

Research article**Synthesis and Characterization of Natural HAp/ β -TCP Biphasic Calcium Phosphate from Salmon Bone Using a Simplified, Low-cost Technique****Pensri Pramukkul¹, Surirat Yotthuan², Aurawan Rittidech³, Tawat Suriwong^{4,5}, Theerachai Bongkarn^{5,6} and Chittakorn Kornphom^{1*}**¹*Department of Physics and General Science, Faculty of Science and Technology, Chiang Mai Rajabhat University, Chiang Mai, 50300, Thailand*²*Division of Engineering Materials, Department of Science Service, Ratchathewi, Bangkok 10400, Thailand*³*Department of Physics, Faculty of Science, Mahasarakham University, Mahasarakham, 44150, Thailand*⁴*School of Renewable Energy and Smart Grid Technology, Naresuan University, Phitsanulok, 65000, Thailand*⁵*Research Center for Academic Excellence in Applied Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand*⁶*Department of Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand*

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Abstract

Bioceramics containing biphasic calcium phosphates (BCP) are the preferred material for various bone healing applications. BCP consists of β -tricalcium phosphate (β -TCP) and hydroxyapatite (HAp) and offers a balance between solubility and resorption, which promotes cell interaction and tissue growth. There is high demand to synthesize BCP from natural sources using simple and inexpensive methods. This study investigated the effects of calcination temperature on the phase structure, chemical composition, and microstructure of BCP powders synthesized from raw salmon bone (Atlantic salmon) using a simplified, low-cost technique. The successful synthesis of BCP powder from raw salmon bone was confirmed using X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR). The physical and chemical characteristics were analyzed using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). XRD results revealed the coexistence of HAp and β -TCP phases at calcination temperatures above 600°C for 2 h, indicating the formation of BCP compounds. The relative phase content of HAp and β -TCP changed when the calcination temperature increased from 600 to 1000°C. The crystallite size of HAp and β -TCP increased while the lattice strain decreased as the calcination temperature increased. All samples showed polyhedral lumps of irregular sizes, and the Ca/P ratio decreased from 2.14 to 1.95 with higher calcination temperatures. The FTIR results of all samples revealed the existence of the functional

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groups of phosphate (PO_4^{3-}) hydroxyl (OH^-) and carbonate (CO_3^{2-}), which are characteristic of the BCP structure. The optimal phase ratio of HAp/ β -TCP at approximately 60:40 was obtained by the samples at a calcination temperature of 800°C . This study reports on a new simplified, low-cost technique to synthesize BCP powder from salmon bone.

Keywords: biphasic calcium phosphate; bioceramic; calcination; fish bone; a simplified; low-cost technique

1. Introduction

The primary composition of human teeth and bone consists of calcium and phosphate, accounting for approximately 70% of the structure (Abdulridha et al., 2024). Teeth and bone are the second most commonly implanted tissues in the human body, following blood. Over the years, teeth and bone graft scaffolds have become essential in treating, repairing, and augmenting skeletal injuries, functioning as bone replacement materials (Venkatesan & Kim, 2014). Bioceramics composed of calcium and phosphate are widely valued for their chemical compatibility and bioactivity, making them useful for regenerating and replacing human teeth and bones (Gallant et al., 2014). However, bioceramics are expensive because they require costly precursor chemicals or complex synthetic processes (Shi et al., 2018). Additionally, concerns about bioactivity and the potential for rejection within the human body present serious concerns when developing substitute materials (Gallant et al., 2014; Shi et al., 2018).

Biphasic calcium phosphate (BCP) is a biomaterial composed of two phases: hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$; HAp] and β -tricalcium phosphate [$\text{Ca}_3(\text{PO}_4)_2$; β -TCP]. BCP has recently garnered interest as a scaffolding material. The chemical composition of BCP is similar to the mineral component of human bone, with a molar Ca/P ratio near 1.67, and its solubility promotes biomineralization around bone implants (Ebrahimi et al., 2017; Ahmadi et al., 2022; Deng et al., 2022a; 2022b). BCP is less hydrophobic than β -TCP but more hydrophobic than HAp (Wang et al., 2012). Compared to HAp, BCP demonstrates better osteopromotion because of its hydrophobic interactions, which promote protein adsorption (Wang et al., 2012). In addition to encouraging efficient bone ingrowth, this property ensures good stability (Suneelkumar et al., 2008; Cheng et al., 2010; Ebrahimi et al., 2017). To address bone deformities in high-load-bearing locations, BCP materials can be tailored to maintain their shape over extended periods (de Oliveira et al., 2007) by appropriately modifying the phase concentrations. Additionally, BCP can be consolidated by controlling the degree of Ca deficiency in the initially formed non-stoichiometric apatite and optimizing the conditions of subsequent firing (Duta et al., 2021). BCP can be produced through both natural and chemical methods, although chemical synthesis involves complex processes that require chemical reagents (Zhang et al., 2013; Chen et al., 2015; Malakausaite-Petruleviciene et al., 2015; Iyyappan et al., 2016; Othman et al., 2016; Duta et al., 2021). Moreover, various chemical routes to synthesize BCP powders have been developed, such as wet chemical precipitation, hydrothermal reaction, mechanochemical-hydrothermal synthesis, and sol-gel synthesis (Duta et al., 2021). On the other hand, there are a few drawbacks to these approaches. One of them is that it may be challenging to keep the pH value over 9 in the initial solution using these methods (Duta et al., 2021). Another is that they produce calcium-deficient BCP powders, which quickly break down to β -TCP when heated further. It is well established that HAp and β -TCP are the primary constituents of natural bones, such as those from fish, bovine, and pig sources. Fish bones are rich in calcium, carbonate, and phosphate compounds, making them a reliable source

for producing BCP from natural materials (Duta et al., 2021). Moreover, the HAp and β -TCP derived from fish sources exhibit thermal stability at higher temperatures (Duta et al., 2021).

Increasing global fish consumption has led to the generation of significant amounts of fish bone waste annually. Globally, approximately 970-2700 billion tons of fish are harvested, of which humans consume 450-1000 billion tons, with nearly 50% of the total being wasted (Muhammad et al., 2017; Shi et al., 2018, Duta et al., 2021;). This has led to interest in utilizing fish bone waste as a resource for sustainable BCP production. Recent studies have synthesized BCP from the fish bones of various species, including Sheelavati (roho labio) fish (Sunil et al., 2016), tuna fish (Latif et al., 2020), milkfish (Lolo et al., 2022), *Tylosurus crocodilus* (Permatasari et al., 2020) and butterflyfish (Deng et al., 2022a), each employing distinct synthesis processes. Larosi et al. (2009) reported simplified procedures for extracting BCP powders from several kinds of fish. One approach involves calcining the fish bones at 950°C for 12 h and then crushing the resulting powder for 1 min in a ball mill. Another approach combined laser irradiation with calcination treatment (200-400°C). This method of obtaining powders from fish bones was much quicker than the traditional calcination one, thanks to the high energy density of the laser (Larosi et al., 2009). Moreover, BCP with HAp/ β -TCP ratios of 50/50 or 60/40 significantly enhanced cell proliferation (Kong et al., 2008; Ahmadi et al., 2022). BCP powder with HAp/ β -TCP ratios of 64/36 was successfully synthesized with salmon bones using the calcination process (Zhu et al., 2017). This process used a calcination temperature of 1000°C for 1 h with a heating rate of 5°C/min in air and then cooling at 20°C/min to room temperature (Zhu et al., 2017). In recent years, salmon bone has gained interest as a promising material for synthesizing high-quality HAp powder due to its availability and low cost (Komur et al., 2017; Tri et al., 2020; Nguyen et al., 2022). However, researchers are attempting to resolve the ongoing issues in developing BCP bioceramics with a high concentration of β -TCP components using an easy and practical approach.

This study aimed to synthesize BCP powder with HAp/ β -TCP ratios of 60/40 from salmon bone using a simplified and low-cost technique. The bone was heat-treated using an air fryer and ground by hand milling before the calcination process. The effect of calcination temperature on salmon bone's chemical composition, structural formation, and microstructure was studied.

2. Materials and Methods

Raw salmon bones (Atlantic salmon) obtained from the salmon processing industry were boiled in water at 100°C for 2 h to remove any remaining flesh. To eliminate proteins, lipids, and other organic contaminants, the cleaned salmon bones were treated with 1% NaOH in acetone for 24 h and then rinsed with pure water. The cleaned bones were dried and heat-treated at 200°C for 30 min using an air fryer. The dried and crisped salmon bones were ground by hand milling for 20 min using a mortar and then sieved through a 200-mesh screen. The resulting salmon bone powder was calcined at temperatures ranging from 600 to 1000°C for 2 h in air with a heating rate of 5°C/min and allowed to cool down naturally. This procedure was repeated 3 times. The synthesis process of biphasic calcium phosphates from salmon bone powder is summarized schematically in Figure 1.



Figure 1. Schematic diagram of the synthesis process for biphasic calcium phosphates from salmon bone powders using a simplified, low-cost technique

The thermal transformations during the calcination of salmon bone powders were analyzed using a TG-DSC analyzer (NETZSCH, STA 449 F3). Thermogravimetric analysis (TG) and differential scanning calorimeter (DSC) were performed on the powders over a temperature range of 40°C to 1000°C at a heating rate of 10°C/min. The crystal structure of calcined salmon bone powders at room temperature, prepared at various calcination temperatures, was determined using X-ray diffraction (XRD, Rigaku, SmartLab) with Cu-K α radiation ($\lambda = 1.5418 \text{ \AA}$). XRD data were recorded over a 2θ range of 10-80° with a scanning rate of 0.05°/s. The phase formation was identified by comparing experimental XRD patterns with standard data from the Joint Committee on Powder Diffraction Standards (JCPDS) files No. 09-0432 and No.09-0169. The microstructure of all samples was examined using field-emission scanning electron microscopy (FE-SEM; Thermoscientific Model, Apreo S). Chemical compositions were analyzed using energy dispersive spectroscopy (EDS). Samples were prepared for SEM analysis by mounting them on conductive adhesive and supported on conventional carbon microgrids. The chemical functional groups of all samples were analyzed using Fourier-transform infrared spectroscopy (Perkin Elmer, Frontier) in transmission mode, with wavelengths ranging from 450 to 4000 cm^{-1} .

3. Results and Discussion

Figure 2 displays the TG and DSC results of salmon bone powders being calcined over a temperature range of 40-1000°C. The TG and DSC curves revealed three distinct decomposition zones (Figure 2). In the first zone (I) at around 40-150°C, the TG curve exhibited a weight loss of 4.15%, attributed to the elimination of incorporated water, which was supported by an endothermic peak in the DSC curve at approximately 150°C as seen in Figure 2. The second zone (II) (150-520°C) exhibited a rapid weight loss of 28.67% in the TG curve, corresponding to the removal of organic components such as protein and

collagen (Figure 2). This decomposition corresponded to the exothermic peaks in the DSC curve at 341°C and 421°C. In the third zone (III), at around 520-800°C, the TG curve indicated slight changes with total weight loss reaching 33.73% as observed in Figure 2. A small, broad DSC peak around 690°C suggested the decomposition of certain mineral phases. The formation of HAp/ β -TCP phases likely occurred at temperatures above 690°C, as the %weight stabilized. The TG results revealed a total weight loss of approximately 33.73% across the temperature range of 40-1000°C, indicating that the final BCP content was approximately 66.27% of the initial material. The TG and DSC results of the salmon bone powders in this work are similar to those previously reported (Onishi et al., 2008, Naga et al., 2015)

The raw Atlantic salmon bones were investigated by X-ray diffraction (XRD), as shown in Figure 3 (a). The XRD pattern revealed the major XRD peak of monocrystalline apatite in the bone matrix, which matched the HAp pattern in the data standard JCPDS No. 09-0432. The crystalline phase of the BCP powders calcined from salmon bones was analyzed using XRD at room temperature, as shown in Figure 3 (b). At a calcined temperature of 600°C, the XRD patterns exhibited broader peaks, and some characteristic hydroxyapatite (HAp) phase peaks (indexed as $\bullet$) were observed. In contrast, peaks for beta-tricalcium phosphate (β -TCP) did not appear (Figure 3 (b)). This suggests that organic matter in the salmon bone matrix was not completely eliminated, based on the data standard JCPDS No. 09-0432 (Figure 3 (b)) (Rajesh et al., 2012). When calcination temperatures increased from 700 to 1000°C, the XRD peaks became sharper, and the peaks corresponding to the HAp structure were clearly observable, indicating a rise in crystallinity. Additionally, the β -TCP phase (indexed as $\blacklozenge$) emerged at higher calcination temperatures, and the peaks became more defined and aligned with the JCPDS standard data (No. 09-0169). These results demonstrate that calcination temperatures above 700°C can produce BCP powders because the XRD pattern revealed the coexisting HAp and β -TCP phases, corresponding with the TG-DSC data.

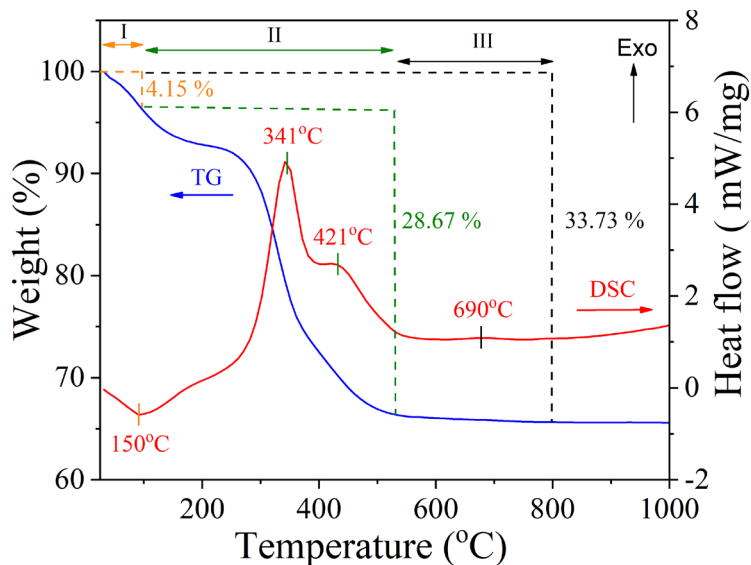


Figure 2. TG and DSC curves of salmon bone powder calcined over a temperature range of 40-1000°C

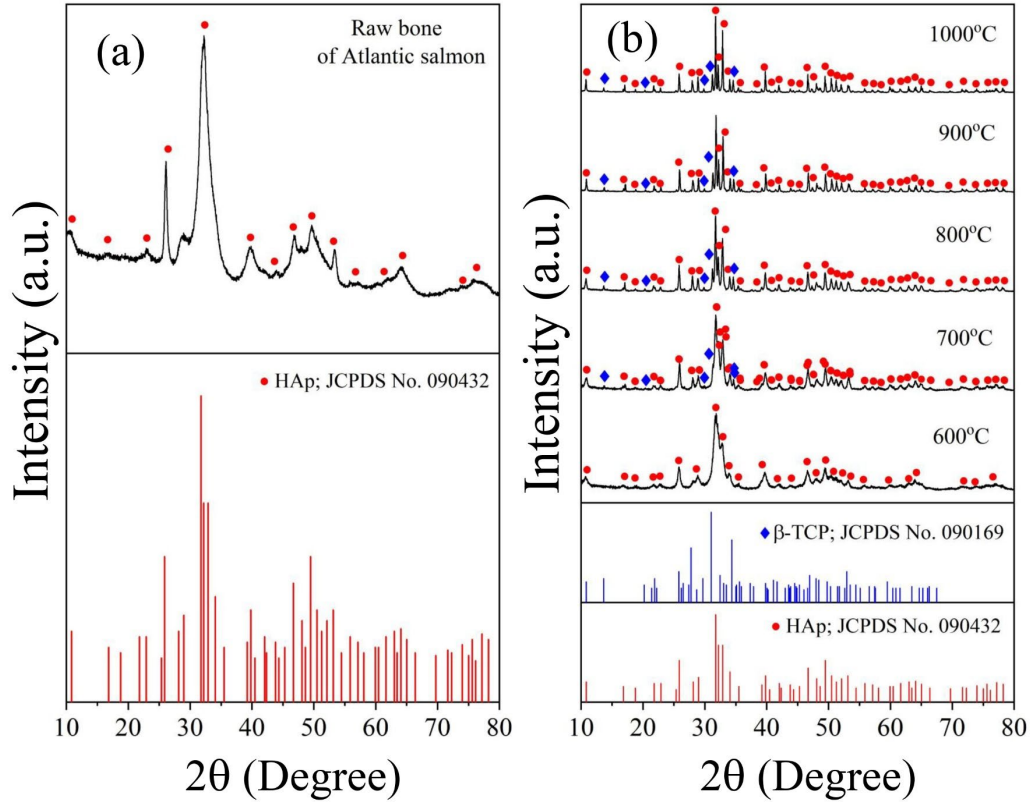


Figure 3. XRD pattern of (a) Atlantic salmon raw bone and (b) salmon bones calcined with temperature from 600 to 1000°C for 2 h

The weight percentages of the HAp phase (% W_{HAp}) and β -TCP phase (% $W_{\beta\text{-TCP}}$) in the calcined powders were calculated using equations (1) and (2) (Deng et al., 2022b).

$$\% W_{\text{HAp}} = \frac{I_{\text{HAp}}}{I_{\text{HAp}} + \frac{I_{\beta\text{-TCP}}}{K_{\beta\text{-TCP}}^{\text{HAp}}}} \times 100 \quad (1)$$

$$\% W_{\beta\text{-TCP}} = \frac{I_{\beta\text{-TCP}}}{I_{\beta\text{-TCP}} + I_{\text{HAp}} K_{\text{HAp}}^{\beta\text{-TCP}}} \times 100 \quad (2)$$

Where I_{HAp} represents the intensity of the maximum diffraction peak of the HAp crystal (the (211) plane at 2θ around 31.77°), and $I_{\beta\text{-TCP}}$ represents the intensity of the maximum diffraction peak of the β -TCP crystal (the (0210) plane at 2θ around 31.02°). The intensities were derived from XRD data of calcined powders at 800-1000°C, where the peaks for the HAp and β -TCP phases were clearly distinguishable. The analysis revealed that as the calcination temperature increased from 800 to 1000°C, the % W_{HAp} increased from 65.65 to 80.65%, while the % $W_{\beta\text{-TCP}}$ decreased from 35.35 to 19.35%, as summarized in Table 1.

Table 1. % W_{HAp} , % $W_{\beta\text{-TCP}}$, crystallite size, and lattice strain of HAp and β -TCP synthesized from salmon bone at various calcination temperatures

Calcination Temperatures (°C)	% W_{HAp}	% $W_{\beta\text{-TCP}}$	The Crystallite Size of HAp (Å)	The Crystallite Size of β -TCP (Å)	Lattice Strain of HAp (%)	Lattice Strain of β -TCP (%)
700	-	-	350	-	0.362	-
800	65.65	35.35	466	432	0.271	0.276
900	79.88	20.12	526	524	0.241	0.246
1000	80.65	19.35	843	525	0.151	0.245

The crystallite size and lattice strain of HAp and β -TCP in the calcined powders were calculated using equations (3) and (4), respectively (Bhardwaj et al., 2023).

$$D = \frac{k\lambda}{\beta\cos\theta} \quad (3)$$

$$B_r\cos\theta = \frac{k\lambda}{D} + \epsilon\sin\theta \quad (4)$$

Where D represents the crystallite size, k is Scherer's constant (0.89), λ is the X-ray wavelength, β is the full width at half-maximum (FWHM) of the (211) peak for HAp and the (0210) peak for β -TCP, θ is the diffraction angle in radians, B_r is the broadening of the diffraction peak (FWHM in radians), and ϵ is the stress distribution within the material. The lattice strain (ϵ) was determined using the linear relationship between $B_r\cos\theta/\lambda$ and $\sin\theta/\lambda$, according to the Hall–Williamson principle (Bhardwaj et al. 2023). The calculated crystallite size (D) and lattice strain of HAp and β -TCP for all calcined powders are listed in Table 1. It was observed that the crystalline sizes of the HAp and the β -TCP increased with rising calcination temperature, while the lattice strain decreased. The larger crystallite size with higher calcination temperatures can be attributed to the elimination of imperfections and abnormalities during heat treatment, leading to a well-defined crystalline phase (Saikumari et al. 2021). Conversely, the decrease in lattice strain is affected by the larger crystallites, which reduce atomic configuration changes in nanoregions and eliminate numerous defects within the lattice structure, resulting in decreased lattice strain (Bhardwaj et al., 2023).

To confirm the phase percentages of the HAp and β -TCP phases, the Rietveld method was used to evaluate the XRD patterns and determine the phase content of each calcined powder. In the Rietveld refinement process, the crystal symmetry of the space group P63/m of the HAp phase (COD file no. 1011242) and the R3c:H of the β -TCP phase (COD file no. 1517238) was analyzed using a Pseudo Voigt peak shape function for all diffraction patterns. The atomic positions were treated as variable parameters. Throughout the refinement process, lattice parameters, cation occupancies, isothermal parameters, peak shape parameters, and scale factors were designated as free parameters. The background was also refined via the Pseudo Voigt function. Several factors, including crystallite size, cation arrangement, and electron density, were subsequently specified by refinement, resulting in an optimal value of chi-square (χ^2). Furthermore, analysis of structural bonding was carried out based on the results of the Rietveld refinement (Kornphom et al. 2023; 2024). The refinement results for each calcined powder are presented in Figures 4 (a)-(c), and the refinement parameters are in Table 2. In Figures 4

(a)-(c), the experimental data are represented by red circles, while the simulated data are shown as black lines. The solid blue line represents the difference between the calculated and experimental plots, and the vertical green bars represent the Bragg reflections for the selected space groups of R3c:H and P63/m (Figures 4 (a)-(c)). It is widely accepted that R_{wp}^2/R_{exp}^2 and χ^2 values below 4 indicate good agreement between the fits and the data (Kornphom et al., 2024). The R_{wp}^2/R_{exp}^2 and χ^2 values in this work were ≤ 2.65 and $\chi^2 \leq 2.65$, respectively, demonstrating good fits for all samples, as seen in Table 1. The refinement results confirmed the presence of mixed β -TCP and HAp phases in all samples. The % phase of β -TCP increased from 11 to 40%, while the % phase of HAp decreased from 89 to 60% when the calcination temperature increased from 600 to 800°C (Table 2). However, at calcination temperatures above 800°C, the phase trend reversed, and the amount of β -TCP decreased. The phases percentages found from the refinement results are close to the weight percentages found using equations (1) and (2). Previous research reported that BCP with HAp/ β -TCP ratios of 50/50 or 60/40 significantly enhanced cell proliferation (Kong et al., 2008; Ahmadi et al., 2022). In this work, the sample calcined at 800°C exhibited an HAp/ β -TCP phase ratio of approximately 60/40, highlighting its potential for biomedical applications.

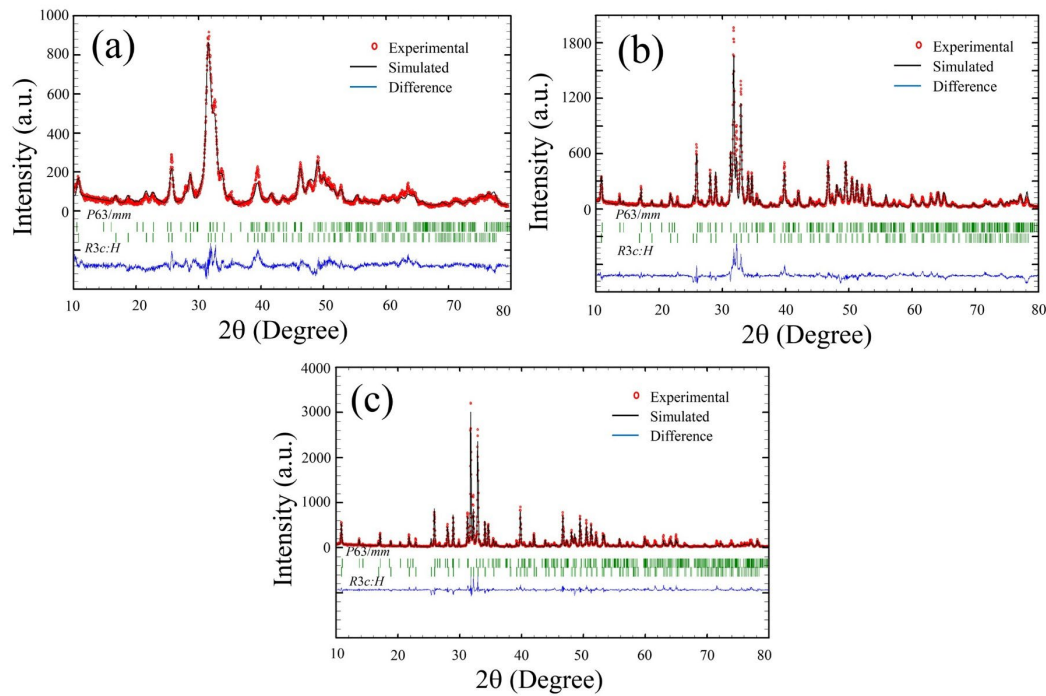


Figure 4. Rietveld refinement results of samples calcined at temperatures of (a) 600°C, (b) 800°C, and (c) 1000°C for 2 h

Table 2. Refinement parameters and phase percentages of HAp and β -TCP in calcined salmon bone powders produced with various temperatures

Calcination Temperatures	Refinement Parameters	Phase Structures	Profile Parameters	Atom Information					The Percentage of Phase					
				Label	x	y	z	Occ.						
600°C	$\chi^2=2.65$ $R_p=31.6\%$ $R_{wp}=32.8\%$ $R_{exp}=20.13\%$ $R_{wp}^2/R_{exp}^2=2.65$	β -TCP $R\ 3\ c:H$	$a=7.0726\text{\AA}$ $c=50.6757\text{\AA}$ $u=84.2187$ $v=9.57050$ $w=-3.4666$	Ca1	0.7259	0.8618	0.1663	0.59363	11					
				Ca2	0.6188	0.8255	-0.0332	0.68149						
				Ca3	0.7266	0.8514	0.0611	0.55214						
				Ca4	0.0000	0.0000	-0.0851	0.65353						
				Ca5	0.0000	0.0000	0.7336	0.48645						
				P1	0.0000	0.0000	0.0000	0.50193						
				P2	0.6872	0.8606	0.8685	0.95768						
				P3	0.6530	0.8464	0.7668	0.43555						
				O1	0.7256	-0.0944	-0.0917	1.23050						
				O2	0.7674	0.7833	0.8548	1.06014						
				O3	0.7298	0.0088	0.8486	1.08407						
				O4	0.5221	0.7608	0.8627	1.18374						
				O5	0.5987	-0.0488	0.7794	1.02568						
				O6	0.5738	0.6930	0.7850	0.95472						
				O7	0.0803	0.8990	0.7771	0.99183						
				O8	0.6320	0.8258	0.7268	1.13171						
				O9	0.0057	0.8624	-0.0115	1.03531						
				O10	0.0000	0.0000	0.0421	0.99849						
				HAp $P63/m$	$a=9.5014\text{\AA}$ $c=6.9259\text{\AA}$ $u=-0.8552$ $v=1.2185$ $w=0.1326$	Ca1	0.3333	0.6667		0.0000	0.86708	89		
						Ca2	0.2500	0.0000		0.2500	1.00863			
						P1	0.4170	0.3610		0.2500	1.12709			
						O1	0.3330	0.5000		0.2500	1.17241			
						O2	0.6000	0.4670		0.2500	0.99872			
						O3	0.3330	0.2500		0.0630	1.24120			
						O4	0.0000	0.0000		0.2500	0.96713			
				700°C	$\chi^2=3.00$ $R_p=24.3\%$ $R_{wp}=29.2\%$ $R_{exp}=16.22\%$ $R_{wp}^2/R_{exp}^2=3.22$	β -TCP $R\ 3\ c:H$	$a=6.7788\text{\AA}$ $c=50.3978\text{\AA}$ $u=17.1934$ $v=6.6225$ $w=1.9762$	Ca1		0.7259	0.8618	0.1663	0.73254	35
								Ca2		0.6188	0.8255	-0.0332	0.77967	
								Ca3		0.7266	0.8514	0.0611	0.59894	
								Ca4		0.0000	0.0000	-0.0851	0.62649	
Ca5	0.0000	0.0000	0.7336					0.58849						
P1	0.0000	0.0000	0.0000					0.19259						
P2	0.6872	0.8606	0.8685					0.64491						
P3	0.6530	0.8464	0.7668					0.53283						
O1	0.7256	-0.0944	-0.0917					0.83552						
O2	0.7674	0.7833	0.8548					1.06014						
O3	0.7298	0.0088	0.8486					1.08407						
O4	0.5221	0.7608	0.8627					1.18374						
O5	0.5987	-0.0488	0.7794					1.02568						
O6	0.5738	0.6930	0.7850					0.95472						
O7	0.0803	0.8990	0.7771					0.99183						
O8	0.6320	0.8258	0.7268					1.12522						
O9	0.0057	0.8624	-0.0115					1.03531						
O10	0.0000	0.0000	0.0421					0.99849						
HAp $P63/m$	$a=9.4531\text{\AA}$ $c=6.8922\text{\AA}$ $u=-0.2907$ $v=0.5878$ $w=0.0024$	Ca1	0.3333					0.6667	0.0000	0.82652	65			
		Ca2	0.2500					0.0000	0.2500	0.96319				
		P1	0.4170					0.3610	0.2500	0.95287				
		O1	0.3330					0.5000	0.2500	1.01605				
		O2	0.6000					0.4670	0.2500	0.99872				
		O3	0.3330					0.2500	0.0630	1.64355				
		O4	0.0000					0.0000	0.2500	0.96713				

Table 2. Refinement parameters and phase percentages of HAp and β -TCP in calcined salmon bone powders produced with various temperatures (continued)

Calcination Temperatures	Refinement Parameters	Phase Structures	Profile Parameters	Atom Information					The Percentage of Phase			
				Label	x	y	z	Occ.				
800°C	$\chi^2=3.83$ $R_p=24.9\%$ $R_{wp}=29.4\%$ $R_{exp}=15.00\%$ $R_{wp}^2/R_{exp}^2=3.84$	β -TCP $R\ 3\ c:H$	$a=10.3503\text{\AA}$ $c=37.0992\text{\AA}$ $u=0.2779$ $v=0.0030$ $w=37.0992$	Ca1	0.7259	0.8618	0.1663	1.10002	40			
				Ca2	0.6188	0.8255	-0.0332	1.01006				
				Ca3	0.7266	0.8514	0.0611	1.14601				
				Ca4	0.0000	0.0000	-0.0851	0.19726				
				Ca5	0.0000	0.0000	0.7336	0.29203				
				P1	0.0000	0.0000	0.0000	0.25913				
				P2	0.6872	0.8606	0.8685	0.83218				
				P3	0.6530	0.8464	0.7668	1.16063				
				O1	0.7256	-0.0944	-0.0917	1.12727				
				O2	0.7674	0.7833	0.8548	1.27731				
				O3	0.7298	0.0088	0.8486	1.03580				
				O4	0.5221	0.7608	0.8627	1.12282				
				O5	0.5987	-0.0488	0.7794	1.56812				
				O6	0.5738	0.6930	0.7850	0.92978				
				O7	0.0803	0.8990	0.7771	0.87641				
				O8	0.6320	0.8258	0.7268	0.88162				
				O9	0.0057	0.8624	-0.0115	1.04578				
				O10	0.0000	0.0000	0.0421	0.52432				
				HAp $P63/m$	$a=9.4221\text{\AA}$ $c=6.8814\text{\AA}$ $u=0.0414$ $v=-0.0045$ $w=0.0457$	Ca1	0.3333	0.6667		0.0000	0.69253	60
						Ca2	0.2500	0.0000		0.2500	0.86187	
						P1	0.4170	0.3610		0.2500	1.01969	
						O1	0.3330	0.5000		0.2500	1.09772	
						O2	0.6000	0.4670		0.2500	0.77899	
						O3	0.3330	0.2500		0.0630	1.57032	
						O4	0.0000	0.0000		0.2500	0.59084	
900°C	$\chi^2=3.16$ $R_p=17.1\%$ $R_{wp}=21.5\%$ $R_{exp}=12.09\%$ $R_{wp}^2/R_{exp}^2=3.18$	β -TCP $R\ 3\ c:H$	$a=10.3569\text{\AA}$ $c=37.1215\text{\AA}$ $u=0.1196$ $v=-0.0159$ $w=0.0141$	Ca1	0.7259	0.8618	0.1663	1.05651	29			
				Ca2	0.6188	0.8255	-0.0332	1.11065				
				Ca3	0.7266	0.8514	0.0611	0.94146				
				Ca4	0.0000	0.0000	-0.0851	0.23923				
				Ca5	0.0000	0.0000	0.7336	0.31207				
				P1	0.0000	0.0000	0.0000	0.33556				
				P2	0.6872	0.8606	0.8685	1.20882				
				P3	0.6530	0.8464	0.7668	1.15913				
				O1	0.7256	-0.0944	-0.0917	1.12727				
				O2	0.7674	0.7833	0.8548	0.43889				
				O3	0.7298	0.0088	0.8486	0.79484				
				O4	0.5221	0.7608	0.8627	1.25091				
				O5	0.5987	-0.0488	0.7794	1.73015				
				O6	0.5738	0.6930	0.7850	1.01840				
				O7	0.0803	0.8990	0.7771	0.41085				
				O8	0.6320	0.8258	0.7268	0.97681				
				O9	0.0057	0.8624	-0.0115	1.55044				
				O10	0.0000	0.0000	0.0421	0.41758				
				HAp $P63/m$	$a=9.4245\text{\AA}$ $c=6.8840\text{\AA}$ $u=0.0272$ $v=-0.0059$ $w=0.0144$	Ca1	0.3333	0.6667		0.0000	0.69476	71
						Ca2	0.2500	0.0000		0.2500	0.84036	
						P1	0.4170	0.3610		0.2500	1.01466	
						O1	0.3330	0.5000		0.2500	1.13982	
						O2	0.6000	0.4670		0.2500	0.75105	
						O3	0.3330	0.2500		0.0630	1.61349	
						O4	0.0000	0.0000		0.2500	0.60321	

Table 2. Refinement parameters and phase percentages of HAp and β -TCP in calcined salmon bone powders produced with various temperatures (continued)

Calcination Temperatures	Refinement Parameters	Phase Structures	Profile Parameters	Atom Information					The Percentage of Phase
				Label	x	y	z	Occ.	
1000°C	χ^2 =2.99 R_p =19.3% R_{wp} =24.2% R_{exp} =14.02% R_{wp}^2/R_{exp}^2 =2.98	β -TCP $R\ 3\ c:H$	a =10.3629Å c =37.1488Å u =0.1279 v =-0.0291 w =0.0132	Ca1	0.7259	0.8618	0.1663	0.99410	20
				Ca2	0.6188	0.8255	-0.0332	1.12582	
				Ca3	0.7266	0.8514	0.0611	0.91730	
				Ca4	0.0000	0.0000	-0.0851	0.25558	
				Ca5	0.0000	0.0000	0.7336	0.21733	
				P1	0.0000	0.0000	0.0000	0.35579	
				P2	0.6872	0.8606	0.8685	0.76850	
				P3	0.6530	0.8464	0.7668	1.29235	
				O1	0.7256	-0.0944	-0.0917	1.20420	
				O2	0.7674	0.7833	0.8548	1.26885	
				O3	0.7298	0.0088	0.8486	1.09856	
				O4	0.5221	0.7608	0.8627	0.63754	
				O5	0.5987	-0.0488	0.7794	0.67983	
				O6	0.5738	0.6930	0.7850	1.22429	
				O7	0.0803	0.8990	0.7771	0.74656	
				O8	0.6320	0.8258	0.7268	1.19240	
				O9	0.0057	0.8624	-0.0115	0.61246	
				O10	0.0000	0.0000	0.0421	0.85913	
		HAp $P63/m$	a =9.424739Å c =6.884093Å u =0.077038 v =-0.049849 w =0.018359	Ca1	0.3333	0.6667	0.0000	0.60956	80
				Ca2	0.2500	0.0000	0.2500	0.79743	
				P1	0.4170	0.3610	0.2500	0.92481	
				O1	0.3330	0.5000	0.2500	1.11017	
				O2	0.6000	0.4670	0.2500	0.73011	
				O3	0.3330	0.2500	0.0630	1.33323	
				O4	0.0000	0.0000	0.2500	0.56379	

Figures 5 (a) and (b) show the EDS mapping results for the elemental distribution in salmon bone powder calcined at 800°C for 2 h. The mapping revealed a uniform distribution of Ca, P, O, and C across the surface, which confirmed the homogeneous composition of the calcined sample. The microstructure of salmon bone powders calcined with various temperatures exhibited polyhedral lumps of irregular sizes, as seen in Figures 6 (a)(I)-(e)(V). These shapes resulted from all samples being hand-milled into powders before the calcining process. The distribution and average grain size are shown in the inset in Figures 6 (a)(I)-(e)(V). The average particle size of all samples was measured from an SEM image using the Image J program. It was found that average grain size increased from 64.72 to 122.52 μm when the calcination temperature increased from 600 to 1000°C. High calcination temperatures can cause an increase in crystallite size and particle size due to the growth, agglomeration, or fusion of individual domains of particles (Berent et al. 2019). The change in the grain size distribution was insignificant with increasing calcination temperature, which may be caused by hand milling creating non-uniform particle sizes before the calcination process (inset of Figures 6 (a)(I)-(e)(V)).

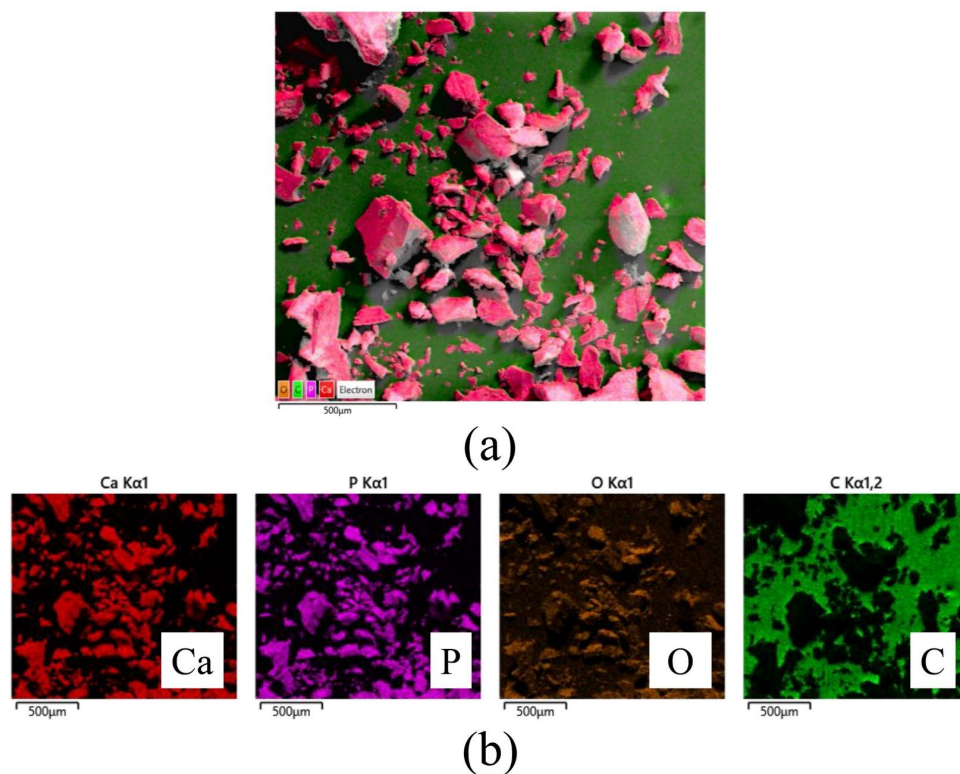


Figure 5. EDS mapping of surface elemental distribution of the powder calcined at 800°C for 2 h (a) combined elements and (b) individual elements of Ca, P, O, and C

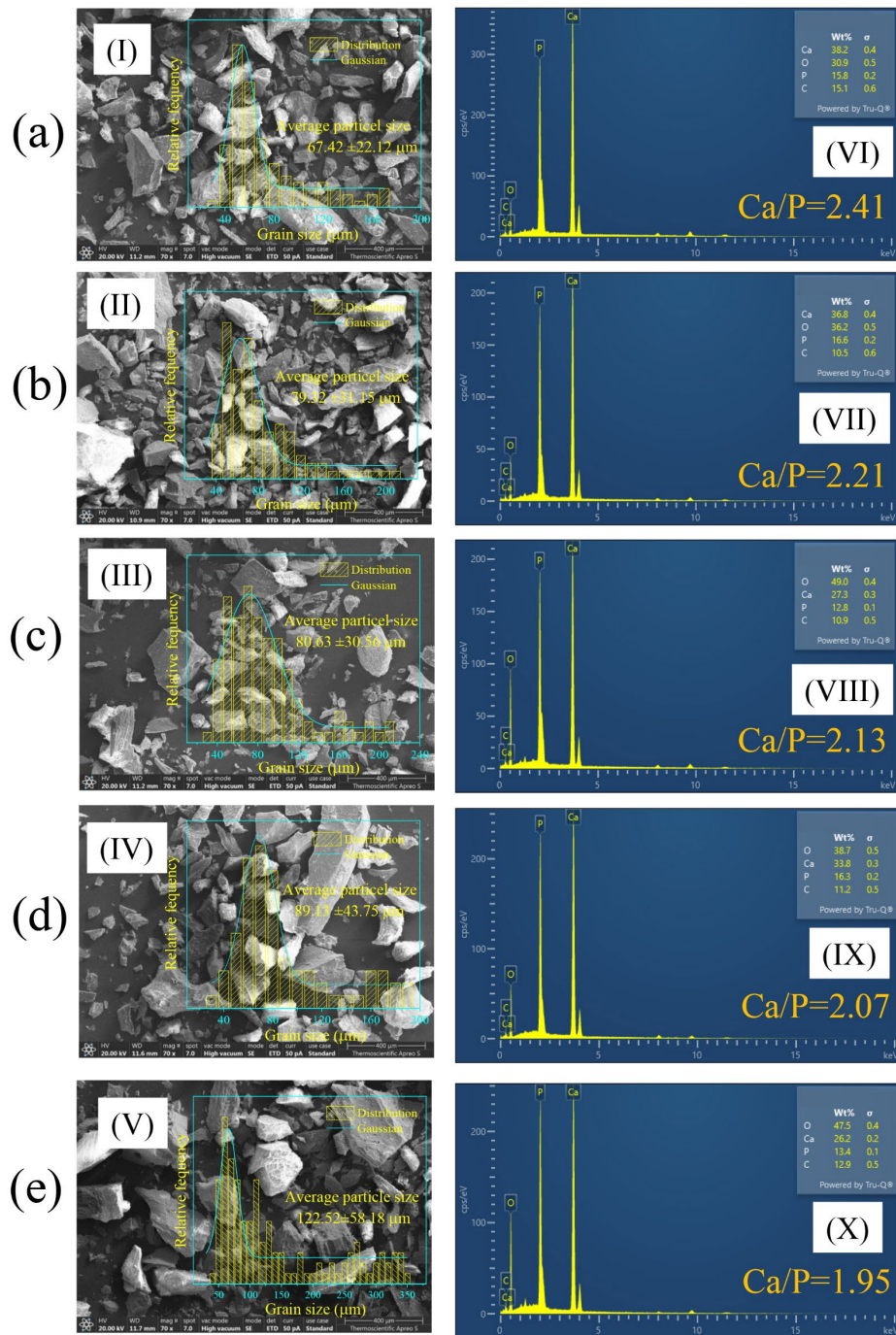
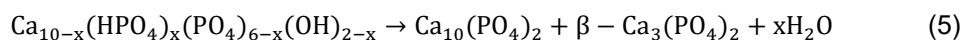


Figure 6. SEM images with the distribution and average grain size and EDS analysis of salmon bone powders calcined at (a) 600°C, (b) 700°C, (c) 800°C, (d) 900°C, and (e) 1000°C for 2 h

The elemental distribution and Ca/P ratios of the calcined samples were determined using EDS, as shown in Figures 5 (a)(VI)-(e)(X). The EDS results revealed high amounts of Ca, P, and O, with small amounts of C. The unspecified spectra is the Au electrode coating. The Ca/P chemical ratio decreased from 2.41 to 1.95 as the calcination temperature increased from 600 to 1000°C for 2 h, as seen in Figures 6 (a)(VI)-(e)(X). The Ca/P ratio in this study was higher than the previous stoichiometric value of HAp (1.67) (Afriani et al., 2020), likely due to HAp breaking down into β -TCP and other phases as the Ca component was lost during the calcination process, which was consistent with the reaction described by equation (5) (Kostov-Kytin et al. 2018). The EDS results corresponded with the XRD results, confirming the formation of the HAp and β -TCP phases. These phases were uniformly dispersed in the calcined samples, resulting in the production of the BCP compound.



Fourier transform infrared spectroscopy (FTIR) is crucial for the chemical characterization of predominant functional groups. This method is applicable for the chemical examination of BCP and other organic constituents. BCP consists of phosphate (PO_4^{3-}) hydroxyl (OH^-) and carbonate (CO_3^{2-}) groups which exhibit characteristic infrared (IR) vibrations in the range between 400 and 4000 cm^{-1} (Koutsopoulos et al., 2002). Generally, the PO_4^{3-} group exhibits characteristic IR absorption bands, with bending vibrations of P-O groups around 565-573 cm^{-1} and 602-603 cm^{-1} , and stretching vibrations at 960-962 cm^{-1} , 1040-1050 cm^{-1} , and 1089-1090 cm^{-1} . For the OH group, the stretching vibrations of O-H bonds produce characteristic IR peaks near 632-635 cm^{-1} and 3570-3572 cm^{-1} (Liou et al., 2004; Xu et al., 2004; Molskin et al., 2009). The CO_3^{2-} groups show characteristic stretching deformation bands of C=O bonds between 1400 and 1500 cm^{-1} and around 875 cm^{-1} , respectively (Truite et al., 2022).

In this work, the FT-IR results of samples calcined at various temperatures are shown in Figures 7 (a)-(e), and the frequency range of characteristic IR spectra in all samples are summarized in Table 3. It was observed that the FT-IR curve of all samples showed the PO_4^{3-} peak with bending bands in the range of 559-565 cm^{-1} and 598-600 cm^{-1} , respectively, as well as PO_4^{3-} bands with stretching vibrations in the range of 962-963 cm^{-1} , 1011-1030 cm^{-1} , and 1086-1087 cm^{-1} , as seen in Figures 7 (a)-(e) and Table 3. The OH⁻ peak with stretching vibrations in the range of 629-632 cm^{-1} and 3571-3573 cm^{-1} was seen in all samples (Figures 7 (a)-(e) and Table 3). The CO_3^{2-} peaks were observed around 879 cm^{-1} and 1457 cm^{-1} for the sample calcined at 600°C (Figure 7 (a) and Table 3), while the samples calcined at 700-1000°C, showed only the CO_3^{2-} peak at 1457 cm^{-1} (Figures 7 (b)-(e) and Table 3). The FT-IR results in this work confirmed that the samples had typical chemical groups of BCT, consistent with previous work (Koutsopoulos et al., 2002; Shi et al., 2018). Therefore, a BCP powder with an optimal HAp: β -TCP ratio of 60:40 can be synthesized from salmon bone using a simplified, low-cost technique with a calcination temperature of 800°C, with a calcination temperature lower than in previous studies (Larosi et al., 2009; Zhu et al., 2017).

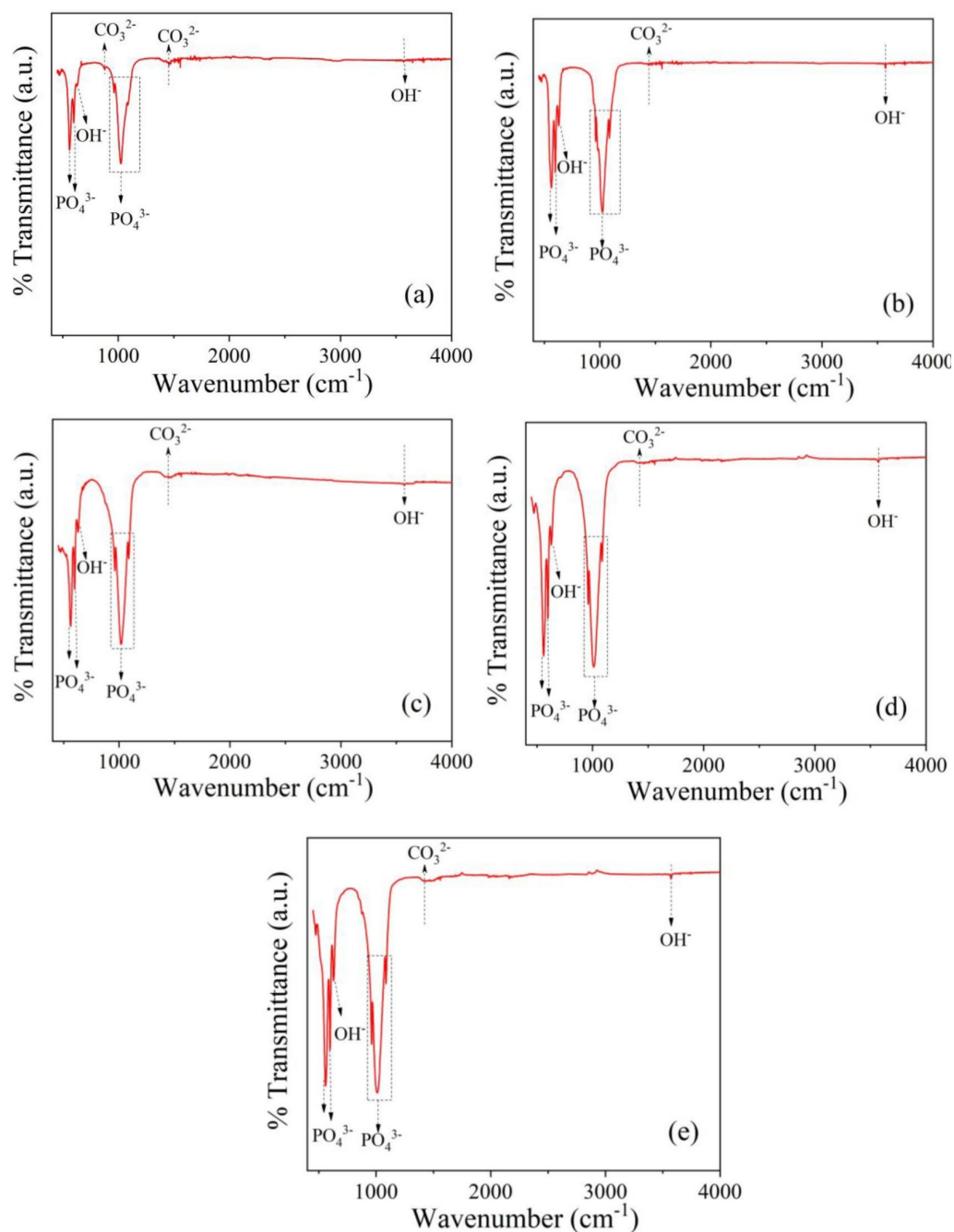


Figure 7. FT-IR spectra of calcined powders at temperatures of (a) 600°C, (b) 700°C, (c) 800°C, (d) 900°C, and (e) 1000°C for 2 h

Table 3. Characteristic IR peaks in the FT-IR spectra of calcined salmon bone powders at various temperatures

Calcination Temperatures (°C)	Characteristic IR Frequency Range (cm ⁻¹)			
	PO ₄ ³⁻	OH ⁻	PO ₄ ³⁻	CO ₃ ²⁻
600	562, 600	630, 3571	962, 1024, 1087	879, 1457
700	563, 599	630, 3573	963, 1024, 1087	1457
800	565, 600	632, 3571	963, 1030, 1087	1457
900	560, 599	630, 3571	962, 1011, 1086	1457
1000	559, 598	629, 3572	962, 1011, 1086	1437

4. Conclusions

BCP powder was successfully synthesized from raw salmon bone using a simplified and low-cost technique. The effects of calcination temperature on the phase structure, microstructure, and chemical composition of the samples were studied. Samples calcined at temperatures above 600°C exhibited mixed HAp and β -TCP phases. As the calcination temperature increased, the phase proportions of HAp and β -TCP, as well as the Ca/P ratios, were influenced by the decomposition of the Ca component during the calcination process. The FTIR spectra in all samples confirmed the formation of phosphate (PO₄³⁻) hydroxyl (OH⁻) and carbonate (CO₃²⁻), which are characteristic of the BCP structure. The sample calcined at 800°C was identified as the most suitable BCP compound due to its nearly equal phase ratio of HAp to β -TCP (60/40). These findings suggest that the BCP synthesized in this study holds promise as a biomaterial for bone replacement applications in the future. However, the synthesized crystalline powder needs to be further studied in depth, for biocompatibility and mechanical properties.

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6. Authors' Contributions

Pensri Pramukkul: Methodology, Validation, Formal analysis, Writing - Original draft, and Writing- Review & Editing. Surirat Yotthuan: Investigation, Resources. Aurawan Rittidech: Investigation, Resources. Tawat Suriwong: Investigation, Resources. Theerachai Bongkarn: Writing - Original Draft and Writing - Review & Editing. Chittakorn Kornphom: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft and Writing - Review & Editing.

7. Conflicts of Interest

The authors and the institutes where the work has been carried out declare that there are no conflicts of interest regarding the publication of this article.

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