Volume 34, Issue 8 – December

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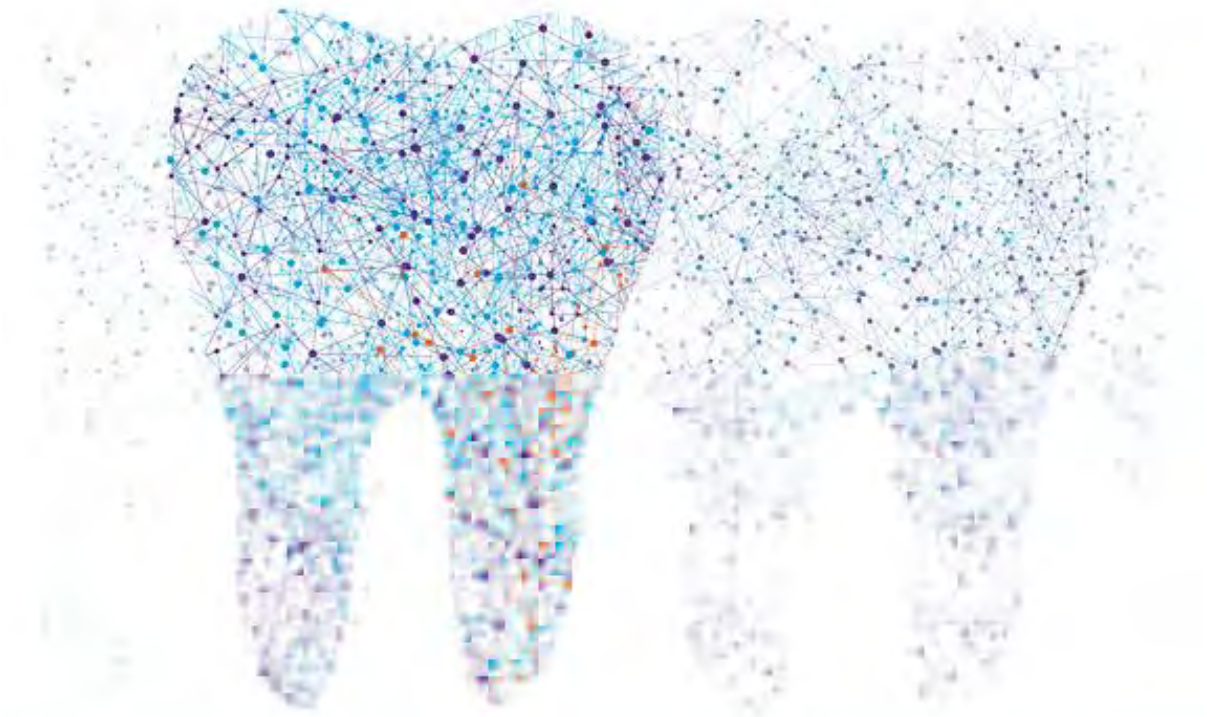

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ORIGINAL ARTICLE

The potential of eggshell hydroxyapatite, collagen, and EGCG (HAp-Col-EGCG) scaffold as a pulp regeneration material

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Received 24 June 2022; revised 23 October 2022; accepted 26 October 2022
Available online 1 November 2022

KEYWORDS

Characterization;
Hydrogel scaffold;
HAp-Col-EGCG;
Pulp regeneration material

Abstract *Background:* Hydrogel scaffold is a biomaterial that can facilitate cells in forming a tissue structure. It can promote cell adhesion, migration, and proliferation. Further research to find a new scaffold from natural resources is challenging, so this study aimed to characterize a hydrogel composite scaffold, which has the potential to be used as a regenerative material.

Methods: The formulation of HAp-Col-EGCG was mixed with different ratios of 1%, 2%, and 4% hydroxyapatite. We analyzed its injectability, pH, and gelation time. Scanning electron microscopy (SEM), energy X-ray Spectroscopy (EDX), and Fourier-transform infrared spectroscopy (FTIR) were used to evaluate the surface morphologies, element composition, and chemical properties of HAp-Col-EGCG.

Results: The results showed that the injectability test was almost 90 % in all groups. There was no significant difference in the median value of the pH at 0, 20, and 60 min in all groups, but there was a significant difference at 40 min. The average gelation times in all groups were not significant. SEM-EDX showed a microporous scaffold, with the HAp particles well distributed in the collagen pores at a ratio of 1.9, 2.29, and 1.89 Ca/P. The FTIR results showed intermolecular bonds in the

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https://doi.org/10.1016/j.sdentj.2022.10.004

HAp-Col-EGCG scaffold. The X-ray diffraction analysis showed that collagen and EGCG did not affect the crystal structure and size of HAp. Cytotoxicity test showed more dental pulp cell viability at the 4 % HAp concentration at 514.35 ± 15.45.

Conclusion: This study indicates that hydrogel scaffold from eggshell hydroxyapatite, collagen, and EGCG has a high potential for pulp regenerative therapy.

1. Introduction

Nowadays, regenerative treatment approaches in developing pulp dentin complex repair involve using mesenchymal stem cells, growth factors, and a scaffold (Khurshid et al., 2022; Paduano et al., 2016). The scaffold can provide a framework for the cell homing process. It should be biocompatible, simple application in the dentin, injectable, non-toxic, biodegradable, and solidified at 37 °C. Based on several criteria, a hydrogel scaffold can be considered to develop (Abbass et al., 2020; Chang et al., 2017; Raucci et al., 2018). Scaffolds from natural sources can be obtained from eggshell hydroxyapatite, bovine collagen type I with epigallocatechin-3-gallate modification. Hydroxyapatite is a material with a similar composition to bone and teeth, and eggshell is a popular one (Ahmadian et al., 2019; Elline and Ismiyatin, 2021; Khandelwal and Prakash, 2016). An eggshell nanohydroxyapatite scaffold has interconnected pores, contains high levels of calcium carbonate that induces the differentiation of dental pulp cells (Afriani, 2015; Okamoto et al., 2020; Sancilio et al., 2018).

Collagen is a material that can penetrate intermolecularly and forms a gel, so it is suitable for use in rigid dentin composition (Kwon et al., 2017). Hydroxyapatite and collagen are humans' leading natural components of tissues and proteins and can be synthesized using the sol–gel method (Sathiyavimal et al., 2020; Yu et al., 2020). Nanohydroxyapatite can be distributed between collagen fibers, and EGCG addition can create a smooth surface, stimulating bone regeneration (Permatasari and Yusuf, 2019). Crosslinked EGCG has been beneficial as an anti-inflammation agent (Kwon et al., 2017). In this research, a hydrogel scaffold was formulated from eggshell hydroxyapatite, collagen, and EGCG to benefit each material (HAp-Col-EGCG). This study aimed to prove that HAp-Col-EGCG composite has the potential to be used as a scaffold for pulp regeneration material.

2. Materials and methods

2.1. Fabrication of HAp-Col-EGCG hydrogel

The preparation of the material was done using eggshell nanohydroxyapatite (Pertiwi Technology, Bogor, Indonesia), 5 mg/mL collagen I bovine (Gibco, Thermofisher Scientific, USA), and EGCG (Sigma Aldrich, E4268, ≥80 %, USA). Hydroxyapatite was dissolved in deionized water at a concentration of 1 %, 2 %, and 4 % and stirred for one h at 350 rpm (Permatasari and Yusuf, 2019). Then, ten µmol/L of EGCG was added to the hydroxyapatite solution and stirred until homogenous at a cold temperature (Kwon et al., 2017). 3 mg/mL collagen solution was prepared by adding phosphate-buffered saline (Gibco, Thermofisher Scientific, USA), sodium hydroxide, and distilled water (Merck Millipore Mili-Q) (Gibco, Thermofisher, 2014). The collagen solution was mixed with hydroxyapatite and the EGCG solution at a cold temperature for 30 min. After that, 2 % hydroxypropyl methylcellulose (HPMC) (Benecel, K100M, Ashland, Wilmington, USA) was added until homogenous and colloidal at room temperature. The mixing process was performed at Biocore laboratory (Universitas Trisakti,Indonesia) and several characterization were obtained from LIPI Fisika (Serpong, Tangerang, Indonesia).

2.2. Injectability test

The characteristic of the flow was determined through a 10 cc, 21G syringe (Terumo Corporation, Tokyo, Japan) with 64.1 N maximal force (1 ml/10 s) (Gutierrez and Munakomi, 2022; Sharma et al., 2016). The mass before injection and mass extruded from the syringe were weighed. The percentage of injectability was using the following formula: % injectability = (*mass extruded from the syringe*/*total mass before injection*)- × 100 %, and the procedure was repeated three times (Hikmawati et al., 2019; Takallu et al., 2019).

2.3. Gelation time and pH

Gelation time was measured by the inverted tube method (De Mori et al., 2019). The process was determined by the color changes to an opaque color. The optimal gelation time is 5 to 30 min, providing enough time for application with a stable gel formulation (Bendtsen and Wei, 2017). Three replications were done to get the average value. The pH value was measured using a pH-meter (PHS- 3E, INESA Instrument, Shanghai, China) and repeated three times for 1 h; right after mixing, 20, 40, and 60 min at room temperature (Yan et al., 2016).

2.4. Microporosity of HAp-Col-EGCG hydrogel scaffold

The morphology of the HAp-Col-EGCG scaffold was analyzed using SEM-EDX (Hitachi S4700, Tokyo, Japan). Before the SEM imaging, HAp-Col-EGCG hydrogels were freeze-dried at − 80 °C for 24 h. The freeze-dried samples were coated with an Au layer, and we measured the largest and smallest pore diameters (Mulyawan et al., 2022; Podhorská et al., 2020).

2.5. Fourier-transform infrared spectroscopy (FT-IR)

The functional group of the HAp-Col-EGCG formulation was analyzed using FTIR (Thermo Fisher Scientific Nicolet iS-10, USA). Samples of HAp-Col-EGCG with 1 %, 2 %, and 4 %

HAp were investigated at the 400–4,000 cm^{-1} wavenumber range (Mulyawan et al., 2022).

2.6. X-ray diffraction (XRD) analysis

The XRD pattern was analyzed by XRD (Smartlab Rigaku, Tokyo, Japan) using copper (Cu) as the X-ray source, with a voltage of 40 kV and current of 40 mA, at a range of 2θ from 10° to 90° scan rate of 5° min^{-1}. It can determine the microstructure characteristics such as compound phase composition and crystallinity using the Bragg–Bentano scan method.

2.7. Cytotoxicity test

Human dental pulp stem cells (hDPSCs) obtained from PT Prodia Stem Cell, Indonesia. Cytotoxicity test of was done by the 3-(4,5- dimethyl-2-thiazolyl)-2.5-diphenyl-2H-tetrazo lium bromide (MTT) assay. The cell viability information was known by the change of formazan salt due to mitochondrial activation of living cells. An enzyme-linked immunosorbent assay reader was to analyze the optical density of the formazan salt. The percentage of cell viability formula using a relative optical density. The material of the samples is not toxic if the cell viability is > 50 % (ISO 10993–5) (Hikmawati et al., 2019; Srisomboon et al., 2022).

$$Relative\ OD = \frac{OD\ of\ test\ group}{OD\ of\ control} \times 100$$

2.8. Statistical analysis

Shapiro–Wilk normality test was carried out on all data obtained. If the data was normal, one-way analysis of variance (ANOVA) was used. Otherwise, the data was analyzed using Kruskal–Wallis. Data are described as the mean and standard deviation value or its median at $P < 0.05$. Statistics were performed using SPSS 25 (SPSS Inc, Chicago, IL, USA).

3. Results

3.1. Injectability test

According to the injectability test, samples with 1 %, 2 %, and 4 % HAp can be injected (Fig. 1 and Table 1). One-way ANOVA showed no significant difference between all groups ($P > 0.05$).

3.2. Gelation time test

The average gelation time was shown in Fig. 2 and Table 1. Fig. 2 A,B show the HAp-Col-EGCG before and after the gelation process. All samples fulfilled the criteria that should be 5 – 30 min.[23] The concentration of 1 %, 2 %, and 4 % HAp showed no significant difference in gelation time ($P > 0.05$).

3.3. pH value

Data were not normally distributed. The results showed significant differences in the pH value at 0, 20, and 60 min

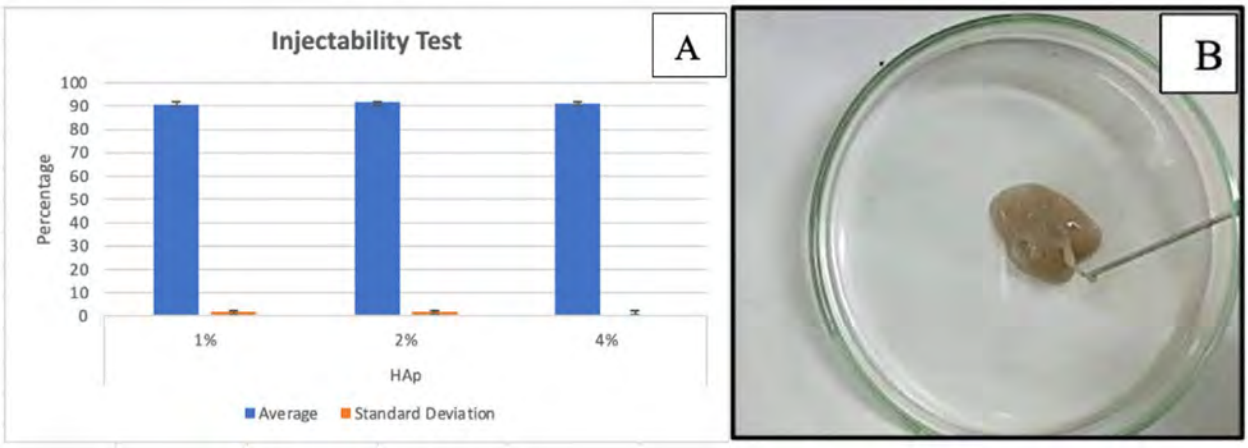

Fig. 1 Graph the injectability test results of HAp-Col-EGCG (A) and injected through the 21-G syringe (B).

Table 1 The statistical result of scaffolds' injectability test and gelation times.

	Mean ± SD			p
Scaffold HAp-Col-EGCG	1 %	2 %	4 %	
Injectibility (%)	90.4 ± 1.93	92.13 ± 1.97	91.06 ± 0.75	0.477
Gelation times (s)	326 ± 23.3	366 ± 9.16	342.33 ± 12.5	0.06

*One-way ANOVA ($p > 0.05$).

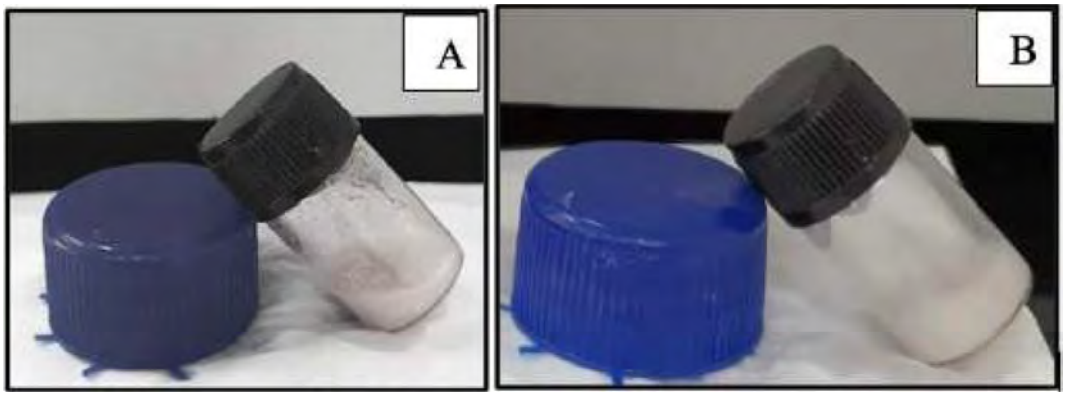

Fig. 2 HAp-Col-EGCG formulation before (A) and after (B) gelation.

Table 2 Comparison of the pH scaffold formulation at different times.

pH				
	Time			
Scaffold	0	20	40	60
	Med (min- max)	Med (min- max)	Med (min- max)	Med (min- max)
1:1	7.98 (7.75– 8.11)	7.82 (7.82– 8.12)	7.98 (7.81–8.11)	8.12 (7.82–8.12)
1:2	7.34 (7.32–7.45)	7.32 (7.32–7.51)	7.98 (7.98–8.11)	8.46 (8.3–8.63)
1:4	9.18 (9.17–9.19)	9.26 (9.26–9.28)	9.26 (9.22–9.35)	9.31 (9.3–9.34)
p	0.027*	0.025*	0.057	0.027*

*Friedmann ($P < 0.05$); *Kruskal–Wallis ($P < 0.05$).

($P < 0.05$). This result showed that pH values are higher at a higher HAp concentration (Table 2).

3.4. Functional group test (FTIR)

The FTIR result showed in Fig. 3. The hydroxyl group in HAp were seen at 3,416.1 cm^{-1} to 3,431.49 cm^{-1}, respectively, which are related to O—H stretching and confirmed the presence of hydrogen bond in Hap (Fern and Salimi, 2021). The major PO_4 groups peaks were obtained at 1022–1023 cm^{-1}, due to asymmetric stretching of the phosphate group. The HAp functional groups were OH^- and PO_4^{3-}, so they were identified as Hap (Fern and Salimi, 2021; Rogina et al., 2019; Siswanto et al., 2020).

The amide I and EGCG were identified, by a wavenumber at 1,651.94 cm^{-1} to 1,653.44 cm^{-1}, with medium N—H bending and strong stretching of C=O.[29] Amide II was found at 1,560.71 cm^{-1} to 1,561.20 cm^{-1} wavenumbers. In amide III, peak absorbance was shown with medium C—N stretching at 1,022.20 cm^{-1} to 1,198.98 cm^{-1}(Vishwakarma et al., 2015). The absorbance at 2,929.38 and 2,927.94 were the stretching of C–CH3, which is specific to the HPMC functional group (Fig. 3) (Hikmawati et al., 2019).

3.5. Xrd analysis

The XRD pattern in all the sample groups showed an identical pattern. The 2θ, characterization with angles of 31.48°, 31.65°, and 31.73°, respectively. It could be concluded that collagen and EGCG did not affect the crystal structure of HAp.

All samples formed a hexagonal crystal structure, but there were difference in crystal size value, 11.4745 nm (1 % HAp), 19.8254 nm (2 % HAp), and 18.1769 nm (4 % HAp). The 1 % HAp concentration resulted in a smaller crystal size and the larger crystal size was found in 2 % HAp concentration.

3.6. Microporosity and EDS analysis of Hap-Col-EGCG hydrogel scaffold

Data were not normal distributed, and they showed no significant difference in the scaffold pore diameter in all samples ($P > 0.05$). The diameter porous (μm) data were performed in median (min–max) value; 21.1 (7.84–44.61) (1 % HAp); 27.19 (8.11–76.71) (2 %HAp); 21.55 (4.96–132.17) (4 % HAp) ($p > 0.05$). The pores in these concentrations could support cell attachment, growth, and proliferation and have the potential for dentin pulp regeneration treatment (Panseri et al., 2016; Vishwakarma et al., 2015). Agglomerated HAp was also dispersed in the porous collagen (Fig. 4.A–C).

EDS analysis of the Ca, P, and O composition proved HAp presence. It showed a homogenous distribution of elements in the synthesis. The Ca/P ratio of 1.9, 2.29, and 1.89. The value of Ca/P approaching the natural extracellular matrix from the mineral phase is 1.67 (EzEldeen et al., 2021). All Ca/P ratios of the samples were above the stochiometric value (1.67); thus, the synthesis of the scaffold modified the ratio of Ca/P from

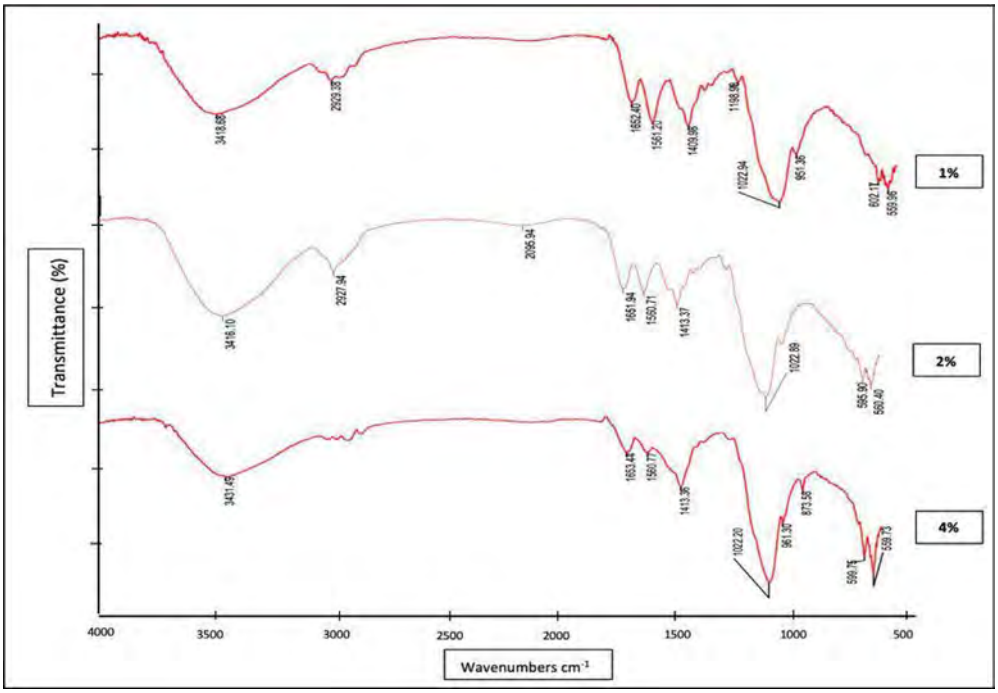

Fig. 3 Spectra of the HAp-Col-EGCG, with three variations in HAp concentration.

Fig. 4 HAp-Col-EGCG scaffold with 1% (A), 2% (B), and 4% (C) showed interconnected pores and agglomerated HAp dispersed in a the scaffold.

stochiometric. The HAp-Col-EGCG scaffold with 4 % HAp was closest to 1.67.

3.7. Cytotoxicity test

This test was performed for 24 h, and it proved that the HAp-Col-EGCG scaffold was non-toxic because the viability of the cells was above 50 %. The results were 158.388 ± 10.484 (1 % HAp); 240.638 ± 10.469 (2 % HAp); 330.016 ± 14.963 (4 % HAp). It showed significant differences in the dental pulp cell viability for each group of scaffolds ($P < 0.05$).

4. Discussion

The results of this study showed that HAp-Col-EGCG can be formed into a hydrogel scaffold. An injectable form hydrogel can improve the biological stability of the biomaterial and is affected by the sample's syringe diameter, viscosity, and solvent (Ren et al., 2018). Suspension agent (2 % HPMC) can increase the viscosity and stability of the formula (Charlena et al., 2020). HPMC does not affect the chemical analysis and biological reaction (Ciolacu et al., 2020; Ghadermazi et al., 2019). Injectable application in the dental pulp region is essential because the dental pulp is in a rigid and limited area Hikmawati et al., 2019).

The inverted test tube method was used to perform a gelation time test of the HAp-Col- EGCG scaffold at 37 °C. Too fast gelation would not make enough time for clinical application, whereas slow gelation time would make it difficult to target the application area (Ren et al., 2018). The recommended gelation time is 5 to 30 min, and all group samples had an ideal gelation time.

The latest literature has reported that the initial pH is crucial in determining the morphology and size of the formulation structure, whether sphere, roller, needle, etc. The pH can indi-

cate supersaturation that can influence the ion balance. If there are increases or decreases in the OH^- composition, these will affect and modify the concentrations of Ca^{2+}, $PO4^{3-}$, and $(HPO4)^{2-}$ ions. The agglomerate nanoparticles in the SEM analysis decreased particle size when the pH value decreased (López-Ortiz et al., 2020). In the present study, the pH value had a hexagonal phase, with a stable pH value in each group.

According to Okamoto et al. (2020), cell death was found in DPC cultures at a pH of 3.5 to 5.5. It showed cell growth or arrest at a pH of 6.5 to 7.5 and showed mild proliferation at a pH of 9.5 (Hirose et al., 2016). In this study, the HAp-Col-EGCG scaffold with 4 % HAp had a pH value approaching 9.5. It can be used to support regeneration in the inflamed pulp (Hirose et al., 2016).

The FTIR results identified that the functional group indicates O—H stretching, which confirmed eggshell HAp, EGCG, and HPMC, similar to the results of Rogina et al., that indicated hydrogel composite at 3,150–3,600 cm^{-1} wavenumbers (Rogina et al., 2019). The evidence of strong PO_4^{3-} groups which confirmed HAp was 1040 cm^{-1} and 1090 cm^{-1} (Hooi et al., 2021) but following the study of Siswanto et al. (2020), $PO4^{3-}$ was also identified the bending of PO_4^{3-} at 500 cm^{-1} to 630 cm^{-1} that also proved of HAp existance, it supports this study that had phosphate bending at 559.96 $cm^{-1}$to 602.17 cm^{-1}.

In this study, the amide I, II, and III peaks were stable for all samples, indicating that the triple helix structure of collagen is still intact and maintained with the addition of EGCG or Hap (Permatasari and Yusuf, 2019). Similar to Hikmawati et al. (2019), HPMC-specific group function was also identified, indicating that HPMC also formed a hydrogen bond.

The possible HAp-Col-EGCG bond is a hydrogen bond which take place between a collagen hydrogen atom and oxygen in HAp. It creates mineralized collagen between collagen structure and the crystal in HAp,which showed from C═O band (Siswanto et al., 2020). Another study also discovered that the bonding mechanism started with Ca^{2+} ions from HAp interacting with amide I (NH2) in collagen (Susanto et al., 2019).

The crystal structure of HAp did not change because of collagen and EGCG addition. A hexagonal structure with the *P*63/*m* space group is still formed. The 1 %, 2 %, and 4 % HAp crystal size result supports previous studies that crystal length and width averages of 21 ± 9 nm and 6 ± 1.5 nm. The main peak of HAp in HAp-Col-EGCG formulation was identified at a range that is similar to a previous study which identified HAp at 2θ of 31.7°, 32.2°, and 32.9° (In et al., 2020). The XRD result showed that the number of crystal sizes would decrease when the pH value is low (López-Ortiz et al., 2020). It was found that the particle size increases when the pH value increases from 6 to 13 (Chithra et al., 2015).

In this study, the nanoparticle crystal size was also larger when the scaffold pH value increased in 4 % HAp. Increasing H^+ can create the favorable formation of monoclinic HAp. Decreasing the OH^- concentration can cause solution saturation reduction, so when the pH decreases, the nucleation and growth of crystals reduce (López-Ortiz et al., 2020).

The median diameter pore of HAp-Col-EGCG scaffold from all groups could support cell attachment, growth, and proliferation. All Ca/P ratio of the samples was above the stochiometric (1.67), and the HAp-Col-EGCG scaffold with 4 % HAp was the nearest to 1.67. The higher Ca/P ratio presents due to higher HAp concentration, it indicated the existence of B-type carbonate phosphate which identical with a mineral in human bones that promotes cell adhesion (Hooi et al., 2021). Higher Ca/P ratio will support the smaller particle size so the degradation in the living body facilitated so the Ca and P component will absorb faster. It can induced bone repair (Zhang et al., 2019).

The modified scaffolds have micropores about 1 μm to 100 μm in size (Iga et al., 2020). Scaffold with a microtubular size (20 μm) is similar to the structure of dentin, and it can support gel proliferation and differentiation of odontoblast cells (Haeri et al., 2017). Microporosity can increase the biomaterial surface area and increased protein adsorption will further increase cell adhesion (Herda and Puspitasari, 2018). It can support the transportation of nutrients and the bone regeneration process (Sobczak-Kupiec et al., 2021).

The combination of HAp or collagen with several flavonoids can support human osteoblast-like cell proliferation and differentiation, and regenerating bone structure. EGCG contains flavonoid can support the proliferation of seeding cells in sponges (Sobczak-Kupiec et al., 2021). In the present study, The percentage of living cell after HAp-Col-EGCG scaffold application was high. All samples support dental pulp cell proliferation. The higher HAp concentration is related to the higher viability of hDPSCs. Several characteristics have not been studied, so the researcher should explore other formula characteristics, such as antibacterial effect or bioactive formula release. Thus, this confirmed the potential of the HAp-Col-EGCG scaffold.

5. Conclusion

The HAp-Col-EGCG fulfilled several ideal hydrogel scaffold criteria. The composition of the scaffold with 4 % HAp concentration indicates the closest to the stoichiometric value. The FTIR analysis showed covalent bonds in all samples. The collagen was not denatured with HAp and EGCG addition. This material is non-toxic and highly likely to be used as a pulp regeneration induction material. In this study, not all the physical characterization tests were performed. Other characterizations such as antibacterial activity, the release of the bioactive material, and the clinical trial in the animal model should be performed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study used a cytotoxicity test by PT Prodia Stemcell Indonesia (ProStem), Jakarta, Indonesia.

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CJ3521

by Klinik Jurnal

Submission date: 31-May-2022 03:44PM (UTC+0800)
Submission ID: 1847675880
File name: CJ3521-Clean.docx (3.06M)
Word count: 5399
Character count: 31236

The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as AaPulp Regeneration Material

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Abstract

Background: Hydrogel scaffold is a biomaterial that can facilitate cells in forming a tissue structure. It can promote cell adhesion, migration, and proliferation. The composite material of the scaffold, which can promote pulp regeneration, is eggshell hydroxyapatite, collagen, and epigallocatechin-3-gallate (EGCG) crosslinked together (HAp-Col-EGCG), and it has never

been studied before. Further research to find a new scaffold from natural resources is challenging, so this study aimed to characterize hydrogel composite scaffold material, which has the potential to be used as a regenerative material.

Methods: The formulation of HAp-Col-EGCG was mixed with different ratios of 1%, 2%, and 4% hydroxyapatite. We analyzed its injectability, pH, and gelation time. Scanning electron microscopy (SEM), energy X-Ray Spectroscopy (EDX), and Fourier-transform infrared spectroscopy (FTIR) were used to evaluate the surface morphologies, element composition, and chemical properties of HAp-Col-EGCG.

Results: The results showed that the injectability test was almost 90% in all groups. There was no significant difference in the median value of the pH at 0, 20, and 60 min in all groups, but there was a significant difference at 40 min. The average gelation times in all groups were 326 ± 23.3; 366 ± 9.16; 342.3 ± 12.5 in seconds, and there was no significant difference between the groups. SEM-EDX showed a microporous scaffold, with the HAp particles well distributed in the collagen pores at a ratio of 1.9, 2.29, and 1.89 Ca/P. The FTIR results showed intermolecular bonds in the HAp-Col-EGCG scaffold. The X-ray diffraction analysis showed that collagen and EGCG did not affect the crystal structure and size of HAp. Cytotoxicity test showed more dental pulp cell viability at the 4% HAp concentration at 514.35 ± 15.45.

Conclusion: This study indicates that hydrogel scaffold from eggshell hydroxyapatite, collagen, and EGCG has a high potential for pulp regenerative therapy.

Keywords: characterization, hydrogel scaffold, HAp-Col-EGCG, pulp regeneration material

1. Introduction

Usually, the treatment for deep caries lesion with pulp exposure is endodontic therapy, but there are several limitations such as losing vitality, which could weaken the teeth, or

secondary infection. Nowadays, regenerative treatment approaches in developing pulp dentin complex repair involves the use of mesenchymal stem cells originating from the teeth, growth factors, and a scaffold.[1,2] The scaffold can provide a framework for cell adhesion, proliferation, and differentiation. It should be biocompatible, with easy application in the rigid area. The scaffold should also be sterilized, injected at a suitable setting time, non-toxic, non-allergenic, biodegradable, and solidified at a physiological pH of 37 °C. Based on several criteria, a hydrogel scaffold can be considered to develop.[3,4]

Scaffolds from natural sources can enhance the viability of dental pulp stem cells and significantly form better pulp-like tissue.[5] Natural sources can be obtained from eggshell hydroxyapatite and bovine collagen type I with epigallocatechin-3-gallate (EGCG) modification. Hydroxyapatite is a biocompatible material and has a similar composition to that of bone and teeth, and eggshell is one of its popular sources.[6,7] A nanohydroxyapatite scaffold from eggshell has interconnected pores and contains high levels of calcium carbonate.[8] Thus, a nanohydroxyapatite scaffold from eggshell can induce the differentiation of dental pulp cells.[9,10]

Collagen is a natural material that can penetrate intermolecularly and forms a gel, so it is suitable for use in rigid dentin structure.[11] Hydroxyapatite and collagen are the leading natural components of hard tissues and proteins in humans and can be created as a composite hydrogel scaffold using the sol-gel method.[12,13] Nanohydroxyapatite can be distributed between collagen fibers, and modification with EGCG can create a smooth surface, stimulating bone regeneration.[14] EGCG has been beneficial as an anti-cariogenic and anti-inflammation agent. Usually, EGCG is crosslinked with other material.[15] In this research, a hydrogel scaffold was formulated from eggshell hydroxyapatite, collagen, and EGCG to take benefit from each material. The aim of this study was to prove that eggshell hydroxyapatite, collagen, and EGCG

(HAp-Col-EGCG) composite has a potential to be used as a scaffold for pulp regeneration material.

2. Materials and Methods

2.1. Fabrication of eggshell hydroxyapatite, collagen, and EGCG (HAp-Col-EGCG) hydrogel

The preparation of the material was done using eggshell nanohydroxyapatite (Pertiwi Technology, Bogor, Indonesia), 5 mg/mL collagen I bovine (Gibco, Thermofisher Scientific, USA), and EGCG (Sigma Aldrich, E4268, ≥80%, USA). Hydroxyapatite was dissolved in deionized water at a concentration of 1%, 2%, and 4% in a magnetic stirrer for 1 h at 350 rpm.[16] Then, 10 µmol/L of EGCG was added to the hydroxyapatite solution, and it was stirred again until homogenous at a cold temperature.[17] The collagen solution was prepared at a concentration of 3 mg/mL through the addition of phosphate-buffered saline (Gibco, Thermofisher Scientific, USA), sodium hydroxide, and distilled water.[18] The collagen solution was mixed with hydroxyapatite and the EGCG solution at a cold temperature for 30 min in a stirrer. After that, 2% hydroxypropyl methyl cellulose (HPMC) (Benecel, K100M, Ashland, Wilmington, USA) was added until homogenous and colloidal at room temperature.[19,20]

2.2. Injectability test

The characteristic of the flow was determined by through a 21-gauge syringe (Terumo Corporation, Tokyo, Japan). The formulation of HAp-Col-EGCG with ratios of 1%, 2%, and 4% HAp was inserted into a syringe. The mass before injection and mass extruded from the syringe were weighed. The percentage of injectability was obtained using the following formula: % injectability = (*mass extruded from the syringe/total mass before injection*) x 100%, and the procedure was repeated three times.[20,21]

2.3. Gelation time and pH

Gelation time was measured by the inverted tube method.[22] Gelation process was determined by the color changes of the formulation to an opaque color, which means that the phase of the sol-gel transition would occur in several minutes. The optimal gelation time is 5 to 30 min, providing enough time for application with a stable gel formulation.[23] Three replications were done to get the average value for each sample.

The measurement of the HAp-Co-EGCG pH value was done using a pH-meter (PHS-3E, INESA Instrument, Shanghai, China) during gelation and repeated three times for 1 h; right after mixing at 20, 40, and 60 min at room temperature.[24]

2.4 Microporosity of HAp-Col-EGCG hydrogel scaffold

The morphology of the HAp-Col-EGCG scaffold was analyzed using SEM-EDX (Hitachi S4700, Tokyo, Japan). Before the SEM imaging, HAp-Col-EGCG hydrogels were freeze-dried at −80 °C for 24 h, and then the freeze-dried samples were coated with an Au layer and analyzed by SEM. As boundaries, the largest and smallest pore diameters were also measured.[25,26]

2.5 Fourier-transform infrared spectroscopy (FT-IR)

The functional group of the HAp-Col-EGCG formulation was analyzed using FTIR (Thermo Fisher scientific Nicolet iS-10, USA). Samples of HAp-Col-EGCG with 1%, 2%, and 4% HAp were positioned in an infrared spectrometer for analysis and at the 400–4,000 cm^{-1} wavenumber range.[26]

2.6 X-ray diffraction (XRD) analysis

The XRD pattern of the samples was analyzed by XRD (Smartlab Rigaku, Tokyo, Japan) using copper (Cu) as the X-ray source, with a voltage of 40 kV and current of 40 mA, which was performed at a range of 2θ from 10° to 90°, with a scan rate of 5° min^{-1}, to determine the microstructure characteristics such as compound phase composition and crystallinity using the Bragg–Bentano scan method.

2.7 Cytotoxicity test

Cells were taken from human dental pulp stem cells (hDPSCs) obtained from PT Prodia Stem Cell, Indonesia. Cytotoxicity test of the samples was performed using the 3-(4,5-dimethyl-2-thiazolyl)-2.5-diphenyl-2H-tetrazolium bromide (MTT) assay to know the biological condition. The substance would give cell viability information, which is known to change to formazan salt due to mitochondrial activation of living cells. An enzyme-linked immunosorbent assay reader was used to measure the optical density of the formazan salt. Cell viability was calculated using the % viability formula using a relative optical density. The material of the samples is not toxic if the cell viability is more than 50%.[20,27]

$$\textit{Relative OD} = \frac{\textit{OD of test group}}{\textit{OD of control}} x\ 100$$

2.8 Statistical analysis

Shapiro–Wilk normality test was carried on all data obtained. If the data was normal, one-way analysis of variance (ANOVA) was used, otherwise the data was analyzed using Kruskal–Wallis. Data are described as the mean and standard deviation value or its median at $P < 0.05$. Statistics was performed using SPSS 25 (SPSS Inc, Chicago, IL, USA).

3 Results

3.1 Injectability test

According to the injectability test, samples with 1%, 2%, and 4% HAp can be injected through the 21-G needle, each at 90.4% ± 1.93, 92.1% ± 1.97, and 91.06% ± 0.75 (Figure 1). One-way ANOVA showed that there was no significant difference between all groups ($P > 0.05$). All samples had a similar injectability percentage statistically.

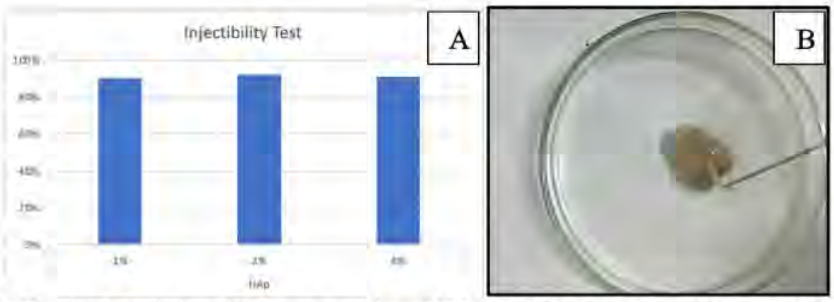

Figure 1. Graph of the injectability test results of HAp-Col-EGCG (A) and HAp-Col-EGCG gel scaffold injected through the 21-G syringe (B).

3.2 Gelation time test

The average gelation time for the 1%, 2%, and 4% HAp was approximately 5 to 6 min or 326 ± 23.3, 366 ± 9.16, and 342.33 ± 12.5 in seconds. Figure 2 shows the HAp-Col-EGCG before (Figure 2A) and after the gelation process (Figure 2B). The optimal gelation time should be 5–30 min,[23] so all samples fulfilled the criteria. According to one-way ANOVA analysis, the concentration of 1%, 2%, and 4% HAp showed no significant difference in gelation time.

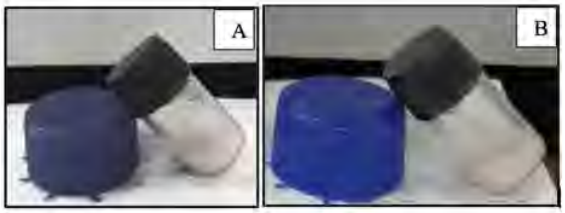

Figure 2. HAp-Col-EGCG formulation before (A) and after (B) gelation.

3.3 pH value

The consecutive median (min-max) pH values in 1%, 2%, and 4% HAp are shown in Table 1. Each group of samples was compared using Kruskal–Wallis test, and they showed differences in the pH value at 0, 20, and 60 min ($P < 0.05$), otherwise there were no significant difference in the pH value between each group at 40 min ($P > 0.5$). This result showed that pH values are higher at a higher HAp concentration (Table 1).

Table 1. Comparison of the scaffold formulation and pH at different times

Waktu / Scaffold	pH								p
	0		20		40		60		
	$\bar{\chi} \pm S$	Med (min-max)	$\bar{\chi} \pm S$	Med (min-max)	$\bar{\chi} \pm S$	Med (min-max)	$\bar{\chi} \pm S$	Med (min-max)	
1:1	7.94 ± 0.18	7.98 (7.75–8.11)	7.92 ± 0.17	7.82 (7.82–8.12)	7.96 ± 0.15	7.98 (7.81–8.11)	8.02 ± 0.17	8.12 (7.82–8.12)	0.183
1:2	7.37 ± 0.07	7.34 (7.32–7.45)	7.38 ± 0.1	7.32 (7.32–7.51)	8.02 ± 0.07	7.98 (7.98–8.11)	8.46 ± 0.16	8.46 (8.3–8.63)	0.109
1:4	9.18 ± 0.01	9.18 (9.17–9.19)	9.26 ± 0.01	9.26 (9.26–9.28)	9.27 ± 0.06	9.26 (9.22–9.35)	9.31 ± 0.02	9.31 (9.3–9.34)	0.074
p	0.027*		0.025*		0.057		0.027*		

*Friedmann ($P < 0.05$); *Kruskal–Wallis ($P < 0.05$)

3.4 Functional group test (FTIR)

The FTIR result of the HAp-Col-EGCG formulation is shown in Figure 3. The results showed peaks at several absorbances correlated to specific functional groups. The peaks of 1%, 2%, and 4% HAp functional groups were shown at wavenumbers of 3,418.68 cm^{-1}, 3,416.1 cm^{-1}, and 3,431.49 cm^{-1}, respectively, which are related to O–H stretching, and confirmed the presence of HAp, EGCG, and HPMC. Phosphate bending at 559.96 cm^{-1} and 602.17 cm^{-1}, 560.4 cm^{-1} and 595.9 cm^{-1}, and 559.73 cm^{-1} and 599.75 cm^{-1} were identified as HAp.[28,29]

The absorbance of HAp-Col-EGCG with 1%, 2% and 4% HAp identified amide I and EGCG, which were related at a wavenumber of 1,652.40 cm^{-1}, 1,651.94 cm^{-1}, and 1,653.44 cm^{-1}, with medium N–H bending and strong stretching of C=O.[29] Amide II was found at 1,561.20 cm^{-1}, 1,560.71 cm^{-1}, and 1,560.77 cm^{-1} wavenumbers, related to N–H *bending* and medium C=N *stretching*. In amide III, peak absorbance was shown with medium C–N stretching at 1,198.98 cm^{-1}, 1,022.89 cm^{-1} and 1,022.20 cm^{-1}.[14] The absorbance at 2,929.38 and 2,927.94 was the stretching of C–CH_3, which is specific to the HPMC functional group (Figure 3).[20]

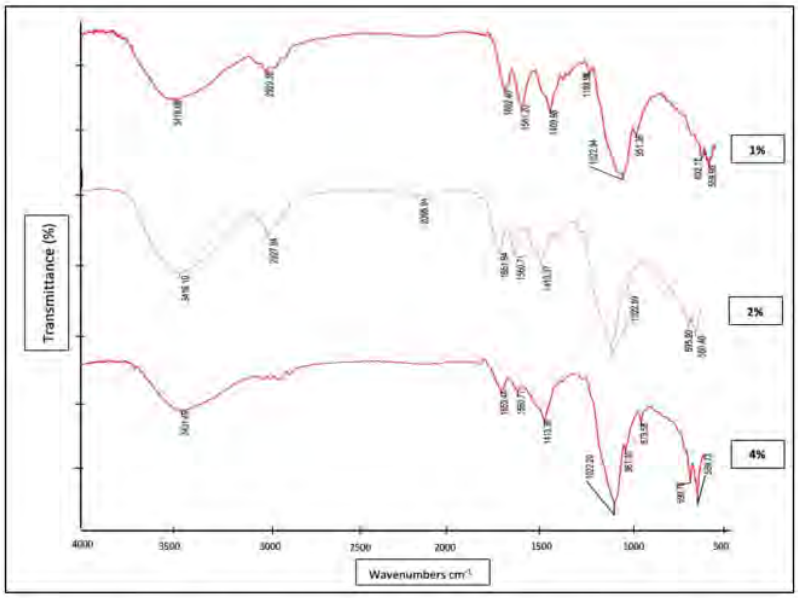

Figure 3. Spectra of the HAp-Col-EGCG, with three variations in HAp concentration, namely, 1%, 2%, and 4% HAp. The peaks of amides I, II, and III were stable for all samples, indicating that the triple helix structure of collagen was maintained with the addition of HAp and EGCG.

3.5 XRD analysis

The XRD pattern in all the sample groups showed an identical pattern. There was little difference between HAp-Col-EGCG formulation with 1%, 2%, and 4% HAp concentration in the formed peak and its characterization at 2θ, with angles of 31.48°, 31.65°, and 31.73°, respectively (Figure 4). Therefore, it could be concluded that collagen and EGCG did not affect the crystal structure of HAp.

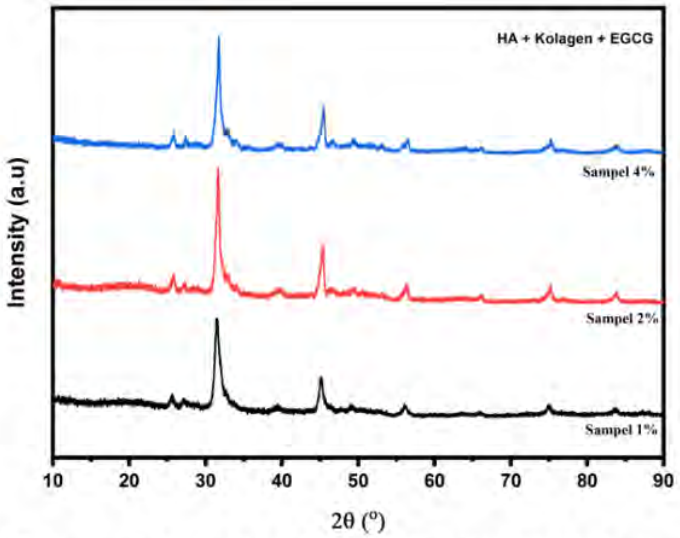

Figure 4. XRD pattern of HAp-Col-EGCG with 1%, 2%, and 4% HAp concentration.

All samples formed a hexagonal crystal structure, and Debye–Scherrer analysis was used to analyze the crystal size, which showed a difference in crystal size in 1%, 2%, and 4% HAp composition, with values of 11.4745, 19.8254, and 18.1769 nm. The 1% HAp concentration resulted in a smaller crystal size than that in 2% or 4% HAp. The larger crystal size was found in 2% HAp concentration. Visualization of the hexagonal HAp crystal structure in the HAp-Col-EGCG hydrogel composite can be seen in Figure 5A–C.

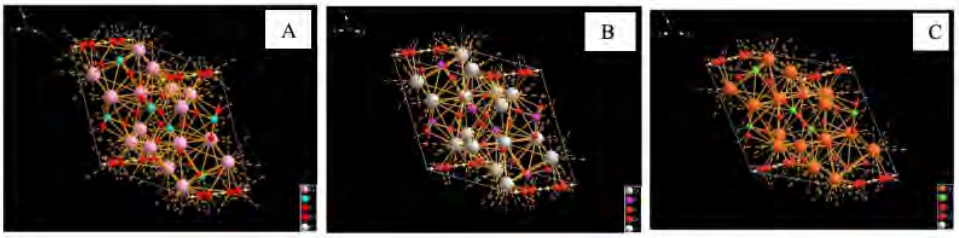

Figure 5. Visualization of the hexagonal crystal structure of HAp at 1% (A), 2% (B), and 4% (C) in the HAp-Col-EGCG scaffold.

3.6 Microporosity and EDS analysis of Hap-Col-EGCG hydrogel scaffold

Data showed no significant difference in the scaffold pore diameter with Hap at 1%, 2%, and 4% concentration ($P > 0.05$). The diameter median of the HAp-Col-EGCG scaffold with 1%, 2% and 4% HAp is shown in Table 2. The pores in these concentrations could support cell attachment, growth, and proliferation and has potential in dentin pulp regeneration treatment.[30,31] Agglomerated HAp was also dispersed in the porous collagen (Figure 6A–C).

Table 2. Microporosity measurement of the HAp-Col-EGCG scaffold.

HAp Samples	Diameter Porous (m)		Median
	Min	Max	
1%	7.01	100.67	21.69
2%	4.33	116.69	27.19
4%	4.96	132.17	21.55

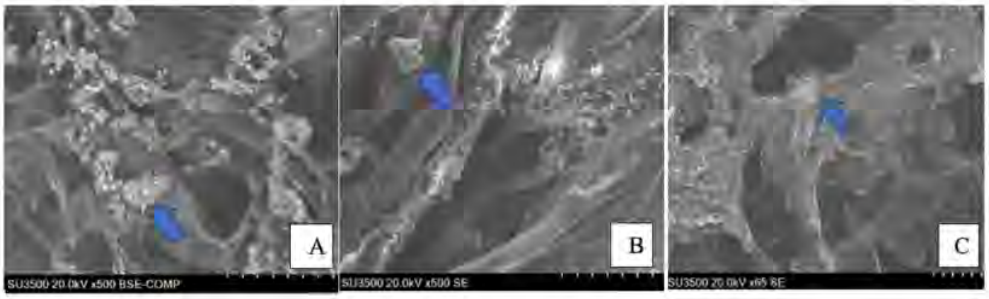

Figure 6. HAp-Col-EGCG scaffold with 1% (A), 2% (B), and 4% (C) HAp showed interconnected pores and agglomerated HAp dispersed in a collagen scaffold.

EDS analysis of the Ca, P, and O composition proved HAp presence. The EDS also showed a homogenous distribution of elements in the synthesis. The components in the HAp-Col-EGCG scaffold with 1%, 2%, and 4% HAp were almost identical, with a Ca/P ratio of 1.9, 2.29, and 1.89, with the distribution of Ca shown in red color, phosphate shown in blue color, and oxygen shown in green color (Figure 7A–C). The value of Ca/P approaching natural extracellular matrix from the mineral phase is 1.67.[32] All Ca/P ratios of the samples were above

the stochiometric value (1.67); thus, the synthesis of the scaffold modified the ratio of Ca/P from stochiometric. So, the HAp-Col-EGCG scaffold with 4% HAp was the nearest to 1.67.

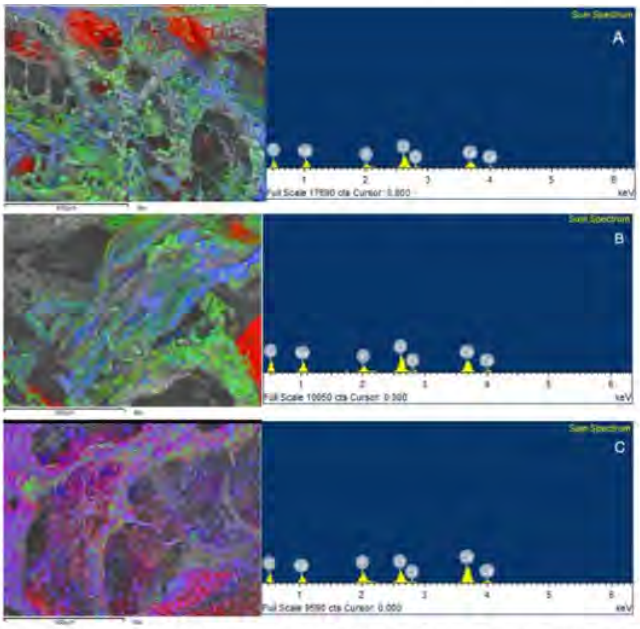

Figure 7. EDS analysis proved the presence of HAp. It showed components of Ca, P, and O, with Ca/P ratios of 1.9 (A), 2.29 (B), and 1.89 (C).

3.7 Cytotoxicity test

This test was performed for 24 h, and it proved that the HAp-Col-EGCG scaffold with 1%, 2%, and 4% HAp was non-toxic because the viability of the cells was above 50% (Figure 8). It also showed that the viability percentage was more than 100%, which means that the scaffold could promote the proliferation of dental pulp cells. The data was normally distributed, and one-way ANOVA result showed significant differences in the dental pulp cell viability for each group of scaffolds ($P < 0.05$). The highest cell viability was obtained in the HAp-Col-EGCG scaffold with 4% HAp, and the lowest viability was obtained at a 1% HAp concentration.

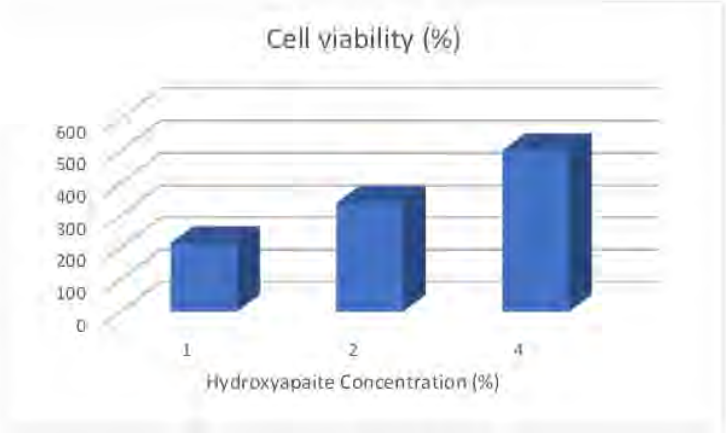

Figure 8. MTT assay was performed to evaluate the cytotoxicity of HAp-Col-EGCG scaffold with 1%, 2%, and 4% HAp concentration to hDPSCs. The highest cell viability and proliferation were HAp-Col-EGCG scaffold with 4% HAp and the lowest at 1% HAp concentration ($P < 0.05$).

4 Discussion

The results of this study showed the potential of HAp, collagen, and EGCG to be used as a hydrogel scaffold to induce pulp regeneration. In the present study, we performed an injectability test. Injectability is the ability of the formulation to be injected from the syringe. An injectable form can improve the biological stability of the biomaterial,[38] and it is affected by the syringe diameter, viscosity, and solvent of the sample. The viscosity of the formula was also affected by adding a suspension agent. The 2% HPMC was used, following previous study.[34] The suspension agent can increase the viscosity and stability of formula. HPMC is colorless; thus, it does not affect the chemical analysis and biological reaction. Pure HPMC is a fairly neutral solution.[35,36] Injectable application in the dental pulp region is also essential because the dental pulp is in a rigid and limited area, so injectability in this particular area can be challenging.[37] The ideal injectable ability is 100%, and, in this study, the injectability was almost ideal.

The inverted test tube method was used to perform a gelation time test of the HAp-Col-EGCG scaffold at 37 °C. Gelation time is crucial because too fast gelation would not make

enough time for clinical application, whereas slow gelation time would make it difficult to target the application area.[38] All group samples had a gelation time of 326 ± 23.3 s, 366 ± 9.16 s, and 342.33 ± 12.5 s (5 to 6 min). According to a previous study, the recommended gelation time is 5 to 30 min. There was no significant difference in gelation time between the three group samples. It means that all group samples had a suitable gelation time.

The latest literature have reported that the initial pH is crucial in the determination of the morphology and size of the formulation structure, whether sphere, roller, needle, etc. The pH can indicate supersaturation that can influence the ion balance. If there are increases or decreases in the OH^- composition, these will affect and modify the concentrations of Ca^{2+}, PO_4^{3-}, and $(HPO_4)^{2-}$ ions. The agglomerate nanoparticles in the SEM analysis decreased in particle size when the pH value decreased.[39] In present study, the pH value had a hexagonal phase, with stable pH value in each group.

According to Hirose et al., cell death was found in DPC cultures at a pH of 3.5 to 5.5. It showed cell growth or arrest at a pH of 6.5 to 7.5 and showed mild proliferation at a pH of 9.5.[40] In this study, the HAp-Col-EGCG scaffold with 4% HAp had a pH value approaching 9.5. It can be used to support regeneration in the inflamed pulp.[40] In this study, increasing in pH values of HAp-Col-EGCG formulation was related to higher HAp concentration.

The FTIR results identified that the functional group indicates O–H stretching, which confirmed eggshell HAp, EGCG, and HPMC, which is similar to the results of Rogina et al., wherein it was confirmed that hydrogel composite presents at 3,150–3,600 cm^{-1} wavenumbers.[28] In accordance with the study of Siswanto et al., $(PO_4)^{3-}$ was also identified at 900–1,200 cm^{-1} wavenumbers. The important marker to determine collagen identification is its helical structure with amide I, amide II, and amide III. In this study, the peak of amide I, II, and III were stable for all samples, indicating that the triple helix structure of collagen is still intact and is maintained with the addition of EGCG or HAp. EGCG can preserve collagen

structure and oppose collagenase degradation.[14] Similar with Hikmawati et al.'s study, HPMC specific group function was also identified, indicating that HPMC also formed a hydrogen bond.[20]

The possible HAp-Col-EGCG bond is a hydrogen bond. Hydrogen bonds take place between a collagen hydrogen atom and oxygen in HAp. It creates mineralized collagen between collagen structure and the crystal in HAp, and it is supported by FTIR data, which showed a C=O band.[29]Another study also discovered that the bonding mechanism started with Ca^{2+} ions from HAp interacting with amide I (NH_2) in collagen.[41]

XRD was performed to analyze the nanomaterial microstructure and determine the crystal system (cuboid, tetragonal, orthorhombic, rhombohedral, hexagonal, monoclinic, or triclinic). The XRD features also give information on the powder composition.[42] In the present study, the crystal structure of HAp did not change because of collagen and EGCG addition. A hexagonal structure with the *P*63/*m* space group still formed (Figure 2A–C). The result of 1%, 2%, and 4% Hap crystal size supports previous studies that also reported crystal length and width average of 21 ± 9 nm and 6 ± 1.5 nm. The main peak of HAp in HAp-Col-EGCG formulation was identified at a range that is also similar to that in a previous study that identified HAp at 2θ of 31.7°, 32.2°, and 32.9°.[43]

The pH can affect the crystal size during synthesis of the formulation. The XRD result showed that the number of crystal size will decrease when the pH value is low.[39]

It is supported by another study, wherein it was found that the particle size also increases when the pH value increases from 6 to 13.[44] In this study, the nanoparticle crystal size was also larger when the pH value increased in HAp-Col-EGCG with 4% HAp. The pH influences the HAp characteristics because of the role of H^+ and OH^- ions. Increasing H^+ can create favorable formation of monoclinic HAp. Decreasing the OH^- concentration can cause solution saturation reduction, so when the pH decreases, the nucleation and growth of crystals reduce.[39]

The median diameter pore of HAp-Col-EGCG scaffold formulation from all groups could support cell attachment, growth, and proliferation, and it had potential in dentin pulp regeneration treatment. All Ca/P ratio of the samples was above stochiometric value (1.67), and the HAp-Col-EGCG scaffold with 4% HAp was the nearest to 1.67. Usually, modified scaffolds have micropores that are 1 μm to 100 μm in size.[45] Polymethyl methacrylate scaffold with a microtubular size (20 μm) is similar to the structure of dentin, and it can support gel proliferation and differentiation of odontoblast cell.[46] Microporosity can increase the biomaterial surface area. The more pores, there are the larger the surface area; thus, increased protein adsorption will further increase cell adhesion.[47] It can support the transportation of nutrients and the bone regeneration process.[48]

In the cytotoxicity test, the MTT enzyme would affect formazan salt and create a violet color because of the reaction with living cells from the mitochondria.[27] The combination of HAp with several flavonoids can support human osteoblast-like cell proliferation and differentiation. Besides that, the combination of collagen and flavonoid were also effective in regenerating bone structure. The concentration of EGCG can relate to the toxicity of the material. Flavonoid can support the proliferation of seeding cell in sponge.[48] In the present study, the highest cell viability was obtained in the HAp-Col-EGCG scaffold with 4% Hap (514.35 ± 17.8), and the lowest viability was obtained at 1% HAp concentration (225 ± 17.7). So, from this study, 4% HAp has a high potential in supporting dental pulp cell proliferation. Thus, higher HAp concentration is related with the viability of hDPSCs. Several characteristics have not been studied, so the researcher should explore other characteristics of the formula, such as antibacterial effect or bioactive formula release. Thus, this confirmed the potential of the HAp-Col-EGCG scaffold.

5 Conclusion

We succeeded in synthesizing a hydrogel scaffold based on nanohydroxyapatite, collagen, and EGCG (HAp-Col-EGCG). It fulfilled the several criteria of an ideal hydrogel scaffold that can be injected and had an optimum gelling time with a suitable pH value for pulp regeneration. HAp-Col-EGCG scaffold performed interconnected porous characterization, which has potential for cell attachment. The composition of 4% HAp in the scaffold indicates the HAp concentration closest to the stoichiometric value. FTIR analysis indicated covalent bonds in all samples, and the collagen was not denatured with HAp and EGCG addition. Therefore, this material is non-toxic and highly likely to be used as a pulp regeneration induction material. We found that HAp-Col-EGCG with 4% HAp concentration can significantly support dental pulp cell proliferation. In this study, not all the physical characterization tests were performed. Another characterization such as HAp-Col-EGCG antibacterial activity, release of the bioactive material, and the clinical trial in animal model should be performed.

Acknowledgments

This study used a cytotoxicity test by PT Prodia Stemcell Indonesia (ProStem), Jakarta, Indonesia.

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The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as AaPulp Regeneration Material

--Manuscript Draft--

Manuscript Number:	SDENTJ-D-22-00458R2
Article Type:	Full Length Article
Keywords:	characterization; hydrogel scaffold; HAp-Col-EGCG; pulp regeneration material.
Corresponding Author:	Elline Elline INDONESIA
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	Kun Ismiyatin
	Theresia Indah Budhy
	Anuj Bhardwaj, Adjunct Professor
Abstract:	Background: Hydrogel scaffold is a biomaterial that can facilitate cells in forming a tissue structure. It can promote cell adhesion, migration, and proliferation. Further research to find a new scaffold from natural resources is challenging, so this study aimed to characterize a hydrogel composite scaffold, which has the potential to be used as a regenerative material. Methods: The formulation of HAp-Col-EGCG was mixed with different ratios of 1%, 2%, and 4% hydroxyapatite. We analyzed its injectability, pH, and gelation time. Scanning electron microscopy (SEM), energy X-Ray Spectroscopy (EDX), and Fourier-transform infrared spectroscopy (FTIR) were used to evaluate the surface morphologies, element composition, and chemical properties of HAp-Col-EGCG. Results: The results showed that the injectability test was almost 90% in all groups. There was no significant difference in the median value of the pH at 0, 20, and 60 min in all groups, but there was a significant difference at 40 min. The average gelation times in all groups were not significant. SEM-EDX showed a microporous scaffold, with the HAp particles well distributed in the collagen pores at a ratio of 1.9, 2.29, and 1.89 Ca/P. The FTIR results showed intermolecular bonds in the HAp-Col-EGCG scaffold. The X-ray diffraction analysis showed that collagen and EGCG did not affect the crystal structure and size of HAp. Cytotoxicity test showed more dental pulp cell viability at the 4% HAp concentration at 514.35 ± 15.45. Conclusion: This study indicates that hydrogel scaffold from eggshell hydroxyapatite, collagen, and EGCG has a high potential for pulp regenerative therapy.
Suggested Reviewers:	Piyaphong Panpisut Thammasat University panpisut@tu.ac.th
	Mostafa EzEldeen KU Leuven University Hospitals Leuven mostafa.ezeldeen@kuleuven.be
Response to Reviewers:	Dear Reviewer, Thank you for reviewing our manuscript. We have revised the manuscript according to your comments/suggestions. Please, kindly find the revised file and rebuttal letter. Thank you. Best regards, Authors

COVER LETTER

Dear Editor-in-Chief
Saudi Dental Journal

We submit article entitle "**The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as AaPulp Regeneration Material**" for publish in Saudi Dental Journal. This is original article which not currently under review elsewhere and does not contain data that are under review or published elsewhere. The authors declare that they have no conflict of interest. All authors have read and approved this manuscript to publish in this journal.

We hope you accept this article for publication because this study aims to characterize hydrogel composite scaffold material, which has the potential to be used as a regenerative material.

What this study found:

- SEM-EDX showed a microporous scaffold, with the HAp particles well distributed in the collagen pores at a ratio of 1.9, 2.29, and 1.89 Ca/P.
- The FTIR results showed intermolecular bonds in the HAp-Col-EGCG scaffold. The X-ray diffraction analysis showed that collagen and EGCG did not affect the crystal structure and size of HAp.Cytotoxicity test showed more dental pulp cell viability at the 4% HAp concentration at 514.35 ± 15.45.
- The hydrogel scaffold from eggshell hydroxyapatite, collagen, and EGCG has a high potential for pulp regenerative therapy.

Thank you,

Elline Elline
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REBUTTAL LETTER

Dear Editor in Chief,

We would like to thank you for giving us the chance to publish our work in your journal. We have checked and answered the queries from the reviewer. However, we found it difficult to reduce the word count. We have reduced the unnecessary paragraphs/statements and left the important ones. If you do not mind, could you give us a recommendation/suggestion on which parts should be removed? Since we think that we have written the manuscript briefly.

Thank you for your concern.

With best regards,
Authors

No.	Comments	Responses
	Reviewer 1	
1	Materials and methods Please indicate the method to standardise the applied force in Newton and the rate of injection (e.g., mm/min) to inject the materials. Please confirm the protocol for interpreting MTT results as non-toxicity with ISO 10993-5 (50 or 70%).	Thank you for the comment. As suggested, we have added the applied force in Newton and the rate of injection in part 2.2, which is 64,1N with 1ml/10s. We have revised the protocol for interpreting MTT results as non-toxicity using ISO 10993-5 (in part 2.7) with viability cells of more than 50%.
2	Results FTIR peaks for HA are usually indicated by strong or very strong phosphate peaks ~ 1040 or 1092 cm-1 Table 1: if the data is not normally distributed, it should be presented as median (min-max) to aid readability. Table 2: Please check the unit of diameter porous. All bar charts should include error bars and statistical results (either sig or non-sig results).	Thank you for the suggestion. In this study, peaks of HAp were identified by hydroxyl groups at 3431 – 3481 cm^{-1} and the major PO_4^{3-} groups peaks were in 1022 – 1023 cm^{-1}. A more explanation of HAp's peak group has been added in lines 313 - 317 Table 1 has been revised by eliminating the average±SD column and replacing it as table 2 We eliminated table 2 into narration with significance value (p) in lines 253-255. The unit of diameter porous is μm. We have added the error bar in figure1. The statistical result with significance (p) has been added to table 1.

3	Discussion What would be the possible reason for the higher Ca/P ratio of HA, and what could be the potential impact of such an outcome.	Thank you for the comment. We have added the possible reason of higher Ca/P ratio of HA and the potential impact in lines 345-350.

No.	Comments	Responses
	Reviewer 1	
1.	Remove the highlights and line numbering from the final manuscript.	Thank you for the suggestion
2.	Please check and mention the word count (Maximum permissible is 2000-2500 for original research, Review article- 3000-3500 Abstract- 300) in the title page.	Thank you for the correction. We have been revised it and reduced the word of manuscript to 2495 (excluded abstract, figure, table, and references).
3.	Total number of Illustrations (Figures+ Tables) must not exceed 6	Thank you. We have reduced the total number od illustrations to 6 in total.
4.	Please check the author details	Thank you for the suggestion However, we could provide it in the text since it is a blinded manuscript. Thus, we send it in separated file.
5.	Add the details of place of research. (If Applicable)	Thank you for the comment.
6.	English scientific writing to be checked and improved by any reputed Editing services. You can also avail services from the below link PLEASE SUBMIT An “ENGLISH EDITING CERTIFICATE” for us to proceed with acceptance	The mixing process was performed at Biocore laboratory (Universitas Trisakti,Indonesia) and several characterization were obtained from LIPI Fisika (Serpong, Tangerang, Indonesia).
7.	Kindly update your Abstract in the submission portal if revised.	Thank you for the suggestion.
8.	Tables *** Please avoid using vertical rules and shading in table cells.(Only horizontal lines and borders are allowed)	Thank you for the suggestion. We revised the tables rules
9.	Referencing style according to AUTHORS GUIDELINES (Author, Year) within text- Check and format Bibiliography	Thank you for the comment. We have revised it.

The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as A Pulp Regeneration Material

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The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as A Pulp Regeneration Material

Word count:

Abstract: 252

Text: 2495 (excluded abstract, figure, table, and references)

Abstract

Background: Hydrogel scaffold is a biomaterial that can facilitate cells in forming a tissue structure. It can promote cell adhesion, migration, and proliferation. Further research to find a new scaffold from natural resources is challenging, so this study aimed to characterize a hydrogel composite scaffold, which has the potential to be used as a regenerative material.

Methods: The formulation of HAp-Col-EGCG was mixed with different ratios of 1%, 2%, and 4% hydroxyapatite. We analyzed its injectability, pH, and gelation time. Scanning electron microscopy (SEM), energy X-Ray Spectroscopy (EDX), and Fourier-transform infrared spectroscopy (FTIR) were used to evaluate the surface morphologies, element composition, and chemical properties of HAp-Col-EGCG.

Results: The results showed that the injectability test was almost 90% in all groups. There was no significant difference in the median value of the pH at 0, 20, and 60 min in all groups, but there was a significant difference at 40 min. The average gelation times in all groups were not significant. SEM-EDX showed a microporous scaffold, with the HAp particles well distributed in the collagen pores at a ratio of 1.9, 2.29, and 1.89 Ca/P. The FTIR results showed intermolecular bonds in the HAp-Col-EGCG scaffold. The X-ray diffraction analysis showed that collagen and EGCG did not affect the crystal structure and size of HAp. Cytotoxicity test showed more dental pulp cell viability at the 4% HAp concentration at 514.35 ± 15.45.

Conclusion: This study indicates that hydrogel scaffold from eggshell hydroxyapatite, collagen, and EGCG has a high potential for pulp regenerative therapy.

Keywords: characterization, hydrogel scaffold, HAp-Col-EGCG, pulp regeneration material

1. Introduction

Nowadays, regenerative treatment approaches in developing pulp dentin complex repair involve using mesenchymal stem cells, growth factors, and a scaffold (Khurshid et al., 2022; Paduano et al., 2016). The scaffold can provide a framework for the cell homing process. It should be biocompatible, simple application in the dentin, injectable, non-toxic, biodegradable, and solidified at 37 °C. Based on several criteria, a hydrogel scaffold can be considered to develop (Abbass et al., 2020; Raucci et al., 2018). Scaffolds from natural sources can be obtained from eggshell hydroxyapatite, bovine collagen type I with epigallocatechin-3-gallate modification. Hydroxyapatite is a material with a similar composition to bone and teeth, and eggshell is a popular one (Ahmadian et al., 2019; Elline and Ismiyatin, 2021; Khandelwal and Prakash, 2016). An eggshell nanohydroxyapatite scaffold has interconnected pores, contains high levels of calcium carbonate that induces the differentiation of dental pulp cells (Afriani, 2015; Okamoto et al., 2020; Sancilio et al., 2018).

Collagen is a material that can penetrate intermolecularly and forms a gel, so it is suitable for use in rigid dentin composition (Kwon et al., 2017). Hydroxyapatite and collagen are humans' leading natural components of tissues and proteins and can be synthesized using the sol-gel method (Sathiyavimal et al., 2020; Yu et al., 2020). Nanohydroxyapatite can be distributed between collagen fibers, and EGCG addition can create a smooth surface, stimulating bone regeneration (Permatasari and Yusuf, 2019). Crosslinked EGCG has been beneficial as an anti-inflammation agent (Kwon et al., 2017). In this research, a hydrogel scaffold was formulated from eggshell hydroxyapatite, collagen, and EGCG to benefit each material (HAp-Col-EGCG). This study aimed to prove that HAp-Col-EGCG composite has the potential to be used as a scaffold for pulp regeneration material

2. Materials and Methods

2.1. Fabrication of HAp-Col-EGCG hydrogel

The preparation of the material was done using eggshell nanohydroxyapatite (Pertiwi Technology, Bogor, Indonesia), 5 mg/mL collagen I bovine (Gibco, Thermofisher Scientific, USA), and EGCG (Sigma Aldrich, E4268, ≥80%, USA). Hydroxyapatite was dissolved in deionized water at a concentration of 1%, 2%, and 4% and stirred for one h at 350 rpm (Permatasari and Yusuf, 2019). Then, ten µmol/L of EGCG was added to the hydroxyapatite solution and stirred until homogenous at a cold temperature (Kwon et al., 2017). 3 mg/mL collagen solution was prepared by adding phosphate-buffered saline (Gibco, Thermofisher Scientific, USA), sodium hydroxide, and distilled water (Merck Millipore Mili-Q) (Gibco, Thermofisher, 2014). The collagen solution was mixed with hydroxyapatite and the EGCG solution at a cold temperature for 30 min. After that, 2% hydroxypropyl methylcellulose (HPMC) (Benecel, K100M, Ashland, Wilmington, USA) was added until homogenous and colloidal at room temperature. The mixing process was performed at Biocore laboratory (Universitas Trisakti,Indonesia) and several characterization were obtained from LIPI Fisika (Serpong, Tangerang, Indonesia).

2.2. Injectability test

The characteristic of the flow was determined through a 10 cc, 21G syringe (Terumo Corporation, Tokyo, Japan) with 64.1 N maximal force (1ml/10s) (Gutierrez and Munakomi, 2022; Sharma et al., 2016). The mass before injection and mass extruded from the syringe were weighed. The percentage of injectability was using the following formula: % injectability = (*mass extruded from the syringe*/*total mass before injection*) x 100%, and the procedure was repeated three times (Hikmawati et al., 2019; Takallu et al., 2019).

2.3. Gelation time and pH

Gelation time was measured by the inverted tube method (De Mori et al., 2019). The process was determined by the color changes to an opaque color. The optimal gelation time is 5 to 30 min, providing enough time for application with a stable gel formulation (Bendtsen and Wei, 2017). Three replications were done to get the average value. The pH value was measured using a pH-meter (PHS- 3E, INESA Instrument, Shanghai, China) and repeated three times for 1h; right after mixing, 20, 40, and 60 min at room temperature (Yan et al., 2016).

2.4 Microporosity of HAp-Col-EGCG hydrogel scaffold

The morphology of the HAp-Col-EGCG scaffold was analyzed using SEM-EDX (Hitachi S4700, Tokyo, Japan). Before the SEM imaging, HAp-Col-EGCG hydrogels were freeze-dried at −80 °C for 24 h. The freeze-dried samples were coated with an Au layer, and we measured the largest and smallest pore diameters (Mulyawan et al., 2022; Podhorská et al., 2020).

2.5 Fourier-transform infrared spectroscopy (FT-IR)

The functional group of the HAp-Col-EGCG formulation was analyzed using FTIR (Thermo Fisher Scientific Nicolet iS-10, USA). Samples of HAp-Col-EGCG with 1%, 2%, and 4% HAp were investigated at the 400–4,000 cm^{-1} wavenumber range (Mulyawan et al., 2022).

2.6 X-ray diffraction (XRD) analysis

The XRD pattern was analyzed by XRD (Smartlab Rigaku, Tokyo, Japan) using copper (Cu) as the X-ray source, with a voltage of 40 kV and current of 40 mA, at a range of 2θ from 10° to 90°, scan rate of 5° min^{-1}. It can determine the microstructure characteristics such as compound phase composition and crystallinity using the Bragg–Bentano scan method.

2.7 Cytotoxicity test

Human dental pulp stem cells (hDPSCs) obtained from PT Prodia Stem Cell, Indonesia. Cytotoxicity test of was done by the 3-(4,5- dimethyl-2-thiazolyl)-2.5-diphenyl-2H-tetrazolium bromide (MTT) assay. The cell viability information was known by the change of formazan salt due to mitochondrial activation of living cells. An enzyme-linked immunosorbent assay reader was to analyze the optical density of the formazan salt. The percentage of cell viability formula using a relative optical density. The material of the samples is not toxic if the cell viability is more than 50% (ISO 10993-5) (Hikmawati et al., 2019; Srisomboon et al., 2022).

$$\text{Cell viability} = \frac{\text{Mean absorbance of test sample}}{\text{Mean absorbance of control}} \times 100$$

2.8 Statistical analysis

Shapiro–Wilk normality test was carried out on all data obtained. If the data was normal, one-way analysis of variance (ANOVA) was used. Otherwise, the data was analyzed using Kruskal–Wallis. Data are described as the mean and standard deviation value or its median at $P < 0.05$. Statistics were performed using SPSS 25 (SPSS Inc, Chicago, IL, USA).

3 Results

3.1 Injectability test

According to the injectability test, samples with 1%, 2%, and 4% HAp can be injected (Figure 1 and Table 1). One-way ANOVA showed no significant difference between all groups ($P > 0.05$).

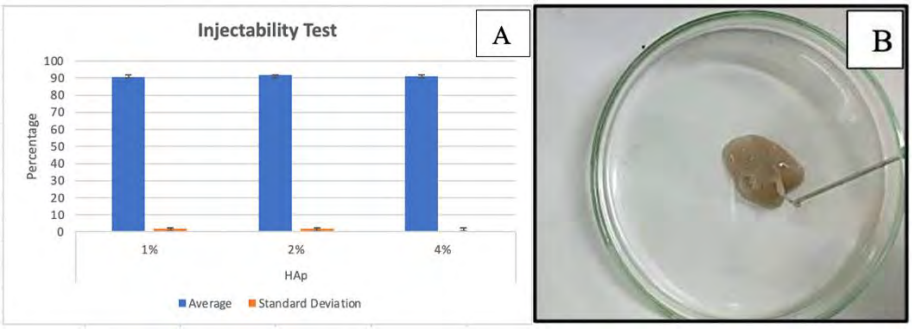

Figure 1. Graph the injectability test results of HAp-Col-EGCG (A) and injected through the 21-G syringe (B).

3.2 Gelation time test

The average gelation time was shown in Figure 2 and Table 1. Figure 2 A,B show the HAp-Col-EGCG before and after the gelation process. All samples fulfilled the criteria that should be 5 – 30 min.[23] The concentration of 1%, 2%, and 4% HAp showed no significant difference in gelation time ($P > 0.05$).

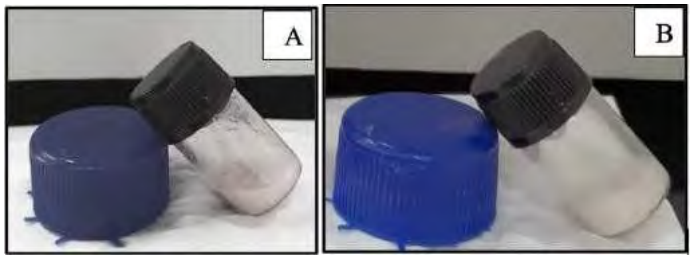

Figure 2. HAp-Col-EGCG formulation before (A) and after (B) gelation.

Table 1. The statistical result of scaffolds' injectability test and gelation times

	Mean±SD			p
Scaffold HAp-Col-EGCG	1%	2%	4%	
Injectibility (%)	90.4±1.93	92.13±1.97	91.06±0.75	0.477
Gelation times (s)	326±23.3	366±9.16	342.33±12.5	0.06

*One-way ANOVA (p>0.05)

3.3 pH value

Data were not normally distributed. The results showed significant differences in the pH value at 0, 20, and 60 min ($P < 0.05$). This result showed that pH values are higher at a higher HAp concentration (Table 2).

Table 2. Comparison of the pH scaffold formulation at different times

pH				
Time / Scaffold	0	20	40	60
	Med (min- max)	Med (min- max)	Med (min- max)	Med (min- max)
1:1	7.98 (7.75– 8.11)	7.82 (7.82– 8.12)	7.98 (7.81–8.11)	8.12 (7.82–8.12)
1:2	7.34 (7.32–7.45)	7.32 (7.32–7.51)	7.98 (7.98–8.11)	8.46 (8.3–8.63)
1:4	9.18 (9.17–9.19)	9.26 (9.26–9.28)	9.26 (9.22–9.35)	9.31 (9.3–9.34)
p	0.027*	0.025*	0.057	0.027*

*Friedmann ($P < 0.05$); *Kruskal–Wallis ($P < 0.05$)

3.4. Functional group test (FTIR)

The FTIR result showed in Figure 3. The hydroxyl group in HAp were seen at 3,416.1 cm^{-1} to 3,431.49 cm^{-1}, respectively, which are related to O–H stretching and confirmed the presence of hydrogen bond in Hap (Fern and Salimi, 2021). The major PO_4 groups peaks were obtained at 1022-1023 cm^{-1}, due to asymmetric stretching of the phosphate group. The HAp functional groups were OH^- and PO_4^{3-}, so they were identified as Hap (Fern and Salimi, 2021; Rogina et al., 2019; Siswanto et al., 2020).

The amide I and EGCG were identified, by a wavenumber at 1,651.94 cm^{-1} to 1,653.44 cm^{-1}, with medium N–H bending and strong stretching of C=O.[29] Amide II was found at 1,560.71 cm^{-1} to 1,561.20 cm^{-1} wavenumbers. In amide III, peak absorbance was shown with medium C–N stretching at 1,022.20 cm^{-1} to 1,198.98 cm^{-1}(Vishwakarma et al., 2015). The absorbance at 2,929.38 and 2,927.94 were the stretching of C–CH_3, which is specific to the HPMC functional group (Figure 3) (Hikmawati et al., 2019).

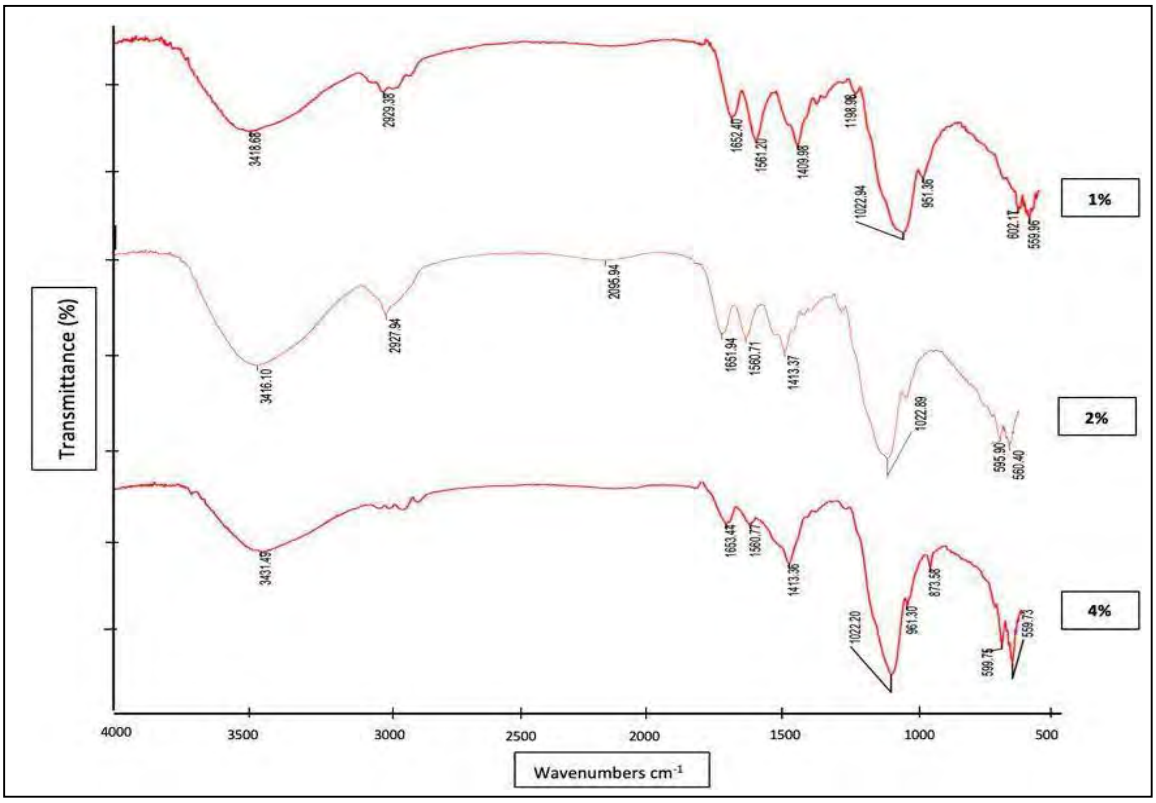

Figure 3. Spectra of the HAp-Col-EGCG, with three variations in HAp concentration

3.5 XRD analysis

The XRD pattern in all the sample groups showed an identical pattern. The 2θ, characterization with angles of 31.48°, 31.65°, and 31.73°, respectively. It could be concluded that collagen and EGCG did not affect the crystal structure of HAp.

All samples formed a hexagonal crystal structure, but there were difference in crystal size value, 11.4745nm (1% HAp), 19.8254 nm (2% HAp), and 18.1769 nm (4% HAp). The 1% HAp concentration resulted in a smaller crystal size and the larger crystal size was found in 2% HAp concentration.

3.6. Microporosity and EDS analysis of Hap-Col-EGCG hydrogel scaffold

Data were not normal distributed, and they showed no significant difference in the scaffold pore diameter in all samples (P>0.05). The diameter porous (μm) data were performed in median (min-max) value; 21.1 (7.84 - 44.61) (1% HAp); 27.19 (8.11-76.71) (2%HAp); 21.55 (4.96-132.17) (4% HAp) (p>0.05). The pores in these concentrations could support cell attachment, growth, and proliferation and have the potential for dentin pulp regeneration treatment (Panseri et al., 2016; Vishwakarma et al., 2015). Agglomerated HAp was also dispersed in the porous collagen (Figure 5A–C).

Figure 4. HAp-Col-EGCG scaffold with 1% (A), 2% (B), and 4% (C) showed interconnected pores and agglomerated HAp dispersed in a the scaffold

EDS analysis of the Ca, P, and O composition proved HAp presence. It showed a homogenous distribution of elements in the synthesis. The Ca/P ratio of 1.9, 2.29, and 1.89. The value of Ca/P approaching the natural extracellular matrix from the mineral phase is 1.67 (EzEldeen et al., 2021). All Ca/P ratios of the samples were above the stochiometric value (1.67); thus, the synthesis of the scaffold modified the ratio of Ca/P from stochiometric. The HAp-Col-EGCG scaffold with 4% HAp was closest to 1.67.

3.7.Cytotoxicity test

This test was performed for 24 h, and it proved that the HAp-Col-EGCG scaffold was non-toxic because the viability of the cells was above 50%. The results were

158.388±10.484 (1% HAp); 240.638±10.469 (2% HAp); 330.016±14.963 (4% HAp). It showed significant differences in the dental pulp cell viability for each group of scaffolds ($P < 0.05$).

4. Discussion

The results of this study showed that HAp-Col-EGCG can be formed into a hydrogel scaffold. An injectable form hydrogel can improve the biological stability of the biomaterial and is affected by the sample's syringe diameter, viscosity, and solvent (Ren et al., 2018). Suspension agent (2% HPMC) can increase the viscosity and stability of the formula (Charlena et al., 2020). HPMC does not affect the chemical analysis and biological reaction (Ciolacu et al., 2020; Ghadermazi et al., 2019). Injectable application in the dental pulp region is essential because the dental pulp is in a rigid and limited area Hikmawati et al., 2019).

The inverted test tube method was used to perform a gelation time test of the HAp-Col- EGCG scaffold at 37 °C. Too fast gelation would not make enough time for clinical application, whereas slow gelation time would make it difficult to target the application area (Ren et al., 2018). The recommended gelation time is 5 to 30 min, and all group samples had an ideal gelation time.

The latest literature has reported that the initial pH is crucial in determining the morphology and size of the formulation structure, whether sphere, roller, needle, etc. The pH can indicate supersaturation that can influence the ion balance. If there are increases or decreases in the OH^- composition, these will affect and modify the concentrations of Ca^{2+}, PO_4^{3-}, and $(HPO_4)^{2-}$ ions. The agglomerate nanoparticles in the SEM analysis decreased particle size when the pH value decreased (López-Ortiz et al., 2020). In the present study, the pH value had a hexagonal phase, with a stable pH value in each group.

According to Okamoto et al. (2020), cell death was found in DPC cultures at a pH of 3.5 to 5.5. It showed cell growth or arrest at a pH of 6.5 to 7.5 and showed mild proliferation at a pH of 9.5 (Hirose et al., 2016). In this study, the HAp-Col-EGCG

scaffold with 4% HAp had a pH value approaching 9.5. It can be used to support regeneration in the inflamed pulp (Hirose et al., 2016).

The FTIR results identified that the functional group indicates O–H stretching, which confirmed eggshell HAp, EGCG, and HPMC, similar to the results of Rogina et al., that indicated hydrogel composite at 3,150–3,600 cm^{-1} wavenumbers (Rogina et al., 2019). The evidence of strong PO_4^{3-} groups which confirmed HAp was 1040 cm^{-1} and 1090 cm^{-1} (Hooi et al., 2021) but following the study of Siswanto et al. (2020), PO_4^{3-} was also identified the bending of $PO4^{3-}$ at 500 cm^{-1} to 630 cm^{-1} that also proved of HAp existance, it supports this study that had phosphate bending at 559.96 $cm^{-1}$to 602.17 cm^{-1}.

In this study, the amide I, II, and III peaks were stable for all samples, indicating that the triple helix structure of collagen is still intact and maintained with the addition of EGCG or Hap (Permatasari and Yusuf, 2019). Similar to Hikmawati et al. (2019), HPMC-specific group function was also identified, indicating that HPMC also formed a hydrogen bond.

The possible HAp-Col-EGCG bond is a hydrogen bond which take place between a collagen hydrogen atom and oxygen in HAp. It creates mineralized collagen between collagen structure and the crystal in HAp,which showed from C=O band (Siswanto et al., 2020). Another study also discovered that the bonding mechanism started with Ca^{2+} ions from HAp interacting with amide I (NH_2) in collagen (Susanto et al., 2019).

The crystal structure of HAp did not change because of collagen and EGCG addition. A hexagonal structure with the *P*63/*m* space group is still formed. The 1%, 2%, and 4% HAp crystal size result supports previous studies that crystal length and width averages of 21 ± 9 nm and 6 ± 1.5 nm. The main peak of HAp in HAp-Col-EGCG formulation was identified at a range that is similar to a previous study which identified HAp at 2θ of 31.7°, 32.2°, and 32.9° (In et al., 2020). The XRD result showed that the number of crystal sizes would decrease when the pH value is low (López-Ortiz et al., 2020). It was found that the particle size increases when the pH value increases from 6 to

13 (Chithra et al., 2015).

In this study, the nanoparticle crystal size was also larger when the scaffold pH value increased in 4% HAp. Increasing H^+ can create the favorable formation of monoclinic HAp. Decreasing the OH^- concentration can cause solution saturation reduction, so when the pH decreases, the nucleation and growth of crystals reduce (López-Ortiz et al., 2020).

The median diameter pore of HAp-Col-EGCG scaffold from all groups could support cell attachment, growth, and proliferation. All Ca/P ratio of the samples was above the stochiometric (1.67), and the HAp-Col-EGCG scaffold with 4% HAp was the nearest to 1.67. The higher Ca/P ratio presents due to higher HAp concentration, it indicated the existence of B-type carbonate phosphate which identical with a mineral in human bones that promotes cell adhesion (Hooi et al., 2021). Higher Ca/P ratio will support the smaller particle size so the degradation in the living body facilitated so the Ca and P component will absorb faster. It can induced bone repair (Zhang et al., 2019).

The modified scaffolds have micropores about 1 µm to 100 µm in size (Iga et al., 2020). Scaffold with a microtubular size (20 µm) is similar to the structure of dentin, and it can support gel proliferation and differentiation of odontoblast cells (Haeri et al., 2017). Microporosity can increase the biomaterial surface area and increased protein adsorption will further increase cell adhesion (Herda and Puspitasari, 2018). It can support the transportation of nutrients and the bone regeneration process (Sobczak-Kupiec et al., 2021).

The combination of HAp or collagen with several flavonoids can support human osteoblast-like cell proliferation and differentiation, and regenerating bone structure. EGCG contains flavonoid can support the proliferation of seeding cells in sponges (Sobczak-Kupiec et al., 2021). In the present study, The percentage of living cell after HAp-Col-EGCG scaffold application was high. All samples support dental pulp cell proliferation. The higher HAp concentration is related to the higher viability of hDPSCs. Several characteristics have not been studied, so the researcher should explore other

formula characteristics, such as antibacterial effect or bioactive formula release. Thus, this confirmed the potential of the HAp-Col-EGCG scaffold.

5. Conclusion

The HAp-Col-EGCG fulfilled several ideal hydrogel scaffold criteria. The composition of the scaffold with 4% HAp concentration indicates the closest to the stoichiometric value. The FTIR analysis showed covalent bonds in all samples. The collagen was not denatured with HAp and EGCG addition. This material is non-toxic and highly likely to be used as a pulp regeneration induction material. In this study, not all the physical characterization tests were performed. Other characterizations such as antibacterial activity, the release of the bioactive material, and the clinical trial in the animal model should be performed.

Acknowledgments

This study used a cytotoxicity test by PT Prodia Stemcell Indonesia (ProStem), Jakarta, Indonesia.

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ICMJE DISCLOSURE FORM

Date: 6/18/2022

Your Name: **Theresia Indah Budhy**

Manuscript Title: **The Potential of Eggshell Hydroxyapatite, Collagen, and EGCG (HAp-Col-EGCG) Scaffold as AaPulp Regeneration Material**

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11	Stock or stock options	☒ **None**	
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Ethical clearance

Not applicable, as this research was not using any animal model.

Authors Statement

The authors declare that there is no conflict of interest.