Synthesis and characterization of fluoridated hydroxyapatite nano-powder via microwave irradiation method

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Abstract. Fluoridated hydroxyapatite (FHA) occur in teeth and form the basis for application as a biomaterial. This work aims to synthesize and analyze the characteristic of FHA nano-powder with different degrees of fluoridation via microwave irradiation method. FHA nano-powder with a chemical formula of Ca_{10}(PO_4)_6(OH_{2-x})F_x (where degrees of fluoridation, x values were selected equal to 0.7 and 1.3) were synthesized using a mixture of calcium hydroxide, diammonium hydrogen phosphate, and ammonium fluoride solutions by utilizing microwave with the variation of irradiation power. X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), and energy dispersive X-ray (EDX) spectroscopy analysis techniques were utilized in order to evaluate the characteristic of synthesized FHA nano-powder. The XRD and FTIR results confirmed highly crystalline FHA powder with the carbonate peaks in the IR spectrum. Using a Scherrer formula, the average crystallite size was found to be 30 nm. The SEM and EDX results indicated various element composition and several morphologies with the lattice parameter increased along with irradiation power. FHA nano-powder could be synthesized via microwave irradiation method. The results from different kind of analysis illustrated that synthesized FHA nano-powder could fulfill the requirement of ASTM F1185-88 for used as biomaterial.

Keywords: Fluor, Hydroxyapatite, Biomaterial, Microwave Irradiation

1. Introduction

Dental caries occurs because of the demineralization process in the structure of the outer layer or tooth enamel. Damaged tooth enamel is difficult to repair (remineralization) due to it is not a living tissue or cell. Therefore, a substitute (synthetic) material that can bind directly (biocompatible) with tissue on tooth enamel is needed [1].

Tooth enamel is composed of biological apatite (97 wt%), along with water (2 wt%) and organic matter (1 wt%) [1]. Although the content of apatite in tooth enamel is mostly hydroxyapatite, biological apatite on tooth enamel always contains fluorine (F), in the form of fluoridated hydroxyapatite (FHA: Ca_{10}(PO_4)_6(OH_{2-x})F_x; where x is a degree of fluoridation). The degree of fluoridation (x) is the quantity parameter of the hydroxyl group (OH ions) substituted by the F ions. The presence of fluorine can increase resistance to the effects of acid, the degree of crystallinity and biocompatibility [1,2] so that FHA has the potential to be a material for tooth enamel restoration.

Synthetic FHA has been successfully made by precipitation method [3]. The precipitation method can produce large amounts of FHA crystals with simple treatment. However, the precipitation method requires a relatively long crystal nucleation and growth time of around 24 hours [3]. In this study, the
microwave irradiation method will be carried out, which uses a microwave to accelerate the nucleation and growth of FHA crystals with enhancement in the product purity and yields [4,5]. The optimal use of microwave irradiation power can save the energy consumption required and will increase the efficiency of this method.

2. Materials and methods

2.1. Synthesis of FHA nano-powder
Calcium hydroxide (Ca(OH)2 Merck KgaA Company Inc.), diammonium hydrogen phosphate ((NH4)2HPO4 Merck KgaA Company Inc.), and ammonium fluoride (NH4F Merck KgaA Company Inc.) were used as the starting materials. Mixing has been done by slowly adding F and PO4 solutions together into Ca suspension under vigorous stirring with a droplet rate of 5 mL/min. The designed Ca/P ratio approximately 1.67 with the degree of fluoridation (x) were selected equal to 0.7 and 1.3. These x values correspond to 35 and 65% fluorine ions (F-) substitution into hydroxyl (OH-) groups.

The mixture was irradiated with microwave (Sharp, R-728(W)-IN, 900 W) using the power of 450, 540, 630, and 720 watts for 15 minutes. As a preference, others mixture have been made without microwave irradiation or precipitate (aging) for 24 hours under room temperature. The semi-dry precipitate was washed with distilled water and filtered using a filter paper (Whatman No. 42, Fisher Scientific, USA). To ensure there is no water content, the filtrate was dried with an oven at 80°C. The dry precipitate was then ground into fine powder using mortar and pestle with mesh #100 filter powder for further characterization and evaluation.

2.2. Characterization
The powders were characterized using several analysis techniques. The crystal phase analysis was carried out by X-ray diffractometer (XRD, Panalytical X’Pert Pro MPD) using 0.02 mm Ni filtered with monochromated Cu Ka (λCuKa = 1.540598 Å, setting the radiation at 40 kV and 30 mA). Particles were examined over the 2θ range of 20-60° with the rate of step 0.4°/s. The obtained XRD patterns were compared to standards compiled by the International Center for Diffraction Data (ICDD) which involved Powder Diffraction File (PDF) No. #09-0432 for HA and #15-0876 for FHA. A Scherrer formula [6] was used to determine the crystallite size (L) of powders. Measurement of L for each powder involve (002) Miller’s plane. The crystallinity index (CI) of the as prepared powders were evaluated [7] at (002) plane along the c-axis.

Fourier transform infrared spectroscopy (FTIR, Bruker Tensor 37) was applied for functional groups analysis of powders in the range of 400-4000 cm⁻¹ or middle IR-spectrum with the resolution of 4 cm⁻¹. The splitting factor (SF) of the powder has been evaluated [8] on the phosphate functional group (PO4) for the 4th vibration mode (νd).

The morphology and element composition of powders were investigated by scanning electron microscopy (SEM, FEI inspect F10) coupled with energy dispersive X-ray (EDX, EDAX Apollo X) spectroscopy.

3. Results and discussion

3.1. Mass efficiency and X-ray diffraction
The total mass formed through microwave irradiation method tends to be much more than by aging for both x values as shown in Figure 1. This implies that microwave significantly enhances crystal formation and product yields by minimizing time consumption [5]. Increased fluorine levels show a slight increase in the amount of apatite mass, which is likely caused by differences in the saturation level of the initial solutions [9].

The XRD patterns of the as synthesized powders are shown in Figure 2. The patterns were matches with ICDD PDF No. #15-0876 data indicating that the as synthesized particles were FHA (Hexagonal, space group of P 63/m, 176). The broad peaks and no additional phases were visible indicates that microwave can be used to synthesize nano-sized FHA with high purity levels [10]. The results of
lattice parameters, crystallite size, and crystallinity index of obtained FHA powder with the variation of microwave power that were calculated using XRD data are shown in Table 1.

Increased microwave power tends to extend the $a$-axis but reduce the $c$-axis of FHA lattice, which corresponds to a slight shift of the diffraction patterns in Figure 2. As the microwave power increased, more compact crystals are formed with the lattice stretches towards the $a$-axis due to compressive stress along the $c$-axis. Decreased $a$-axis as a result of increasing fluorine content was also reported by other studies [2,11]. This downward occurs because the size of the F ion is smaller than OH ion, which is 1.28 Å compared to 1.37 Å [1,2], thus forming a compact apatite structure. The length of $c$, which remains constant with increasing $x$ content proves that most of the fluorine ions in the initial mixture enter into the crystal lattice [11].

The XRD patterns for aging revealed weak reflections of (002) and (300) planes. However, when the synthesis is carried out by microwave irradiation from 450 W to 720 W the intensity and sharpness of the peaks increased, significantly. This confirms the increase in crystallite size and the crystallinity index which is in line with irradiation power. The addition of microwave power up to 720 W for $x$ values 1.3 can produce FHA crystal which has the crystallinity index similar to tooth enamel, within range 0.80 to 1.21 as reported by others [12,13].

![Figure 1](image1.png)

**Figure 1.** The total mass of obtained FHA for Aging, 450 W, 540 W, 630 W, and 720 W with $x$ values 0.7 and 1.3 at $t = 15$ minutes.

![Figure 2](image2.png)

**Figure 2.** XRD patterns of obtained FHA for Aging, 450 W, 540 W, 630 W, and 720 W with $x$ values 0.7 and 1.3 at $t = 15$ minutes.
Table 1. Calculated lattice parameters, crystallite size \((L)\) and crystallinity index \((CI)\) of obtained FHA for Aging, 450 W, 540 W, 630 W, and 720 W with \(x\) values 0.7 and 1.3 at \(t = 15\) minutes.

| Microwave Power | \(a = b\) (Å) | \(c\) (Å) | \(L\) (nm) | \(CI\) | \(a = b\) (Å) | \(c\) (Å) | \(L\) (nm) | \(CI\) |
|----------------|----------------|--------|---------|-------|----------------|--------|---------|-------|
| Aging          | 9.391          | 6.859  | 23.16   | 0.32  | 9.382          | 6.859  | 25.70   | 0.43  |
| 450 W          | 9.388          | 6.858  | 24.99   | 0.40  | 9.379          | 6.858  | 26.11   | 0.45  |
| 540 W          | 9.389          | 6.856  | 26.38   | 0.47  | 9.380          | 6.856  | 27.54   | 0.48  |
| 630 W          | 9.390          | 6.854  | 29.52   | 0.66  | 9.381          | 6.854  | 31.26   | 0.78  |
| 720 W          | 9.391          | 6.852  | 29.85   | 0.68  | 9.382          | 6.852  | 31.70   | 0.81  |

The increase in crystallite size and crystallinity index were associated with the microwave irradiation energy transferred to the reacting molecules within \(10^{-9}\) s, which is faster than the molecules can relax around \(10^{-5}\) s. This results in non-equilibrium condition and high instantaneous temperatures that affect the kinetics of the system, such as motion and collisions between molecules [5]. As the microwave power increases, the temperature in the system rises progressively faster and higher resulting in rapid acceleration of atomic motion and reduction in viscosity of the solvent [5,14]. This triggers a diffusion barrier to decrease, resulting in atoms easily filling the lattice with increasing polarization and aggregation of the apatite nuclei to form larger crystallites with enhanced crystallinity [14]. Increased fluorine levels tend to increase the number of molecules or nuclei present which enhance the driving force and multiply the collisions occurred, thus increasing the temperature in the system followed by the greater crystallites size and crystallinity [9].

3.2. Fourier transform-IR
The FTIR spectrum of the FHA powders with \(x\) value 1.3 is shown in Figure 3. The structure of apatite indicates \(\sim 472, \sim 563, \sim 604, \sim 962,\) and \(\sim 1032, \sim 1092\) cm\(^{-1}\) vibration modes [4,10] for the PO\(_4\) group. A broad peak \(\sim 2600-3800\) cm\(^{-1}\) related to the hydroxyl group. The vibration of adsorbed water in apatite lattice appears at \(\sim 3422\) cm\(^{-1}\) [2]. The band \(\sim 3542\) cm\(^{-1}\) for OH stretching and no peak assigned in \(\sim 630\) cm\(^{-1}\) for OH librational (Ca\(_3\)-OH) clearly show the OH–F interaction, which indicates substitution F ions instead of OH ions into the apatite structure [10,15].

Figure 3. The FTIR spectrum of obtained FHA for Aging, 450 W and 720 W with \(x\) value 1.3 at \(t = 15\) minutes.
The weak band in ~873 cm$^{-1}$ illustrates there was a small formation between C–O related to the adsorbed surface carbonate ions [16]. The decrease of adsorbed carbonate peaks on the apatite surface with irradiation power 720 W could be evidence of pure apatite phase. As the microwave power increase up to 720 W, the IR spectrum for OH$^-$ stretching bands shifted and the structural OH$^-$ disappeared, significantly. This caused by a distortion process to adjust the fluorine ions into the lattice, mainly to stabilize the crystal structure. The evaporation of water molecules in apatite is driven by an increase of irradiation power. This makes the crystal more compact so that the crystallinity increases, which can be estimated by increasing the SF value to the addition of microwave irradiation power (Figure 4.).

3.3. SEM and EDX
The morphology of FHA ($x = 1.3$) for 720 W with different magnifications are shown in Figure 5. The rod-like particles formed with the calculated mean particle size around 67 nm. According to the SEM image at higher magnification, the particle tends to not agglomerate between adjacent particles. During the formation process of apatite, the particles mostly stick together (agglomerate). However, increasing the microwave power up to 720 W causes a decrease in particle agglomeration rate followed by an increase in the rate of fragmentation. Furthermore, the steady-state conditions would occur with the morphology and average particle size of FHA powder remain constant.

Figure 4. The $SF$ of obtained FHA for Aging, 450 W and 720 W with $x$ value 1.3 at $t = 15$ minutes.

Figure 5. The SEM images with magnifications (a) 50 kX and (b) 200 kX of obtained FHA for 720 W with $x$ value 1.3 at $t = 15$ minutes.
Figure 6. The EDX spectrum of obtained FHA for 720 W with x value 1.3 at t = 15 minutes

The EDX spectrum (Figure 6.) illustrates that elements of Ca, P, O, and F are present in FHA powder with a power of 720 W. The calculated Ca/P ratio was 1.64 with the concentration of fluorine ion approximately 2.43 wt%. This suggests that FHA powder obtained is less soluble and may be suitable for application to tooth enamel, which is in an environment with instant acidity changes.

4. Conclusions
Fluoridated hydroxyapatite (FHA) nano-powder with x values 0.7 and 1.3 were successfully synthesized via microwave irradiation method. The X-ray diffraction result combined with FTIR indicates that a single phase of well crystalline FHA with low surface carbonate peaks can be obtained after the mixture is irradiated by microwaves with the power of 720 W. The presence of large amounts of fluorine ions results in an increase of driving force for nucleation and crystal growth during the reaction time. The FHA formed by this method consists of 30–89 nm rod particles with Ca/P ratio around 1.64 and could fulfill the requirement of ASTM F1185–88 for used as biomaterial.

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