen demand (COD) further validated the material's capability to lower organic pollutant levels, highlighting its suitability for wastewater treatment applications. n addition, thermally processed goat bone–derived hydroxyapatite demonstrated strong catalytic activity as a solid base in the two-stage transesterification of waste cooking oil, achieving a biodiesel conversion efficiency of 95.05%. The successful formation and quality of the synthesized biodiesel were confirmed through spectroscopic characterization, flame combustion assessment, and thermophysical analysis. The catalyst also demonstrated the ability to reduce free fatty acid content while promoting stable and cleaner combustion behavior, indicating strong catalytic performance. Overall, the integrated utilization of goat bone osteo-waste offers a single, cost-effective, and scalable approach that simultaneously addresses solid waste valorization, pharmaceutical pollutant removal, and renewable energy generation. These findings establish goat bone osteo-waste as a promising low-cost precursor for advanced environmental remediation and energy conversion technologies, reinforcing its importance within circular economy and sustainable development frameworks.

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