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Scientific paper

Camel Bones as a Source of Fat: Optimization of Extraction Methods and Fatty Acid Composition Analysis

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Abstract

This study explores the viability of using camel bones, an abundant by-product in North Africa and the Middle East, as a novel source of fat for biodiesel production. A moist-heat extraction process using a pressure cooker was employed to extract fat from both hollow and flat bones. The initial phase of the study optimized temperature (40–100 °C) and duration (0.5–5 hours) using ordinary water, confirming that fat yield increased with both parameters. A subsequent phase significantly enhanced extraction efficiency by introducing two key optimizations: grinding the bones to increase surface area and using distilled water to eliminate ionic interference. This approach achieved a peak yield of 26.69% (by bone mass) for hollow bones at 100 °C after 6 hours. Compositional analysis indicated a predominance of saturated fatty acids. The findings confirm that camel bones are a promising fat source for industrial applications, such as biodiesel production via transesterification, with an optimal extraction window of 3 to 5 hours identified for an efficient process.

Keywords: Camel bones; hollow bones; flat bones; saturated fatty acids; yield optimization; distilled water

1. Introduction

Fat is a fundamental dietary component that plays a vital role in maintaining overall health. Among diverse fat sources, lipids rendered from animal bones are of particular interest due to their unique composition and applications.[1–3]

In this context, "bone fat" refers to the lipid fraction (primarily triglycerides and associated fatty acids) extractable from bone tissue for nutritional and industrial use.[4,5] These compounds contribute significantly to cardiovascular health by modulating cholesterol levels, reducing low-density lipoproteins while promoting high-density lipoproteins.[8,9]

Furthermore, bone fat is a valuable source of fat-soluble vitamins and nutrients. It contains vitamin K2, which is crucial for bone metabolism and vascular health through its role in regulating blood clotting.[10–12] The extract also provides vitamins A and D, supporting immune function, growth, and development, in addition to being a concentrated energy source.[13,14]

The applications of bone-derived fat extend beyond nutrition into various industries. It is utilized in food production, such as in sauces, chocolates, and baked goods.[15,16] In cosmetics, its nourishing composition makes it beneficial for moisturizing and protecting the skin from environmental damage.[17,18] From a sustainability perspective, extracting fat from bone (a common waste product of meat processing) helps reduce environmental waste and promotes the full utilization of animal resources, thereby supporting more sustainable food systems.[19,20]

Camels represent a promising and regionally relevant source for such extraction, particularly in North Africa and the Middle East, where they are integral to cultural and culinary heritage.[21,22] The widespread consumption of camel meat generates significant bone waste, which presents an opportunity for valorization through fat extraction in accordance with health guidelines.[23,24] Therefore, this study investigates the efficiency of fat extraction from both hollow and flat camel bones by optimizing key parameters such as temperature and time. The composition of the extracted fat was subsequently analyzed using gas chromatography-mass spectrometry (GC-MS).

2. Materials and Methods

2. 1. Sample Preparation

Camel bones (flat and hollow) were obtained from a butcher shop in Ouargla, Algeria. The bones were prepared in two forms: one portion was cut into small pieces (2–4 cm), and another portion was minced. All samples were stored at –15 °C until further use.

2. 2. Fat Extraction

Fat was extracted from both flat and hollow bones using a moist-heat method in a pressure cooker. For each extraction, 1 kg of bones was combined with water in a 3:1 (bone-to-water) ratio. The sealed pressure cooker was immersed in a water bath to maintain precise temperature control (40–100 °C) and prevent direct high-heat exposure to the extracted fat.

Extraction occurred under autogenous pressure generated inside the sealed cooker.[25] Temperature was used as the primary control parameter due to its defined relationship with the internal pressure under saturated steam conditions.[26]

The study was conducted in two phases:

- First Phase: Extraction was performed using ordinary water at six temperatures (40, 50, 70, 80, 90, and 100 °C) over five time intervals (0.5, 1, 3, 4, and 5 hours).
- Second Phase: Based on initial results, 100 °C was selected as the optimal temperature, and the process was further enhanced by evaluating two additional variables: bone preparation (pieces vs. minced) and water type (ordinary vs. distilled).

Three extraction methods were compared for both bone types: Method 1: Bone pieces in ordinary water, Method 2: Minced bones in ordinary water, and Method 3: Minced bones in distilled water.

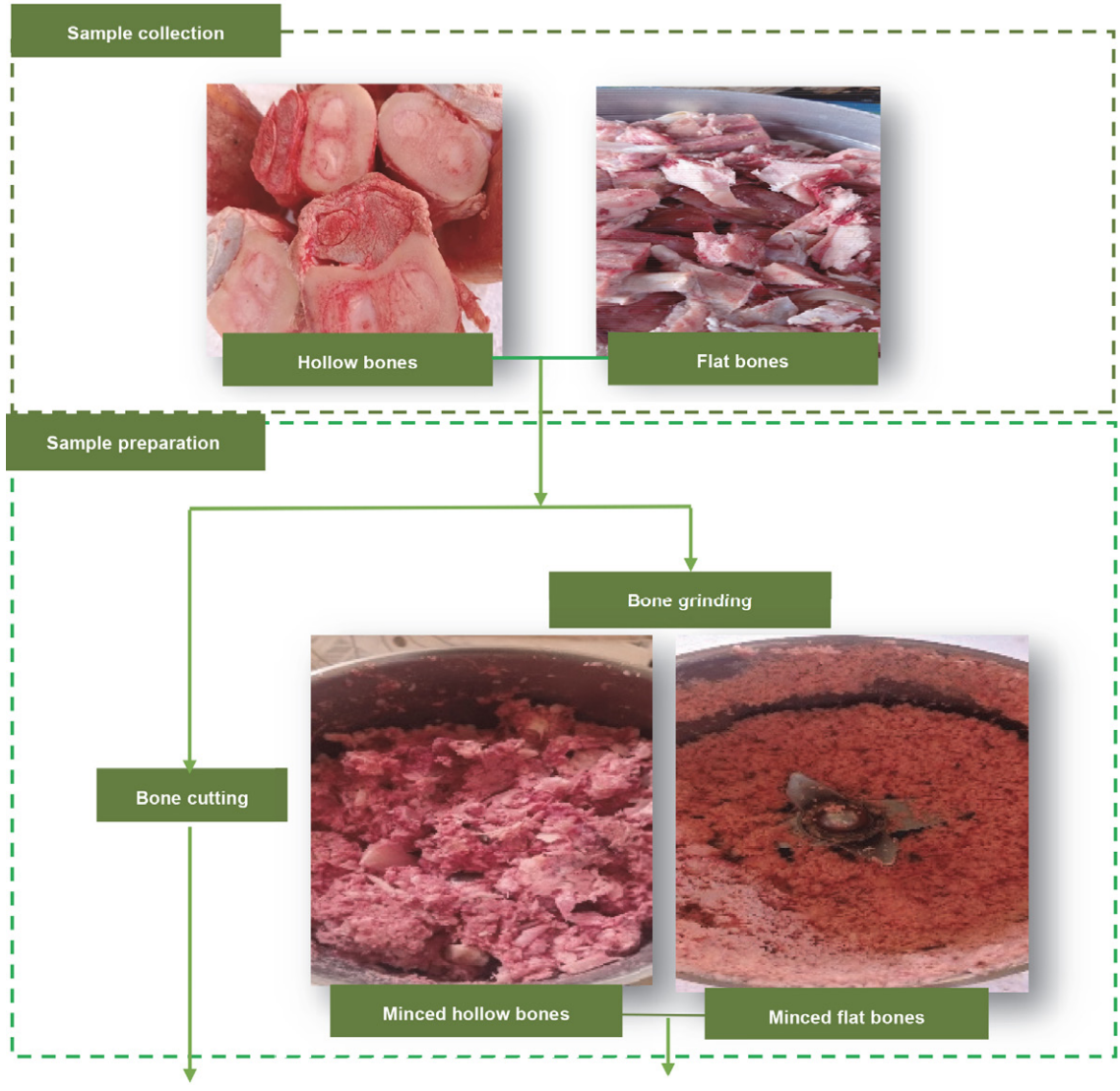

Figure 1. A. Schematic of fat extraction from camel bones

The use of distilled water in Method 3 aimed to eliminate interference from dissolved ions (e.g., Ca^{2+}, Mg^{2+}), which can form insoluble complexes with free fatty acids and reduce yield.[27,28] All extractions were conducted across 11 time intervals (0.25 to 10 hours) to evaluate time-dependent effects.

The mixture was stirred every 15 minutes during extraction. After filtration through a cloth filter funnel, the filtrate was cooled in a water bath (15–35 °C) and then refrigerated to solidify the fat. The solidified fat was separated, reheated, and filtered again to remove impurities. Finally, the fat was treated with anhydrous sodium sulfate (Na_2SO_4) to remove residual moisture and stored at –10 °C until analysis.

The overall experimental workflow is illustrated in Figure 1.A and 1.B.

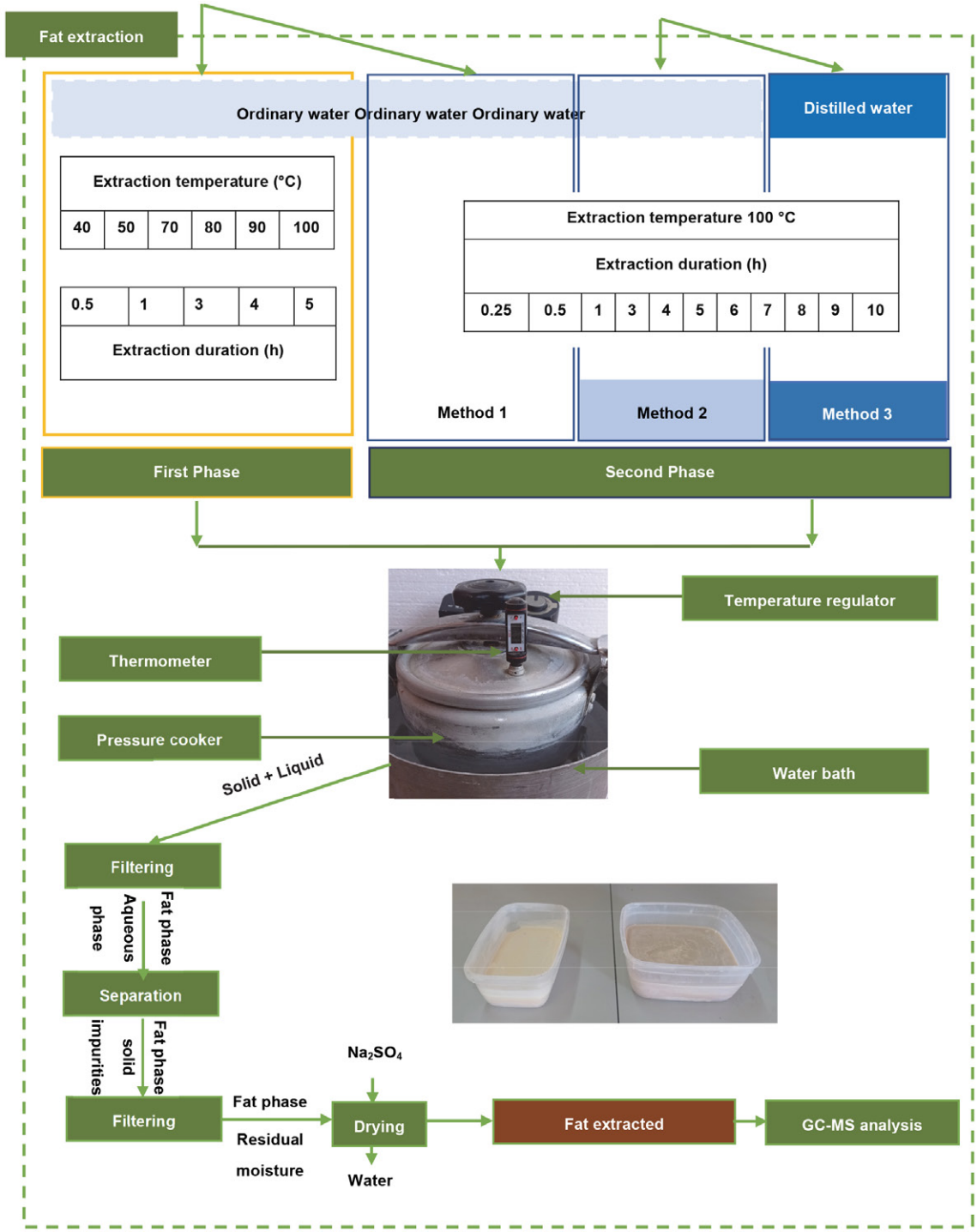

Figure 1. B. Schematic of fat extraction from camel bones

2. 3. GC-MS Analysis of Fatty Acids

Total fatty acids were measured as fatty acid methyl esters (FAMEs). Lipid extracts from bone (50 mg) were saponified with 2.0 mL methanolic KOH (0.5 M) at 50 °C for 10 min, then transesterified with 2.0 mL BF_3–methanol (14% w/w) at 70 °C for 30 min. After cooling, FAMEs were extracted with n-hexane (2 mL), washed with saturated NaCl (2 mL), dried over anhydrous Na_2SO_4, filtered, and transferred to GC vials.[29,30]

GC–MS analyses were performed on a Shimadzu GCMS-TQ8040 NX system fitted with an Rxi-5Sil MS capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). Injections (1.0 µL) were made in split mode (split ratio 200:1) at an injector temperature of 220 °C, using helium as the carrier gas with a programmed column flow (initial flow 2.20 mL min^{-1}), and the total run time was approximately 43.5 min. The mass spectrometer operated in electron impact (EI) mode with an ion source temperature of 200 °C and an interface temperature of 250 °C. Solvent cut time was set at 2.0 min, and data were acquired in full-scan mode (Q3-scan) over a mass range of m/z 35–400. Identification of FAMEs was based on comparison of mass spectra and relative retention times with those of reference standards in the NIST17 library.

The relative percentage of each fatty acid was determined by calculating the ratio of its peak area to the total peak area of all fatty acids identified in the sample.

3. Results and Discussion

3. 1. Hollow Bones

3. 1. 1. Extraction in Ordinary Water

Table 1 presents the yield of fat extracted from hollow camel bones in ordinary water, expressed as a percentage of bone mass, across different temperature and extraction durations.

Table 1: Fat extraction yield from hollow camel bones in ordinary water (% of bone mass) *

Extraction duration (h)	Extraction temperature (°C) 40	50	70	80	90	100
0.5	0.00	0.34	0.51	2.54	4.98	10.68
1	0.24	0.59	2.28	3.56	6.52	11.64
3	0.78	2.42	6.12	7.62	10.87	16.01
4	1.40	2.98	7.31	10.41	14.13	17.65
5	1.57	3.67	9.84	12.98	15.58	19.28

* Yields represent the percentage of fat extracted relative to the initial bone mass (1 kg). Values calculated as (g of fat/1000 g bone) × 100.

The data in Table 1 and Figure 2 illustrate the combined influence of extraction temperature and duration on fat yield. Several key trends emerge from the analysis:

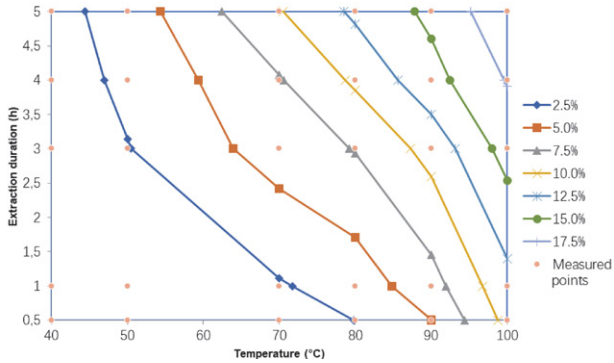

Figure 2. Fat yield (% of bone mass) variation with extraction duration & temperature (Hollow bone pieces in ordinary water)

- Temperature Dependence: Yield exhibited a strong positive correlation with temperature. At 40 °C, the yield was negligible due to the temperature being below the melting point of camel fat. Yield increased progressively with temperature, reaching a maximum of 19.28% at 100 °C for 5 hours. This enhancement is attributed to reduced fat viscosity and increased molecular diffusion rates at elevated temperatures.
- Temporal Kinetics: The extraction process displayed distinct time-dependent kinetics, marked by an initial rapid phase (0.5–3 hours) followed by a slower asymptotic approach to maximum yield. For instance, at 100 °C, approximately 83% of the total extractable fat was recovered within the first 3 hours, with diminishing returns observed thereafter.
- Synergistic Effect: A synergistic interaction between temperature and duration was evident. Increasing the temperature from 80 °C to 100 °C at 5 hours improved the yield by 48.53%, while extending the time from 3 to 5 hours at 100 °C resulted in a 20.42% yield increase. Furthermore, a yield of 10.68% (achieved in 0.5 hours at 100 °C) required 3 h at 90 °C, 4 h at 80 °C, or more than 5 h at 70 °C.

These findings establish a foundational understanding of the extraction dynamics, which informed subsequent optimization steps involving particle size reduction and solvent modification.

A comparative analysis of maximum fat yield from the hollow bones of camels, cows, and sheep[31] was conducted under identical extraction conditions (3–5 hours duration). The results, illustrated in Figure 3, indicate that camel bones demonstrated an intermediate yield, notably higher than sheep bones but lower than cow bones.

This positions camel bones as a sustainable alternative fat source, especially in regions where camel husbandry is prevalent. This valorization of bone by-products supports a circular bioeconomy and provides a valuable raw material for industrial applications.

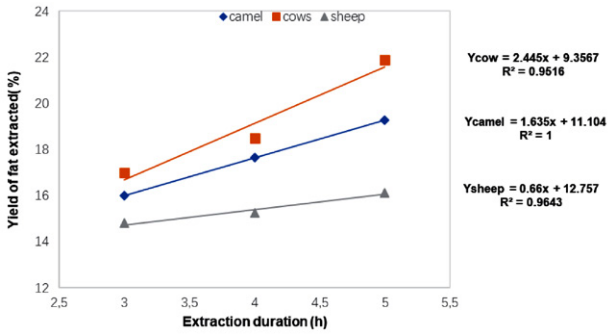

Figure 3. Comparison of maximum fat yield (% of bone mass) from hollow bones of cows, sheep (based on[31]) and camels (present study).

3. 1. 2. Regression Analysis of Fat Extraction from Hollow Bones (Ordinary Water)

3. 1. 2. 1. Simple Regression

The goal of simple regression here is to find the mathematical equations that relate the yield of extracted fat to time *Y* (t) at each temperature, as shown in Figure 4 below.

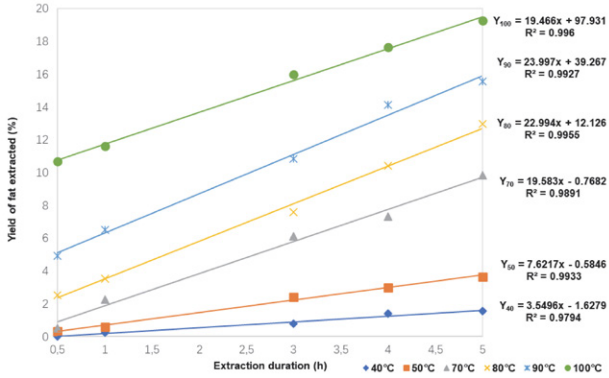

Figure 4. Yield of fat extracted from hollow bones as a function of time with ordinary water (%)

Simple regression analysis produced robust, statistically significant linear models for all tested temperatures, with coefficients of adjustment (R^2) consistently exceeding 0.98. This excellent fit indicates that the linear equations account for over 98% of the variability in fat yield, confirming that extraction yield can be accurately predicted as a linear function of time within the experimental ranges. The mathematical simplicity of these models offers a significant practical advantage, enabling straightforward forecasting and optimization of extraction duration for industrial applications without complex computations.

3. 1. 2. 2. Advanced Regression

The objective of advanced regression analysis was to develop a comprehensive model representing the relationship between fat yield and both independent variables: extraction temperature (T) and time (t). This multivariate analysis was performed using XLSTAT software.

The best-fitting nonlinear regression model is represented by Eq. (1):

$$Y(T,t) = -122.651 + 4.427\,T + 2.944\,t - 0.055\,T^2 - 0.321\,t^2 + 0.00024\,T^3 + 0.034\,t^3 \quad (1)$$

Where:
Y: Fat yield (% of bone mass).
T : Extraction temperature °C.
t : Extraction duration h.

This model achieved an exceptionally high coefficient of adjustment ($R^2 = 0.995$).

Table 2 presents the relative errors between the experimental results and model predictions.

Table 2. Relative error distribution between experimental and predicted yields for hollow bones in ordinary water (nonlinear regression)

Extraction duration (h)	Extraction temperature (°C) 70	80	90	100
0.5	32.82	1.17	9.59	3.41
1	29.62	7.88	2.34	0.51
3	5.10	5.52	0.08	1.44
4	6.07	4.04	9.24	0.47
5	0.35	6.73	4.08	2.95

Relative error > 15 % Relative error 10–15% Relative error < 10 %

The advanced multivariate nonlinear model (Eq. 1) exhibits exceptional predictive power, accounting for 99.5% of the variance in the experimental data (R^2 = 0.995). It performs with high reliability across most conditions, especially at elevated temperatures (80–100 °C) and extended durations (3–5 hours), where relative errors remain below 10%. However, model accuracy declines significantly under extreme conditions (specifically at low temperature (70 °C) combined with short extraction times (0.5–1 hour)) where relative errors approach 30%. This clear definition of the model's operational bounds strengthens the credibility of the study and offers practical utility for process optimization, while cautioning against its use near process initiation at lower temperatures.

3. 1. 3. Extraction in Distilled Water

Table 3 presents the fat yields obtained from hollow camel bones under three different extraction conditions at

100 °C: Method 1 (bone pieces in ordinary water), Method 2 (minced bones in ordinary water), and Method 3 (minced bones in distilled water). The extraction was conducted across 11 time intervals ranging from 0.25 to 10 hours.

Table 3. Yield of fat extracted from hollow camel bones at 100 °C (% of bone mass)

Extraction duration (h)	Method 1 Ordinary water Bone pieces	Method 2 Minced bones	Method 3 Distilled water
0.25	8.59	15.59	16.98
0.5	10.68	18.34	21.32
1	11.64	19.79	23.13
3	16.01	21.40	24.94
4	17.65	22.15	25.71
5	19.28	22.64	26.49
6	20.55	23.23	26.69
7	20.97	23.66	26.69
8	21.36	23.66	26.69
9	21.60	23.66	26.69
10	21.89	23.66	26.69

The data demonstrate the critical importance of both particle size reduction and solvent purity for optimizing extraction efficiency. Method 3 (minced bones in distilled water) achieved the maximum yield of 26.69% within 6 hours, representing a substantial improvement of 21.93% over Method 1 and 12.81% over Method 2.

Key mechanistic insights explain these enhancements:

- Particle size effect (Method 1 vs. Method 2): The dramatic yield improvement (up to 81.49% at 0.25 h) results from the increased surface area created by mincing. This enhances solvent penetration, reduces diffusion path length, and disrupts the bone matrix to release encapsulated fat.
- Solvent purity effect (Method 2 vs. Method 3): The consistent superiority of distilled water, providing an additional 8.9% yield enhancement at 0.25 h, is attributed to the elimination of dissolved ions (Ca^{2+}, Mg^{2+}) found in ordinary water. These ions form insoluble metal soaps with free fatty acids, sequestering a portion of the extractable fat.
- Kinetic and economic advantages: Method 3 demonstrates superior kinetics, reaching 95% of its maximum yield within 6 hours compared to more than 10 hours for Method 1. This rapid saturation, combined with higher ultimate yield, significantly improves process economics by reducing both energy consumption and processing time.

The synergistic optimization of both physical access (through particle size reduction) and chemical environment (through solvent purification) proves essential for maximizing extraction efficiency, reducing processing time, and enhancing overall process economics.

3. 1. 4. Regression Analysis of Fat Extraction from Hollow Bones at 100 °C

3. 1. 4. 1. Simple Regression

This analysis aimed to establish mathematical relationships describing fat yield (Y) as a function of extraction time (t) for each extraction method. The resulting models are presented in Figure 5.

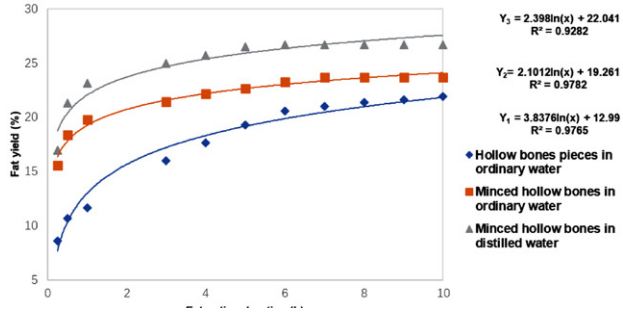

Figure 5. Yield of fat extracted for each method at 100 °C (% of bone mass) for hollow bones

It is worth noting that the second method requires about 6 h to achieve maximum fat extraction, while the third method can reach the same yield in only 1 h. This result highlights the significance of the third method in terms of time and energy savings.

3. 1. 4. 2. Advanced Regression

The objective of the advanced regression analysis was to model the relationship between fat yield and two categorical variables: bone state (pieces or minced) and water type (ordinary or distilled), in addition to extraction time.

The best result of nonlinear regression was according to Eq. (2):

$$Y(t,p,w) = 16.188 + 3.901\,t - 4.290\,p - 2.913\,w - 0.485\,t^2 + 0.021\,t^3 \quad (2)$$

Where:
Y: Fat yield (% of bone mass).
t: Extraction duration h.
p = 1 if Bone pieces, 0 if Minced bones.
w = 1 if Ordinary water, 0 if Distilled water.
With R^2 = 0.963.

Based on the experimental and predicted yield results, the relative errors are shown in Table 4.

The error analysis (Table 4) shows that only 5 of the 33 data points (15.2%) exhibited relative errors exceeding

Table 4. Relative error distribution between experimental and predicted yields for hollow bones at 100 °C (nonlinear regression)

Extraction duration (h)	Method 1 Ordinary water Bone pieces	Method 2 Minced bones	Method 3 Distilled water
0.25	15.57	8.80	0.92
0.5	1.30	17.65	15.48
1	6.77	15.56	15.15
3	5.47	1.04	3.41
4	2.90	1.34	1.37
5	1.68	2.69	1.25
6	5.58	1.97	0.33
7	6.42	1.07	0.50
8	7.56	1.58	0.95
9	7.93	2.17	1.48
10	7.85	3.38	2.55

Relative error > 15 % Relative error 10–15% Relative error < 10 %

15%, while the majority of results (72.7%) showed errors less than 10%. The highest errors occurred primarily at shorter extraction times (0.5–1 h), particularly for Methods 2 and 3. This pattern suggests the model is slightly less accurate in predicting the rapid initial extraction phase but demonstrates strong predictive capability for longer extraction durations. The overall high accuracy confirms the model's utility for optimizing extraction parameters in industrial applications.

3. 2. Flat Bones

3. 2. 1. Extraction in Ordinary Water

Table 5 presents the yield of fat extracted from flat camel bones in ordinary water across different temperatures and extraction durations, expressed as a percentage of bone mass.

Table 5. Fat extraction yield from flat camel bones in ordinary water (% of bone mass)

Extraction duration (h)	Extraction temperature (°C) 40	50	70	80	90	100
0.5	0.00	0.37	0.80	2.46	4.99	8.41
1	0.43	1.28	2.16	3.95	5.78	9.55
3	1.80	3.19	4.86	6.53	8.20	11.52
4	2.24	4.10	5.85	7.25	8.73	12.29
5	3.07	4.48	6.64	8.63	9.92	13.41

* Yields represent the percentage of fat extracted relative to the initial bone mass (1 kg). Values calculated as (g of fat/1000 g bone) × 100.

The yield data presented in Table 5 and Figure 6 reveal fundamental insights into the extraction kinetics and thermodynamics of fat recovery from flat camel bones:

- Temperature Dependence: The negligible yield at 40 °C indicates that this temperature is below the activation threshold for effective fat mobilization. Yields showed a marked increase with temperature, rising from 3.07% at 40 °C to 13.41% at 100 °C after 5 hours, demonstrating the strong thermal dependence of the extraction process.
- Extraction Kinetics: The time-dependent increase in yield progression across all temperatures suggests a diffusion-controlled mechanism. An initial rapid extraction phase (0-4 hours) is followed by a slower asymptotic approach to maximum yield, indicating the progressively limited diffusion of encapsulated lipids from the bone matrix.
- Synergistic Effect: The combination of elevated temperature and extended duration resulted in substantial improvements. Increasing the temperature from 80 °C to 100 °C at 5 hours resulted in a 55.4% relative increase in yield (from 8.63% to 13.41%), while extending the time from 3 to 5 hours at 100 °C increased the yield by a relative 16.4% (from 11.52% to 13.41%).
- Comparative Efficiency with Hollow Bones: The maximum yield from flat bones (13.41%) is approximately 30.44% lower than that achieved from hollow bones (19.28%) under identical conditions, reflecting anatomical differences in fat distribution and bone density between the two bone types.

These findings establish fundamental extraction parameters for flat bones and provide a baseline for subsequent optimization through particle size reduction and solvent modification.

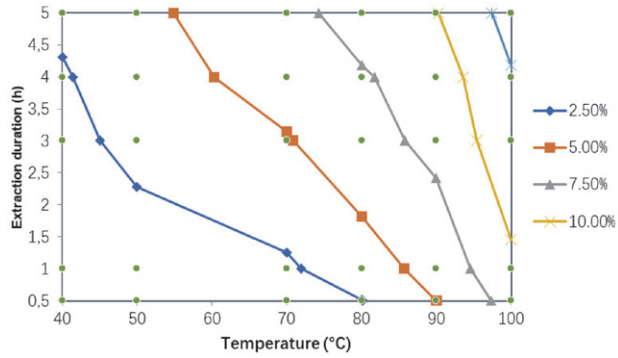

Figure 6. Fat yield variation with extraction duration & temperature (Flat bone pieces in ordinary water)

When compared to extraction yields from the flat bones of cows and sheep[31] under identical conditions (100 °C and 3–5 h duration), camel bones demonstrated intermediate performance, yielding less fat than bovine bones but slightly higher than ovine bones (Figure 7). This comparative yield profile, achieving approximately 13.4% extraction efficiency, positions camel bones as a viable fat source among common livestock species.

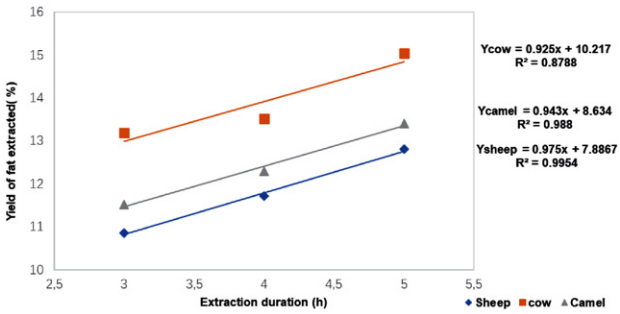

Figure 7. Comparison of fat extraction yields from flat bones of cows and sheep (based on[31]) and camel (present study) at 100 °C

3. 2. 2. Regression Analysis of Fat Extraction from Flat Bones (Ordinary Water)

3. 2. 2. 1. Simple Regression

The objective of simple regression in this context is to derive mathematical equations that describe the relationship between the yield of extracted fat and time at each temperature, denoted as $Y(t)$, as illustrated in Figure 8.

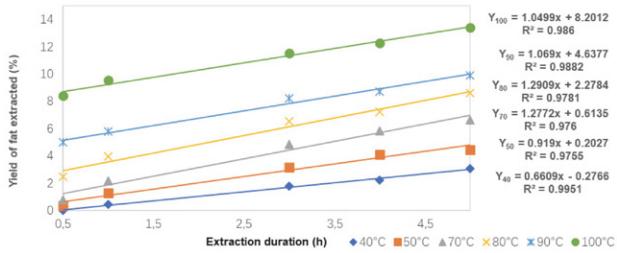

Figure 8. Yield of fat extracted from flat as a function of time with ordinary water (% of bone mass)

Linear regression analysis produced excellent fits to the experimental data, with all R^2 approaching 1. This confirms that fat extraction from flat bones follows zero-order kinetics under the tested conditions, indicating a constant extraction rate throughout the process across the entire temperature range studied.

3. 2. 2. 2. Advanced Regression

The advanced regression analysis aimed to develop a comprehensive model relating fat yield to both extraction temperature (T) and time (t). The optimal nonlinear regression model is represented by Eq. (3):

$$Y(T,t) = -130.985 + 4.674\,T + 3.592\,t - 0.057\,T^2 - 0.860\,t^2 + 0.00023\,T^3 + 0.0861\,t^3 \quad (3)$$

Where:
Y: Fat yield (% of bone mass).
t: Extraction duration h.
T : Extraction temperature °C.
With a $R^2 = 0.9965$.

The relative error between experimental results and model predictions is shown in Table 6.

Table 6. Relative error distribution between experimental and predicted yields for flat bones in ordinary water (nonlinear regression).

Extraction duration (h)	Extraction temperature (°C) 70	80	90	100
0.5	25.31	10.96	9.77	7.81
1	3.58	0.23	0.94	5.99
3	1.62	0.48	0.86	0.03
4	5.13	0.19	3.53	0.03
5	0.29	2.92	2.35	0.06

Relative error > 15 % Relative error 10–15% Relative error < 10 %

The error analysis demonstrates that the model provides excellent predictive accuracy, with 92% of data points showing relative errors below 10%. The only exceptions occur at the shortest extraction time (0.5 h) and lower temperatures (70–80 °C), where the model slightly overestimates the yield. This high accuracy confirms the robustness of the nonlinear regression model for predicting fat extraction from flat bones across most experimental conditions.

3. 2.3. Extraction in Distilled Water

Table 7 presents the fat yields obtained from flat camel bones under three conditions at 100 °C: ordinary water (pieces and minced bones) and distilled water (minced bones). Experiments were conducted across 11 time intervals, ranging from 0.25 to 10 hours.

Comprehensive analysis of the data reveals several key findings:

- Particle size effect (Method 1 vs. Method 2): The significant yield improvement (up to 34.9%) achieved through bone mincing demonstrates the crucial role of increased surface area in enhancing extraction efficiency. This mechanical pre-treatment improves solvent penetration, reduces diffusion path length, and enhances mass transfer rates.
- Solvent purity effect (Method 2 vs. Method 3): The consistent superiority of distilled water, providing an additional 8–12% yield enhancement, results from the elimination of ionic interference. Dissolved minerals (particularly Ca^{2+} and Mg^{2+}) in ordinary water form insoluble metal soaps with free fatty acids, reducing available yield.
- Kinetic saturation behavior: All methods exhibit characteristic extraction kinetics with rapid initial rates (0-6 hours) followed by asymptotic approach to equilibrium. Method 3 demonstrates the most favorable kinetics, reaching 95% of maximum yield within 6 hours compared to 10+ hours for Method 1.

This represents a 40% reduction in processing time while achieving higher final yields.

- Maximum yield potential: The plateau at 19.04% yield in Method 3 represents the practical maximum extractable fat under these conditions. This value likely reflects the fundamental lipid content of flat bone tissue and represents a mass transfer equilibrium between the bone matrix and extraction solvent.

Table 7. Fat extraction yield from flat camel bones at 100 °C (% of bone mass)

Extraction duration (h)	Method 1	Method 2	Method 3
	Ordinary water		Distilled water
	Bone pieces	Minced bones	
0.25	6.99	9.43	11.73
0.5	8.41	10.77	12.46
1	9.55	12.30	13.46
3	11.52	13.56	15.75
4	12.29	14.30	16.94
5	13.41	14.97	18.13
6	14.03	15.53	19.02
7	14.56	16.22	19.04
8	14.77	16.22	19.04
9	14.84	16.22	19.04
10	15.03	16.22	19.04

The data demonstrate that optimal fat extraction from flat bones requires addressing both physical access limitations (through particle size reduction) and chemical interference challenges (through solvent purification). The synergistic combination of these approaches in Method 3 provides the most effective strategy for maximizing yield while minimizing processing time and energy consumption.

3. 2. 4. Regression Analysis of Fat Extraction From Flat Bones at 100 °C

3. 2. 4. 1. Simple Regression

This simple regression analysis aims to identify mathematical relationships between fat extraction yield and time for each method *Y* (t), as illustrated in Figure 9 below.

Method 3 achieved maximum fat yield in just 2 hours (significantly faster than the 6 hours required by Method 2) highlighting its superior time and energy efficiency. In addition, Method 3 consistently produced approximately 1.18 times higher yields than Method 2 across all time points, demonstrating stable and enhanced performance when using distilled water. This consistent improvement ratio (≈1.2-fold) aligns with results reported in Tables 4 and 8, further validating the reproducible advantage of solvent purification under consistent experimental conditions.

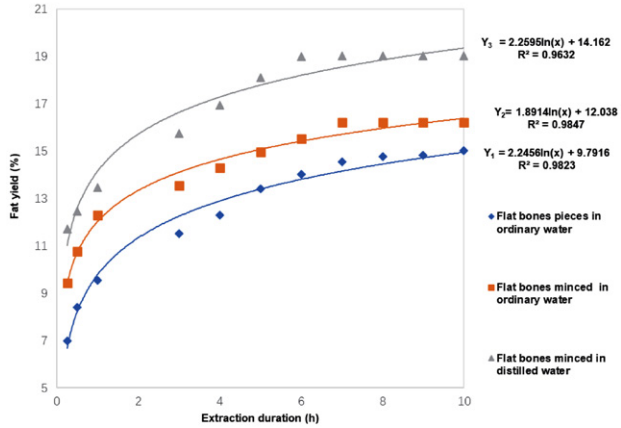

Figure 9. Yield of extracted fat as a function of time for each method at 100 °C (% of bone mass) for flat bones

3. 2. 4. 2. Advanced Regression

The advanced regression analysis aimed to model the relationship between fat yield and the categorical variables of bone state (pieces or minced) and water type (ordinary or distilled), in addition to extraction time. The optimal nonlinear regression model is given by Eq. (4):

$$Y(t,p,w) = 11.440 + 1.986\,t - 1.690\,p - 2.678\,w - 0.166\,t^2 + 0.0044\,t^3 \quad (4)$$

Where:
Y: Fat yield (% of bone mass).
t: Extraction duration h.
p = 1 if Bone pieces, 0 if Minced bones.
w = 1 if Ordinary water, 0 if Distilled water.
With a $R^2 = 0.9937$.

Table 8 presents the relative errors between experimental results and model predictions.

The error analysis demonstrates exceptional predictive accuracy, with only one data point (1.1%) showing a relative error exceeding 10%. The vast majority of predictions (97.0%) exhibited errors below 10%, confirming the model's robustness for predicting fat extraction from flat bones. Given the superior performance of the nonlinear regression compared to linear approaches, Eq. (4) is recommended for predicting extraction yields under these conditions.

3. 3. Ideal Extraction Zone

To select the optimal extraction duration for the third method (minced bones, distilled water), we analyzed the extraction yield relative to the duration for both bone types, as illustrated in Figure 10.

Table 8. Relative error distribution between experimental and predicted yields for flat bones at 100 °C (nonlinear regression).

Extraction duration (h)	Method 1 Ordinary water Bone pieces	Method 2 Minced bones	Method 3 Distilled water
0.25	8.16	1.93	1.66
0.5	4.59	9.78	0.51
1	6.86	13.94	1.45
3	1.17	1.58	1.76
4	2.95	0.26	0.46
5	0.05	0.91	1.93
6	0.34	0.97	3.58
7	1.17	0.90	1.38
8	0.83	0.68	0.02
9	0.35	1.55	0.72
10	1.35	1.87	0.99

Relative error > 15 % Relative error 10–15% Relative error < 10%

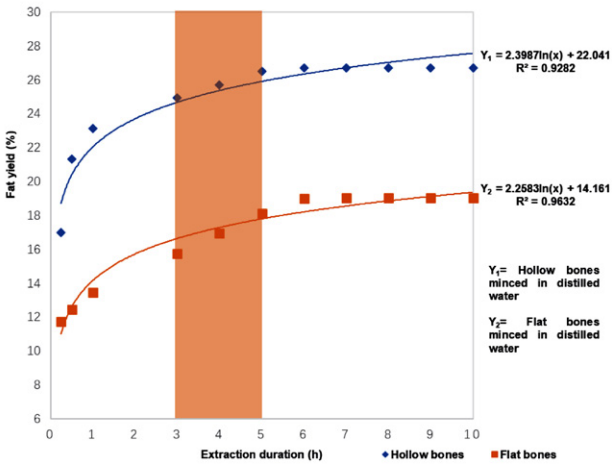

Figure 10. Comparison of the maximum yield of hollow and flat bones

The analysis reveals that hollow bones yield approximately 1.4 times more extractable fat than flat bones under optimal conditions, establishing hollow bones as the superior source for fat extraction.

Based on the extraction kinetics and efficiency considerations, we recommend an optimal extraction time between 3 and 5 hours for the following reasons:

- Minimum time consideration (3 hours): Extraction periods shorter than 3 hours may leave significant amounts of fat unextracted from the bone matrix, resulting in a suboptimal yield and inefficient resource utilization.
- Maximum time consideration (5 hours): Beyond 5 hours, the additional fat yield becomes only marginal (diminishing returns), while energy consumption continues to increase substantially. This represents an inefficient use of energy resources with a negligible gain in output.

This 3 to 5 hour window represents the optimal balance between maximizing fat recovery and minimizing energy consumption, ensuring both economic viability and process efficiency for industrial applications. The recommended duration applies particularly to hollow bones, which demonstrate superior extraction potential compared to flat bones.

3. 4. Fatty Acid Composition

To contextualize the nutritional and industrial potential of bone-derived fat, its fatty acid profile was compared to that of a well-known and commercially valued camel fat source: the hump[32]. This comparison aims not only to assess the quality of bone fat as a dietary alternative but also to determine its suitability for industrial applications, such as its use as a raw material for biofuel production, similar to the known uses of camel hump fat.[33]biodiesel has been gaining market share against fossil-origin diesel due to its ecological benefits and because it can be directly substituted for traditional diesel oils. However, the high cost of the raw materials required to produce biodiesel makes it more expensive than fossil diesel. Therefore, low-priced raw materials, such as waste cooking oil and animal fats, are of interest because they can be used to drive down the cost of biodiesel. We have produced biodiesel from camel fat using a transesterification reaction with methanol in the presence of NaOH. The experimental variables investigated in this study were the temperature (30–75 °C)

Table 9 presents the percentage of SFAs in the fat extracted from flat and hollow bones, as determined by GC-MS analysis. Three major compounds myristic, palmitic and stearic represent 73.73% of total extracted fat and 95.16% of the SFAs in hollow bones. In flat bones, these three compounds represent 78.92% of the amount of fat extracted and 98.18% of the SFAs. Compared to camel hump,[32] bone fat contained higher proportions of palmitic and stearic acids, while the percentage of myristic acid was similar between the two sources.

Palmitic, myristic, and stearic acids play important roles in human health. They serve as essential energy sources, facilitate the absorption of fat-soluble vitamins (A, D, E, and K), contribute to cell membrane structure, and possess anti-inflammatory properties.[34,35] Specifically ,palmitic acid enhances vitamin absorption, myristic acid is involved in hormone production and stearic acid helps regulate neurological function and is used in cosmetic manufacturing.[35] However, these saturated fats should be consumed in moderation within a balanced diet, as excessive intake may increase cardiovascular disease risk.[36]

Table 10 presents an analysis of UFAs in flat and hollow bones. Two major unsaturated fatty acids, palmitelaidic and oleic acid comprise a significant portion (21.73%) of the total fat and 96.49% of the UFAs in hollow bones. Flat bones show a similar trend, with these acids making up

Table 9. SFAs in fat extracted from hollow, flat bones compared to fatty acids in the hump

Fatty acids	Systematic name	Common name	Composition%		
			Hollow bones	Flat bones	Camel hump
C12:0	Dodecanoic acid		0.22	0.03	0.66
C13:0	Tridecanoic acid		0.12	0.07	0.10
C14:0	Tetradecanoic acid	Myristic	7.25	5.21	8.83
	12-methyltridecanoic acid	Isomyristic	0.74	0.35	–
C14:0			7.99	5.56	8.83
C15:0	Pentadecanoic acid		0.91	0.45	0.34
	9-Methyltetradecanoic acid		–	–	1.67
C15:0			0.91	0.45	2.01
C16:0	Hexadecanoic acid	Palmitic	38.03	43.63	26.16
	14-Methylpentadecanoic acid	Isopalmitic	–	–	0.46
C16:0			38.03	43.63	26.62
C17:0	Heptadecanoic acid	Margaric	0.82	0.50	0.67
	14-methylhexadecanoic acid	Anteisomargaric	0.95	0.41	–
	15-Methylhexadecanoic acid		0.36	–	2.32
C17:0			2.13	0.91	2.99
C18:0	Octadecanoic acid	Stearic	27.71	29.73	10.07
C20:0	Eicosanoic acid		–	–	0.18
Total saturated			77.48	80.38	51.46

19.25% of total fat and 97.81% of UFAs. Comparatively, camel hump fat[32] contains significantly higher proportions of these acids, particularly oleic acid, which accounts for 33.35% of total fat composition.

These unsaturated fatty acids play crucial roles in human health. Palmitelaidic acid demonstrates anti-inflammatory properties that may benefit cardiovascular health and arthritis management, with some studies suggesting potential anticancer effects.[37,38] and evaluating the effects of exogenous POA on blood pressure and aortic remodeling in spontaneously hypertensive rats (SHRs). Oleic acid is particularly valuable for its ability to modulate cholesterol levels by reducing LDL (low-density lipoprotein) while increasing HDL (high-density lipoprotein),[39] thereby reducing cardiovascular disease risk, Additionally, oleic acid exhibits anti-inflammatory properties and may support cognitive function and memory.[40]

The substantially higher UFA content in camel hump fat (48.41%) compared to bone fat (19.68–22.52%) suggests superior nutritional quality for dietary applications.

Table 10: UFAs in fat extracted from hollow, flat bones compared to fatty acids in the hump

Fatty acids	Systematic name	Common name	Composition%		
			Hollow bones	Flat bones	Camel hump
Monounsaturated					
C14:1 n-3	11-Tetradecenoic acid		–	–	0.58
C16:1 n-5	11-Hexadecenoic acid		–	0.06	0.06
C16:1 n-6	10-Hexadecenoic acid		–	–	0.24
C16:1 n-7	9-Hexadecenoic acid	Palmitelaidic	1.91	0.64	9.56
C16:1 n-9	7-Hexadecenoic acid		–	–	0.75
C16:1			1.91	0.70	10.61
C18:1 n-9	9-Octadecenoic acid	Oleic	19.82	18.61	33.35
C18:1 n-7	11-Octadecenoic acid		0.24	–	0.76
C18:1			20.06	18.61	34.11
C20:1 n-9	11-eicosenoic acid		–		0.44
Total monounsaturated			21.97	19.31	45.74
Polyunsaturated					
C18:2 n-6,9	9,12-Octadecadienoic acid		0.25	0.37	2.67
C18:2 n-7,10	8,11-Octadecadienoic acid		0.31	–	–
C18:2			0.55	0.37	2.67
Total polyunsaturated			0.55	0.37	2.67
Total unsaturated			22.52	19.68	48.41

However, the significant saturated fatty acid (SFA) content of bone fat (77.48-80.38%) may make it particularly suitable for industrial applications where high oxidative stability is required, such as biofuel production or soap manufacturing.

4. Conclusions

This study investigated the use of readily available camel bones from North Africa and the Middle East as a valuable source of fat. Fat was extracted from the bones using a pressure cooker and hot water. Various parameters, including temperatures, duration, bone preparation (pieces or minced), and water type (ordinary or distilled), were tested to determine the optimal method for achieving the highest fat yield.

The experiments demonstrated that fat yield is directly proportional to temperature, with the maximum yield obtained at the highest temperature tested (100 °C) for both bone types. Additionally, grinding the bones into minced pieces significantly improved the extraction efficiency. For instance, the fat yield from hollow bones increased from 19.28% to 22.64% when minced bones were used with ordinary water. The use of distilled water, which lacks salts and minerals that impede fat solubility, further enhanced the process. A significant improvement was observed with distilled water, as the yield increased from 22.64% to 26.49% for hollow bones after a 5-hour extraction. The maximum yields obtained were 26.69% for hollow bones and 19.03% for flat bones.

Regarding the regression study of the obtained results, it provided an adjustment coefficient R2 very close to 1 for both the simple regression and the advanced regression with ordinary water. As for the distilled water, it provided an acceptable R^2 value for the simple regression and an excellent adjustment coefficient for the advanced regression. These results allow us to use the obtained equations to predict fat extraction yields without the need for practical experiments, with only a minimal margin of error.

The results obtained were also compared with their counterparts from cows and sheep under the same conditions, and showed that the fat yield from both types of camel bones is higher than from sheep bones, but less than that found in cow bones. On the other hand, we suggest that the optimal extraction time be 3–5 h to achieve a balance between efficiency and productivity.

Regarding the composition in terms of fatty acids, it was observed that the percentage of saturated fats is higher than the unsaturated ones, representing 77.48% and 80.38% for the hollow and flat bones, respectively.

Based on the results obtained, we suggest conducting further research and studies to explore the potential uses of this new source of fats, whether in the field of nutrition or in other industrial applications. These explorations include studying the possibility of using these fats as raw materials for the production of biofuels such as biodiesel, typically produced through the transesterification process. Testing this renewable and sustainable fuel is necessary to optimize its quality for future uses, like in engines.

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Povzetek

Študija opisuje izvedljivost uporabe kameljih kosti, ki so pogost stranski proizvod v Severni Afriki in na Bližnjem vzhodu, kot novega vira maščob za proizvodnjo biodizla. Za ekstrakcijo maščobe iz votlih in ploščatih kosti je bil uporabljen postopek vlažne toplotne ekstrakcije s tlačnim loncem. V začetni fazi raziskave so optimizirali temperaturo (40–100 °C) in trajanje postopka (0,5–5 ur) z uporabo navadne vode ter potrdili, da se donos maščobe povečuje z obema parametroma. V naslednji fazi so učinkovitost ekstrakcije bistveno izboljšali z dvema ključnima optimizacijama: mletjem kosti za povečanje površine in uporabo destilirane vode za odpravo ionskih motenj. Ta pristop je omogočil največji donos 26,69 % (glede na maso kosti) pri votlih kosteh pri 100 °C po 6 urah. Analiza sestave je pokazala prevlado nasičenih maščobnih kislin. Ugotovitve potrjujejo, da so kamelje kosti obetaven vir maščobe za industrijske namene, kot je proizvodnja biodizla s transesterifikacijo, pri čemer je bilo kot optimalen okvir ekstrakcije za učinkovit postopek določeno 3 do 5 ur.