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Three-dimensional (3D) printing-assisted freeze-casting of processed pyritum-doped β-tricalcium phosphate biomimetic scaffold with angiogenesis and bone regeneration capability

Chenxu WEI[1,2,4*], Zongan LI[3*], Xiaoyun LIANG[5*], Yuwei ZHAO[1,2], Xingyu ZHU[1,2], Haibing HUA[4], Guobao CHEN[4], Kunming QIN[6], Zhipeng CHEN[1,2], Changcan SHI[1,2✉], Feng ZHANG[3✉], Weidong LI[1,2✉]

[1]*School of Pharmacy, Nanjing University of Chinese Medicine, Nanjing 210023, China*
[2]*Nanjing University of Chinese Medicine, Jiangsu Key Laboratory of Chinese Medicine Processing, Engineering Center of State Ministry of Education for Standardization of Chinese Medicine Processing, Nanjing 210023, China*
[3]*Jiangsu Key Laboratory of 3D Printing Equipment and Manufacturing, School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing 210023, China*
[4]*Jiangyin Hospital Affiliated to Nanjing University of Chinese Medicine, Jiangyin 214400, China*
[5]*School of Pharmacy, Changchun University of Chinese Medicine, Changchun 130117, China*
[6]*School of Pharmacy, Jiangsu Ocean University, Lianyungang 222005, China*

Abstract: Bone repair remains an important target in tissue engineering, making the development of bioactive scaffolds for effective bone defect repair a critical objective. In this study, β-tricalcium phosphate (β-TCP) scaffolds incorporated with processed pyritum decoction (PPD) were fabricated using three-dimensional (3D) printing-assisted freeze-casting. The produced composite scaffolds were evaluated for their mechanical strength, physicochemical properties, biocompatibility, in vitro pro-angiogenic activity, and in vivo efficacy in repairing rabbit femoral defects. They not only demonstrated excellent physicochemical properties, enhanced mechanical strength, and good biosafety but also significantly promoted the proliferation, migration, and aggregation of pro-angiogenic human umbilical vein endothelial cells (HUVECs). In vivo studies revealed that all scaffold groups facilitated osteogenesis at the bone defect site, with the β-TCP scaffolds loaded with PPD markedly enhancing the expression of neurogenic locus Notch homolog protein 1 (Notch1), vascular endothelial growth factor (VEGF), bone morphogenetic protein-2 (BMP-2), and osteopontin (OPN). Overall, the scaffolds developed in this study exhibited strong angiogenic and osteogenic capabilities both in vitro and in vivo. The incorporation of PPD notably promoted the angiogenic-osteogenic coupling, thereby accelerating bone repair, which suggests that PPD is a promising material for bone repair and that the PPD/β-TCP scaffolds hold great potential as a bone graft alternative.

Key words: Bone defect; Processed pyritum; Three-dimensional (3D) printing-assisted freeze-casting; Angiogenesis; Bone regeneration; VEGF-Notch1-BMP-2-OPN coupling

1 Introduction

Each year, millions of people worldwide suffer from painful bone defects and require bone grafts (Giannoudis et al., 2005). The repair of large bone defects caused by trauma, infection, tumor resection, and other factors remains a major clinical challenge for reconstructive surgeons (Zhao et al., 2011; Lee et al., 2018; Zha et al., 2021; Wang et al., 2023; Zhang et al., 2023). Advances in tissue engineering have provided new options for bone defect repair (Maazouz et al., 2020; Wang et al., 2020; Liu et al., 2023), with artificial bone scaffolds offering advantages such as abundant donor sources, low immune rejection, and personalization, while avoiding the risk of donor-transmitted infectious diseases (Qin et al., 2019, 2022a, 2022b; Putra et al., 2022). However, the physicochemical

✉ Changcan SHI, cshi@njucm.edu.cn
Feng ZHANG, fengzhan@njnu.edu.cn
Weidong LI, liweidong0801@njucm.edu.cn
* The three authors contributed equally to this work
Changcan SHI, https://orcid.org/0000-0003-2416-6278
Feng ZHANG, https://orcid.org/0000-0001-6206-5537
Weidong LI, https://orcid.org/0000-0002-7664-1512

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properties of most artificial bone repair products are insufficient for supporting the skeletal structure (Zhang et al., 2019), and they often have low mechanical strength, limited osteogenic capacity, and poor vascularization potential (Li et al., 2020; Zhang et al., 2023).

Processed pyritum is one of the most important traditional Chinese medicines (Shi et al., 2023). Clinical applications have demonstrated that processed pyritum can promote bone reconstruction (Zhu et al., 2018), relieve pain, and enrich blood (Liu et al., 2017; Shi et al., 2023). Experimental studies revealed that processed pyritum could promote osteoblast differentiation and osteogenic function (Wang et al., 2021; Xu et al., 2023). Pyritum contains iron, magnesium, calcium, and other beneficial metal elements that are clinically efficient in the recovery of tendons and connecting bones. These metal elements can promote the process of bone vascularization by facilitating the expression of vascular endothelial growth factor (VEGF) and angiogenesis-related genes, along with activating related pathways to regulate bone angiogenesis and by promoting the expression of osteogenesis-related genes and proteins, such as bone morphogenetic protein-2 (BMP-2) and osteopontin (OPN). Iron is the most abundant trace element in the body. Appropriate amounts of iron promote osteoblastogenesis and exhibit a certain antimicrobial activity (Li et al., 2022; Yang et al., 2023). Magnesium contributes to forming an immune microenvironment that promotes osteogenesis and induces the production of anti-inflammatory cytokines and tissue repair factors during the early inflammatory period (Qiao et al., 2021). Furthermore, it affects angiogenesis and mineralization during bone repair (Tao et al., 2023; Qi et al., 2024). Calcium and zinc can induce osteoprogenitor cell differentiation through growth factor signaling pathways or stimulate other processes supporting bone tissue growth (Bai et al., 2023). Zinc supports the proliferation of osteoblasts, increases alkaline phosphatase activity, and exhibits antimicrobial properties (Wang et al., 2021). The sulfur contained in pyritum inhibits osteoclasts and exerts a positive effect on promoting osteogenesis and vascularization during bone regeneration (Zhou et al., 2022; Zhou et al., 2023). Research has shown that the addition of metal elements to ceramic materials can enhance their mechanical properties to a certain extent (Dong et al., 2022; Wang et al., 2022; Putra et al., 2023) and simultaneously promote the bone angiogenesis and osteogenic coupling processes.

β-Tricalcium phosphate (β-TCP) is a popular bone filling and graft material owing to its chemical composition similar to bone (Wang et al., 2012) and good biocompatibility (Seidenstuecker et al., 2017), excellent biodegradability (Lee et al., 2016), osteoinductivity, and osteoconductivity (Bohner et al., 2020; Ye et al., 2022). In clinical applications (Wang et al., 2013; Hernigou et al., 2017), β-TCP was found to be an ideal bone substitute for treating bone defects. The scaffolds prepared using β-TCP can be resorbed and remodeled into new bone in vivo, and produce fewer side effects than autologous bone grafts, leading to less pain for the recipient. Recently, the addition of bioactive metal ions into β-TCP to promote its biological performance has attracted much attention (Yu et al., 2018; Salamanca et al., 2022).

A porous microstructure is critical for scaffolds to promote good osteoinductivity and osteoconductivity. Among the various pore structure fabrication methods, freeze-casting technology is widely used to prepare bionic controllable biomaterials, such as ceramics and nanomaterials, because of its simplicity of operation, low cost, and environmentally friendly nature, which greatly broadens the applicability of freeze-casting material (Cheng et al., 2017; Shao et al., 2020; Chen et al., 2022; Deville et al., 2022; Li et al., 2024). In this study, we used three-dimensional (3D) printing-assisted freeze-casting technology to develop a bone repair scaffold with improved physicochemical properties. As for the material choice, we added the traditional Chinese medicine processed pyritum decoction (PPD) to β-TCP ceramic. 3D printing-templated polydimethylsiloxane (PDMS) mold was prepared according to the biological geometry feature of the recipient. The freeze-casting process allowed the formation of biomimetic micropores inside the bulk graft. The two components, PPD and β-TCP, were prepared as the materials for freeze-casting to form a bone repair bio-scaffold. The scaffolds exhibited good mechanical properties, porosity, and other beneficial physicochemical properties. Cell experiments indicated that the scaffold was not cytotoxic and exerted pro-angiogenic activity, while the repair of induced femoral defects in New Zealand white rabbits demonstrated the good in vivo bone repair performance of the scaffolds. Regarding the potential repair mechanism, the VEGF-neurogenic

locus Notch homolog protein 1 (Notch1)-BMP-2-OPN angiogenic-osteogenic coupling signaling pathway may be involved. The preparation of bone repair scaffolds with β-TCP loaded with PPD offers a new technical route for the future development of scaffolds for bone defect regeneration and repair.

2 Materials and methods

2.1 Preparation and characterization of scaffolds

2.1.1 Experimental materials

β-TCP (particle size of 0.20 μm, biomedical grade) was purchased from Suzhou Ding'an Technology Co., Ltd. (China); processed pyritum (lot number 201001311) was provided by Kangmei Pharmaceutical Co., Ltd. (China); glycerol (lot number GY20211107) was purchased from Shandong Ruisheng Pharmaceutical Excipients Co., Ltd. (China); high-glucose Dulbecco's modified Eagle's medium (DMEM) was purchased from Bio-Channel Biotechnology Co., Ltd. (China); fetal bovine serum was purchased from Gibco, Life Technologies Limited (USA); and cell counting kit-8 (CCK-8) was provided by APExBIO Technology LLC (USA).

2.1.2 Preparation of PPD

To prepare PPD, a certain amount of processed pyritum was taken and added with five times the amount of ultrapure water. Subsequently, it was refluxed for extraction for 120 min, filtered, concentrated, passed through a 0.45 μm nylon membrane, and adjusted to a drug content of 10 g/mL. The final solution was stored at 4 ℃ for further use. The four ion concentrations with the highest PPD content are listed in Table 1.

Table 1 Contents of iron, sulfur, calcium, and magnesium in processed pyritum decoction (PPD)

Element	Content (mg/mL)
Iron	43.30±0.03
Sulfur	26.60±0.07
Calcium	2.35±0.01
Magnesium	1.80±0.02

All values (n=3) are demonstrated as mean±standard deviation (SD).

2.1.3 Preparation of the scaffolds

The process flow of scaffold preparation is as follows. First, 3.07 g of β-TCP was weighed, followed by the addition of 1 mL of polyvinyl alcohol (PVA) solution (8.44%, mass fraction), 300 mg of glycerol, and different volumes of PPD, so that the percentages of processed pyritum were 0%, 5% (low PPD, LPPD), and 10% (high PPD, HPPD). Ultrapure water was added to reach the same final volumes. The prepared slurry was mixed thoroughly on an adjustable mixer and then injected into the PDMS molds on a freezing platform at −30 °C. The PDMS molds were prepared according to the geometry feature of the desired graft using a recently reported method (Zhang et al., 2024). After freeze-casting, the molds were demolded, and the scaffolds were lyophilized in a freeze-dryer, taken out, and sintered in a muffle furnace at 2 °C/min according to the set procedure. The sintering temperatures were set at 1050, 1100, and 1150 °C, respectively, for testing the properties of three different sets of scaffolds.

2.1.4 Mechanical properties of the scaffolds

The mechanical strength of the scaffolds sintered at 1050, 1100, and 1150 °C for 360 min was measured under a heating rate at 2 °C/min. The scaffolds in each group were placed in a biomechanical electric servo testing system (MTS Acumen3, MTS Systems Corporation, USA), and the mechanical strength of the scaffolds under compression was recorded at a compression speed of 1.0 mm/min. The force area of the scaffolds was recorded as S and the maximum force was recorded as F. The maximum mechanical strength (P) was calculated using Eq. (1):

$$P = \frac{F}{S}. \tag{1}$$

Simultaneously, the mechanical strength of each scaffold in the β-TCP, LPPD/β-TCP, and HPPD/β-TCP groups with different amounts of PPD extract at a sintering temperature of 1150 °C was determined under the same test conditions.

2.1.5 Properties of the sintered scaffolds

X-ray diffraction analysis of the scaffolds was performed using Cu target Kα radiation, λ=0.154 05 nm, tube voltage=40 kV, current=30 mA (Yazdanian et al., 2020), and scanning range=10°–70°.

The samples were analyzed using a Nicolet iS5 Fourier transform-infrared spectrometer, with a wavenumber range of 4000–400 cm^{-1}, scanning time of 16, and a resolution of 4 cm^{-1}. The measurement was

performed at room temperature, and the ambient humidity was <40%.

For assessing the microscopic surface topography of the scaffolds, the surfaces of the specimens were examined using scanning electron microscopy (SEM; S-4800, Hitachi, Ltd., Japan) to characterize the porous microstructure at 10 kV.

Scaffold materials (20 mg) in different groups were dissolved in 500 μL of phosphate-buffered saline (PBS; 0.01 mol/L, pH 7.2–7.4), with ultrapure water as the positive control and 0.01 mol/L PBS (pH 7.2–7.4) as the negative control. After 30 min of water bath at 37 °C, 500 μL of 2% (volume fraction) red blood cell suspension was added to each tube and mixed. The sample tubes from each group were bathed at 37 °C for 60 min and centrifuged at 1000 r/min for 10 min. The supernatant was transferred into a 96-well cell culture plate (80 μL/well), and the optical density (OD) value of each group was measured at 540 nm. The hemolysis rate (HR) was calculated using the following Eq. (2):

$$\mathrm{HR}=\frac{\mathrm{OD}_{\text{experimental group}}-\mathrm{OD}_{\text{negative group}}}{\mathrm{OD}_{\text{positive group}}-\mathrm{OD}_{\text{negative group}}}\times 100\%. \quad (2)$$

2.1.6 Shrinkage of the scaffolds

An electronic balance was used to weigh the mass (m) of each scaffold, and a digital vernier caliper was employed to measure the diameter (Φ) and height (h) of each corresponding scaffold. The volume of the scaffold was recorded as V. These parameters of the scaffold were recorded as m_1, Φ_1, h_1, and V_1 before sintering in the muffle furnace, and as m_2, Φ_2, h_2, and V_2 after sintering. Then, the mass shrinkage (ω_m), volume shrinkage (ω_v), transverse shrinkage (ω_x), and vertical shrinkage (ω_y) of the scaffolds were calculated according to the following Eqs. (3)–(7):

$$V=\pi h\left(\frac{\Phi}{2}\right)^2, \quad (3)$$

$$\omega_m=\frac{m_1-m_2}{m_1}\times 100\%, \quad (4)$$

$$\omega_v=\frac{V_1-V_2}{V_1}\times 100\%, \quad (5)$$

$$\omega_x=\frac{\Phi_1-\Phi_2}{\Phi_1}\times 100\%, \quad (6)$$

$$\omega_y=\frac{h_1-h_2}{h_1}\times 100\%. \quad (7)$$

2.1.7 Porosity of the scaffolds

The porosity of the scaffolds was evaluated using Archimedes' principle (Kathuria et al., 2009; Arahira and Todo, 2016). Briefly, the specific measurement method was as follows: the weight of the dried scaffold was recorded as W_s. The pycnometer was filled with ethanol (95% (volume fraction)) and the weight was recorded as W_1. The dry scaffold was added to the pycnometer, and a vacuum pump was used to pump ethanol into the pores inside the scaffold under pressure until no air bubbles were generated in the pycnometer. Ethanol was then added to fill the pycnometer and the weight was recorded as W_2. The scaffold was removed, the pycnometer was weighed, and the ethanol remaining in the bottle was recorded as W_3. The density of ethanol was denoted as ρ_e. The porosity (φ) was determined by the following Eq. (8):

$$\varphi=\frac{(W_2-W_3-W_s)/\rho_e}{(W_1-W_3)/\rho_e}\times 100\%. \quad (8)$$

2.1.8 In vitro degradation and release experiments

In these experiments, the scaffolds were placed into centrifuge tubes containing 5 mL of PBS (pH 7.2−7.4). The tubes were then placed in a constant-temperature water bath shaker at 37 °C for cyclotron oscillation, with a rotating speed of 160 r/min. The scaffolds were then removed and placed in a drying oven on the corresponding days. After drying, the samples were weighed, and the cumulative weight loss rates were calculated. Each time a new PBS solution was replaced, the concentrations of calcium and iron in each solution were determined using inductively coupled plasma-mass spectrometry, and the cumulative release was calculated. The pH of the scaffold degradation solution was measured using a pH meter.

2.2 In vitro cell experiments

Human umbilical vein endothelial cells (HUVECs) were used to assess the cytocompatibility and the pro-angiogenic properties of scaffolds.

2.2.1 Preparation of the scaffold extract

Scaffold extracts were prepared according to the ISO 10993 standard. The scaffolds were soaked in a

prepared complete DMEM (high glucose, supplemented with 10% fetal bovine serum (Gibco), 1% penicillin (100 U/mL), and streptomycin (0.1 mg/mL, Bio-Channel Biotechnology Co., Ltd., China), at 10 g/L and incubated in a thermostatic oscillator (37 ℃, 150 r/min). After 48 h, the scaffold extracts were collected and sterile-filtered. Samples were stored at 4 °C and diluted into different concentrations for subsequent use.

2.2.2 Indirect cell cytotoxicity

HUVECs were seeded into 96-well plates. After 24 h of incubation, the medium was replaced with the scaffold extract for one day. The effects of the scaffold extract on cellular cytotoxicity and cell survival were evaluated by live/dead staining of the co-cultured HUVECs and observation under a fluorescence microscopy.

Cell proliferation and viability were detected by the CCK-8 assay. HUVECs were seeded into 96-well plates at a density of 8×10^3 cells/well and cultured for 24 h. Cells were not added to the blank group. The culture medium was changed and the prepared extract was used for the experimental groups, while the complete medium was used for the blank and control groups. Next, four wells were assigned to each group and cultured for 24 h. The medium was discarded at the labeling time, and 100 μL of CCK-8 solution (1∶9 Medium, APExBIO Technology LLC, USA) was added for 1 h. Finally, the absorbance was measured at 450 nm.

2.2.3 Direct cell attachment on the scaffolds

The HUVECs (2×10^6 cells/well) were seeded onto the scaffolds. Following incubation for 24 h, the samples were fixed with a 2.5% (volume fraction) glutaraldehyde solution and progressively dehydrated in ethanol. After gold spraying, the samples were observed using a field emission scanning electron microscope (Hitachi Regulus 8100, Japan).

2.2.4 Wound healing experiments

At the back of a 6-well plate, a marker pen was used to draw lines evenly across the wells compared to a straight line, with three lines across each well. HUVECs in the logarithmic growth phase were digested with trypsin, centrifuged, blown into a single-cell suspension with complete DMEM, and then inoculated into a 6-well plate at a cell inoculation density of 6.5×10^5 cells/well, with 2 mL of medium per well. The cell culture plate was placed in a cell culture incubator (37 °C, 5% CO_2, and saturated humidity) overnight until the cells were fully adhered and spread over the bottom of the plate at approximately 90% to form a single-cell layer. Using 200 μL yellow pipette tips against a ruler, the fused single-cell layer was scratched perpendicular to the horizontal line on the back of the well plate. While keeping the tip of the pipette perpendicular, three strokes were made in per well and then washed gently three times with PBS to remove the unadhered and deciduous cells. Complete DMEM was added to the blank control group, the drug administration group was added with scaffold extracts with different concentrations (the concentration of drug administration was sieved according to the CCK-8 experiment). Then, 2 mL of solution was added to each well and the plate was placed in a cell incubator. After 0, 12, and 24 h of drug administration, the cell culture plate was examined under an inverted biomicroscope and photographed at a fixed position using ZEN software. It was ensured that the photographed positions were the same at different time points. Eight fixed positions were randomly assigned to each group. The wound area was measured using ImageJ software (National Institutes of Health, Bethesda, MD, USA) to calculate the wound healing rate of HUVECs in each group.

2.2.5 Transwell chamber experiments

The experimental groups and administration concentrations were the same as those in the HUVEC scratch-healing experiment. HUVECs under good growth conditions and in the logarithmic growth phase were digested with trypsin, centrifuged, counted after resuspension in basal DMEM (high glucose), and then diluted into a 5×10^5 cells/mL cell suspension. The blank control group was added with complete DMEM (high glucose), and the drug administration group was added with scaffold extracts with different concentrations in the lower chamber of Transwell plates at 600 μL/well. The aforementioned cell suspension was added to the Transwell chamber (chamber membrane pore size is 8.0 μm) at 100 μL/well. The subsequent experimental steps were performed according to the relevant literature (Guo et al., 2022). Cells that migrated to the lower chamber were photographed and counted under an inverted phase-contrast microscope in five randomly selected magnification fields.

2.3 Osteo-promotive effects of scaffolds in vivo

2.3.1 Animal model and scaffold implantation

This study was approved by the Animal Ethics Committee of Nanjing University of Chinese Medicine (No. 202204A075). Male New Zealand white rabbits (3–4 months old) were purchased from Jiangsu Zhenlin Biotechnology Co., Ltd. (Nanjing, China) and maintained in a common facility at the Animal Experiment Center of Nanjing University of Chinese Medicine (license No. SCXK (Su) 2021-0011). All rabbits were raised in standard single cages with appropriate bedding and constant temperature, and fed ad libitum (Dai et al., 2018). Sodium pentobarbital (3% (volume fraction)) was injected into the ear-margin vein at 30 mg/kg to maintain anesthesia during the entire operation process, and the animals were fixed in the supine position. After washing with physiological saline and iodophor, the skin and fascia were cut open to expose the femurs. A medical electric drill was used to produce a cylindrical cavity with a height of 7 mm and a diameter of 8 mm in the distal femur of rabbits, thus creating a bone defect site. After the scaffolds were sterilized using high-pressure steam and ultraviolet rays, they were implanted into the bone defect by placing them in the cavity. The muscle tissue, fascia, and surface skin were disinfected and sutured layer-by-layer. Each animal received an intramuscular injection of penicillin sodium (400 000 units per day) for the first three days after surgery to prevent infections, and the dietary excretion and mental status of the animals were observed. The following groups were set for the purposes of this study: (1) control group without scaffold implantation; (2) positive group implanted with β-TCP scaffold; (3) LPPD/β-TCP group with 5% PPD and β-TCP scaffold implantation; (4) HPPD/β-TCP group with 10% PPD and β-TCP scaffold implantation.

The rabbits were sacrificed at 4, 8, and 12 weeks postoperatively by injecting overdosed pentobarbital sodium through the auricular vein. The bones were isolated for micro-computed tomography (micro-CT) scan and histological analysis.

2.3.2 In vivo biosafety tests

Blood samples were collected from male rabbits four weeks after surgery to measure the concentrations of alanine aminotransferase, aspartate aminotransferase, albumin, globulin, total protein, creatinine, and blood urea nitrogen (Zhang et al., 2022), and the ratio of albumin to globulin. Simultaneously, the elemental contents of iron, calcium, and phosphorus in the blood samples were determined, and the amount of calcium-phosphorus product was calculated. The liver, kidney, spleen, and thymus samples of the rabbits were collected four weeks after surgery to evaluate the biosafety in vivo. After routine embedding, sectioning, and hematoxylin and eosin (H&E) staining, tissue sections were imaged.

2.3.3 Micro-CT

The animals were sacrificed 4, 8, and 12 weeks after implantation, and femur bone samples were immediately harvested and fixed in 4% (volume fraction) paraformaldehyde for further micro-CT analysis (Lee et al., 2018). The images were reconstructed into 3D images and used to measure new bone volume (BV, μm^3), bone volume density (bone volume/tissue volume (BV/TV), %), and trabecular separation (Tb.Sp, mm).

2.3.4 Histological and immunohistochemical analyses

Femur samples were taken 4, 8, and 12 weeks after the implantation of scaffolds and fixed with 4% (volume fraction) paraformaldehyde for one week. The samples were then decalcified with 10% (volume fraction) ethylenediamine tetra-acetic acid (EDTA) until the bone softened, and the specimens were embedded in paraffin wax and sliced. Tissue sections were stained with H&E and Masson's trichrome for histological analysis. Immunohistochemical analysis of the bone samples was performed four weeks after scaffold implantation. Immunohistochemical staining was performed using antibodies to detect the expression of Notch1, VEGF, and BMP-2, and immunofluorescence staining was performed with antibodies against VEGF, BMP-2, and OPN. Semi-quantitative analysis was conducted using Image-Pro Plus software (Media Cybernetics, USA).

2.4 Statistical analysis

All quantitative data were expressed as mean± standard deviation (SD). Data were analyzed using an independent sample *t*-test and one-way analysis of variance (ANOVA) for the assessment of statistical significance. Differences were considered statistically significant when the *P* value was <0.05.

3 Results

3.1 Preparation and characterization of scaffolds

The preparation process of scaffold using 3D printing-assisted freeze-casting technology is shown in Fig. 1a. The scaffold measured 7 mm in height and 8 mm in diameter. The physical and SEM images of the pure β-TCP scaffold and β-TCP scaffolds loaded with PPD are shown in Figs. 1b and 1c, respectively. The scaffolds are regular and cylindrical. In the pure β-TCP scaffold group without PPD, the pure white background color of β-TCP can be observed. Meanwhile, the LPPD/β-TCP scaffold and HPPD/β-TCP scaffold groups loaded with different doses of processed pyritum extract appear dark red with different color depths. The top and side views of the cylindrical scaffolds reveal the microporous structure of the scaffold. The pore sizes range from 2 to 40 μm, which facilitates cell movement.

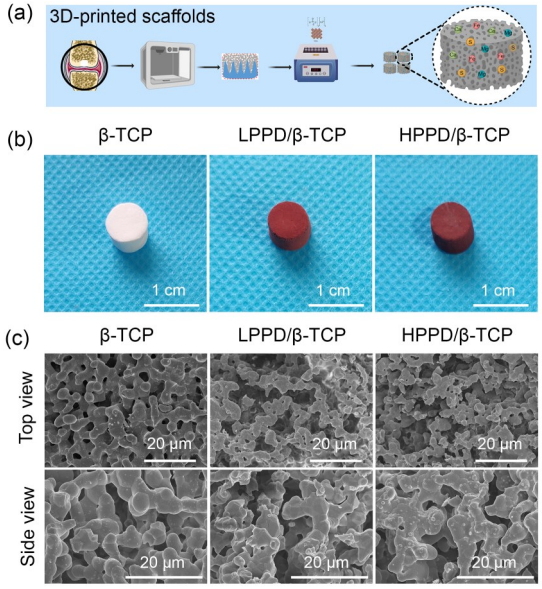

Fig. 1 Preparation and surface morphology of the scaffolds. (a) Preparation process of scaffold using three-dimensional (3D) printing-assisted freeze-casting technology. (b) The final formed scaffolds. (c) Scanning electron microscopy (SEM) image of the scaffolds. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD: 10% PPD and β-TCP scaffold.

Fourier transform-infrared spectroscopy analysis (Fig. 2a) indicated that the scaffolds did not undergo a phase change at this sintering temperature, and no chemical reaction occurred. According to the X-ray diffraction maps (Fig. 2b) of the three sets of scaffold materials, the main phase of each group of scaffolds was β-TCP phase (PDF#09-0169), among which the samples of LPPD/β-TCP and HPPD/β-TCP scaffolds also contained processed pyritum phases (PDF#89-0599). When the sintering temperature reached 1150 ℃, the mechanical strength was greatly improved (Fig. 2c). Under the same sintering procedure, the mechanical strength of the scaffolds after β-TCP drug loading tended to increase. Under the set process conditions of 2 °C/min to a sintering temperature of 1150 °C and holding time of 360 min, the effect of PPD addition on the mechanical strength of the scaffolds are shown in Fig. 2d. Within a certain dose range, the mechanical strength of the scaffold was positively correlated with the PPD dose. Based on mechanical strength measurements, this process was selected for the preparation of the scaffolds. It can be seen in Fig. 2e that the scaffold degradation rate increased over time; by the third week, scaffolds without PPD degraded significantly faster than those with PPD. As shown in Fig. 2f, after five weeks of degradation, there was hardly any effect of the solvent pH change during the scaffold degradation process. The releases of iron (Fig. 2g) and calcium (Fig. 2h) during degradation showed that after loading with PPD, the release of calcium slowed down, which could have a therapeutic effect on sustained release. As shown in Fig. 2i, the microporosity of each group was good, distributed in a reasonable range of 68.00%–82.00%. The scaffolds exhibited good microporous characteristics, as shown in Figs. 2j–2m. HPPD/β-TCP had the most obvious transverse shrinkage (Fig. 2j), vertical shrinkage (Fig. 2k), mass shrinkage (Fig. 2l), and volume shrinkage (Fig. 2m), which might also contribute to the increase of its mechanical strength after sintering. According to the results of in vitro hemolysis experiments shown in Fig. 2n, the average hemolysis rates of the three groups of scaffold materials were <5.00%. Referring to the ISO 10993-4:2002 standard, this material meets the hemolysis requirements of medical biomaterials.

3.2 In vitro cell experiments

As shown in Fig. 3a, the cells grew normally in the range of the administered concentrations of scaffold extract, and therefore, the scaffolds were found to be safe and reliable. In addition, when the dilution factor was 1000, the proliferative effect of HUVECs in the scaffold extract was the best. The β-TCP scaffold

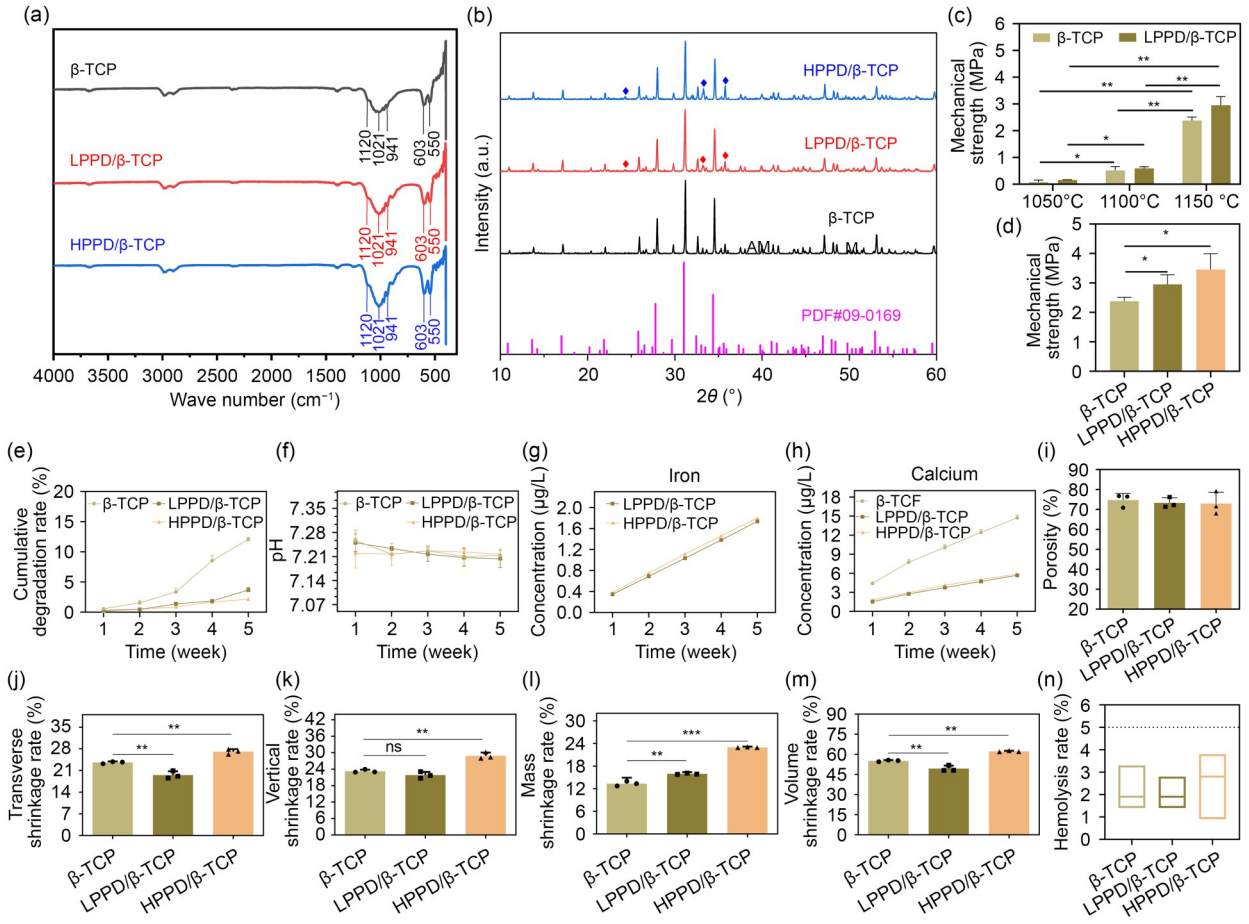

Fig. 2 Characterization of the prepared scaffolds. (a) Fourier transform-infrared spectroscopy of the scaffold powder. (b) X-ray diffraction of the scaffold powder. (c) Mechanical strength test results of each group of scaffolds at different sintering temperatures. (d) Mechanical strength test results of scaffolds with different dosing amounts. (e–h) Degradation and release of scaffolds in vitro: (e) Cumulative degradation rate of scaffolds; (f) Degradation solution pH value; (g) Iron concentration in the degradation solution; (h) Calcium concentration in the degradation solution. (i) The porosity of scaffolds. (j–m) Shrinkage of scaffolds before and after sintering: (j) Transverse shrinkage rate; (k) Vertical shrinkage rate; (l) Mass shrinkage rate; (m) Volume shrinkage rate. (n) In vitro hemolysis experiment. All values (n=3) are demonstrated as mean± standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001; ^{ns} P>0.05. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold; a.u.: arbitrary unit.

loaded with PPD could significantly promote the proliferation of HUVECs; hence this dilution factor was selected as the concentration of HUVECs for subsequent experiments. As shown in Fig. 3b, the HUVECs in each group showed good survival, normal cell morphology, and normal growth, consistent with the aforementioned CCK-8 results (Fig. 3a).

The wound healing images and quantitative statistical results for the healing area are presented in Figs. 3c and 3d, respectively. After 12 and 24 h of administration, relative to the control and β-TCP groups, scaffolds in the LPPD/β-TCP and HPPD/β-TCP groups could significantly promote the wound healing of HUVECs and within a certain range, the trend of wound healing rate increased in a positive correlation with the dose of PPD.

A schematic of the Transwell chamber migration, Transwell chamber migration assay, and quantitative statistical results are shown in Figs. 3e–3g. After administration, the number of HUVECs penetrating the membrane increased significantly and the β-TCP scaffolds loaded with PPD promoted the migration of HUVECs. This was confirmed by the aforementioned wound healing experiment, indicating that the scaffold presented a good ability to promote HUVEC migration and wound healing.

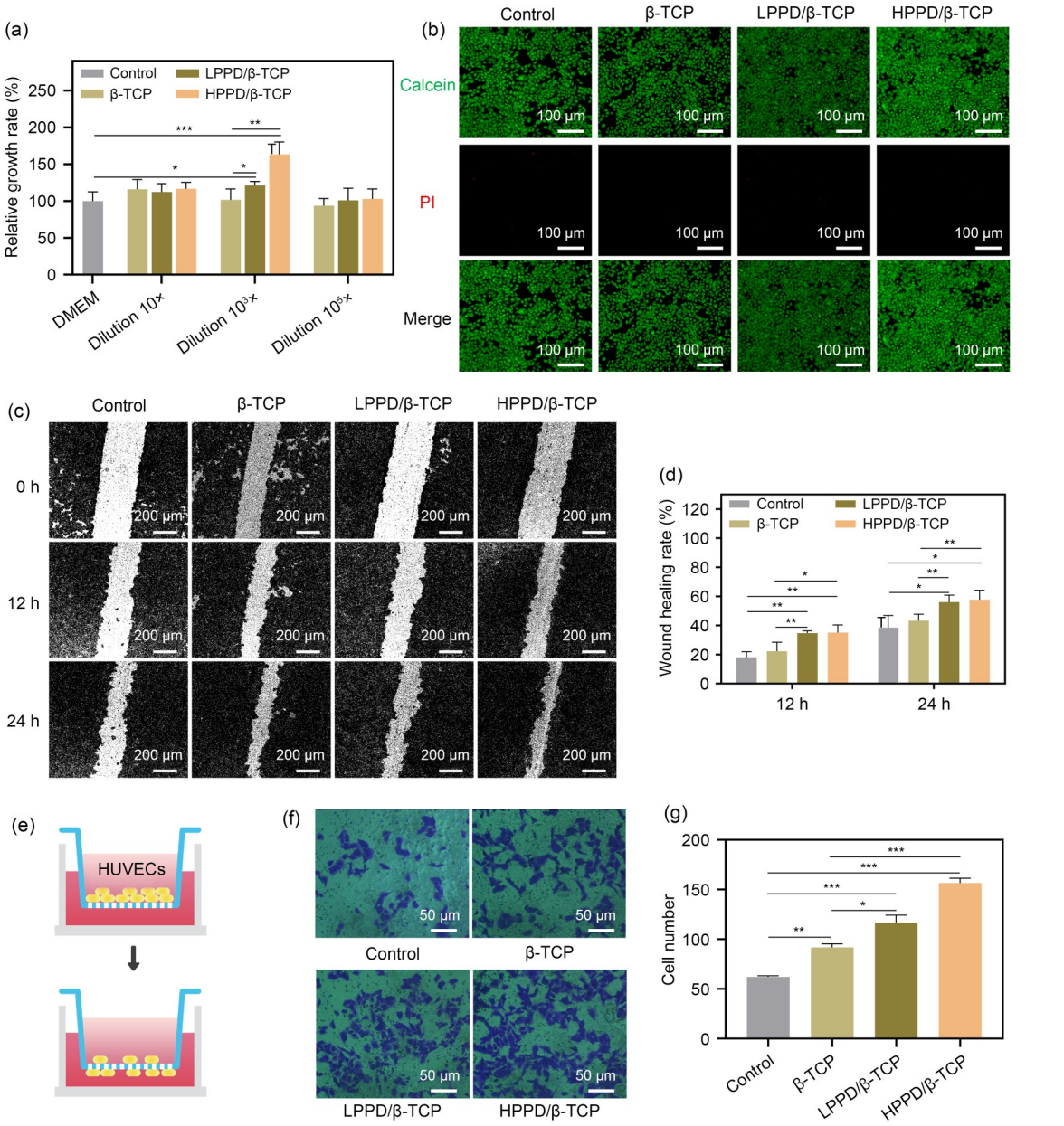

Fig. 3 In vitro cell experiment. (a) 24 h cell counting kit-8 (CCK-8) cell proliferation detection. (b) Live/dead staining of human umbilical vein endothelial cells (HUVECs) after culture using scaffold extract for 1 d. (c, d) Wound healing experiment and quantitative statistical results of the healing area. (e) Schematic of Transwell chamber migration. (f, g) Transwell chamber migration assay and its quantitative statistical results. All values (n=4) are demonstrated as mean±standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold; DMEM: Dulbecco's modified Eagle's medium; PI: propidium iodide.

3.3 Osteo-promotive effects of scaffolds in vivo

The results of serological liver and kidney biochemical indexes are shown in Figs. 4a–4h. Among the main indexes of liver function in all groups of rabbits, the alanine aminotransferase (Fig. 4a) or aspartate aminotransferase (Fig. 4b) level was not significantly increased, and the level of albumin (Fig. 4c), globulin (Fig. 4d), leukoglobulin ratio (Fig. 4e), or total protein (Fig. 4f) was not significantly decreased. The levels of renal function indicators, such as creatinine (Fig. 4g) and blood urea nitrogen (Fig. 4h), were not significantly increased. These results indicate that the scaffold exhibited good biosafety in vivo.

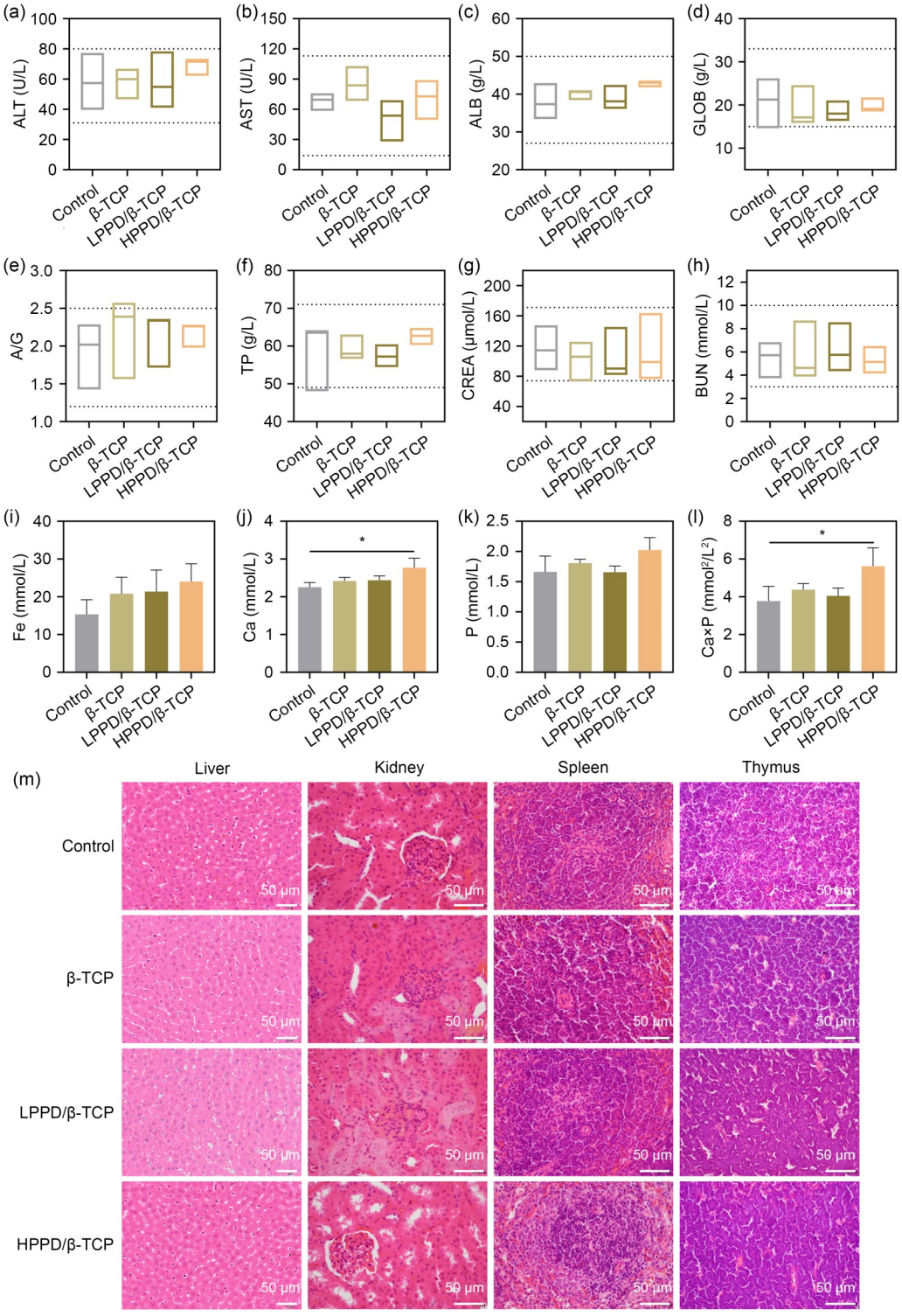

Fig. 4 Serum liver, kidney, and bone biochemical indexes four weeks after operation. (a–h) Biochemical indexes of liver and kidney: (a) alanine aminotransferase (ALT); (b) aspartate aminotransferase (AST); (c) albumin (ALB); (d) globulin (GLOB); (e) albumin/globulin (A/G); (f) total protein (TP); (g) creatinine (CREA); (h) blood urea nitrogen (BUN). (i–l) Bone biochemical markers: (i) content of iron (Fe); (j) content of calcium (Ca); (k) content of phosphorus (P); (l) calcium-phosphorus product (Ca×P). (m) Organ safety evaluation. All values (n=3) are demonstrated as mean±standard deviation (SD). * P<0.05. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold.

The results of bone biochemical analyses show that there was no significant difference in the contents of iron (Fig. 4i) or phosphorus (Fig. 4k) among the groups. On the other hand, the contents of calcium (Fig. 4j) and calcium-phosphorus product (Fig. 4l) in the HPPD/β-TCP group were significantly higher than those in the control group. Pathological analysis revealed that the liver, kidneys, spleen, and thymus were structurally normal without obvious lesions or toxic reactions (Fig. 4m), indicating that the scaffold had good biocompatibility in vivo.

A schematic illustration of our animal study design is shown in Fig. 5a. In the rabbit femoral defect experiment, we analyzed the formation of new bone in the defect area using micro-CT. The result was illustrated in Fig. 5b. Combined with the quantitative analyses of BV (Fig. 5c), BV/TV (Fig. 5d), and Tb.Sp (Fig. 5e), the experiment confirmed that at 4, 8, and 12 weeks postoperatively, there was more bone formation in the area of bone defects in the drug-loaded group than in the pure β-TCP group, which in turn outperformed the control group. The experimental results

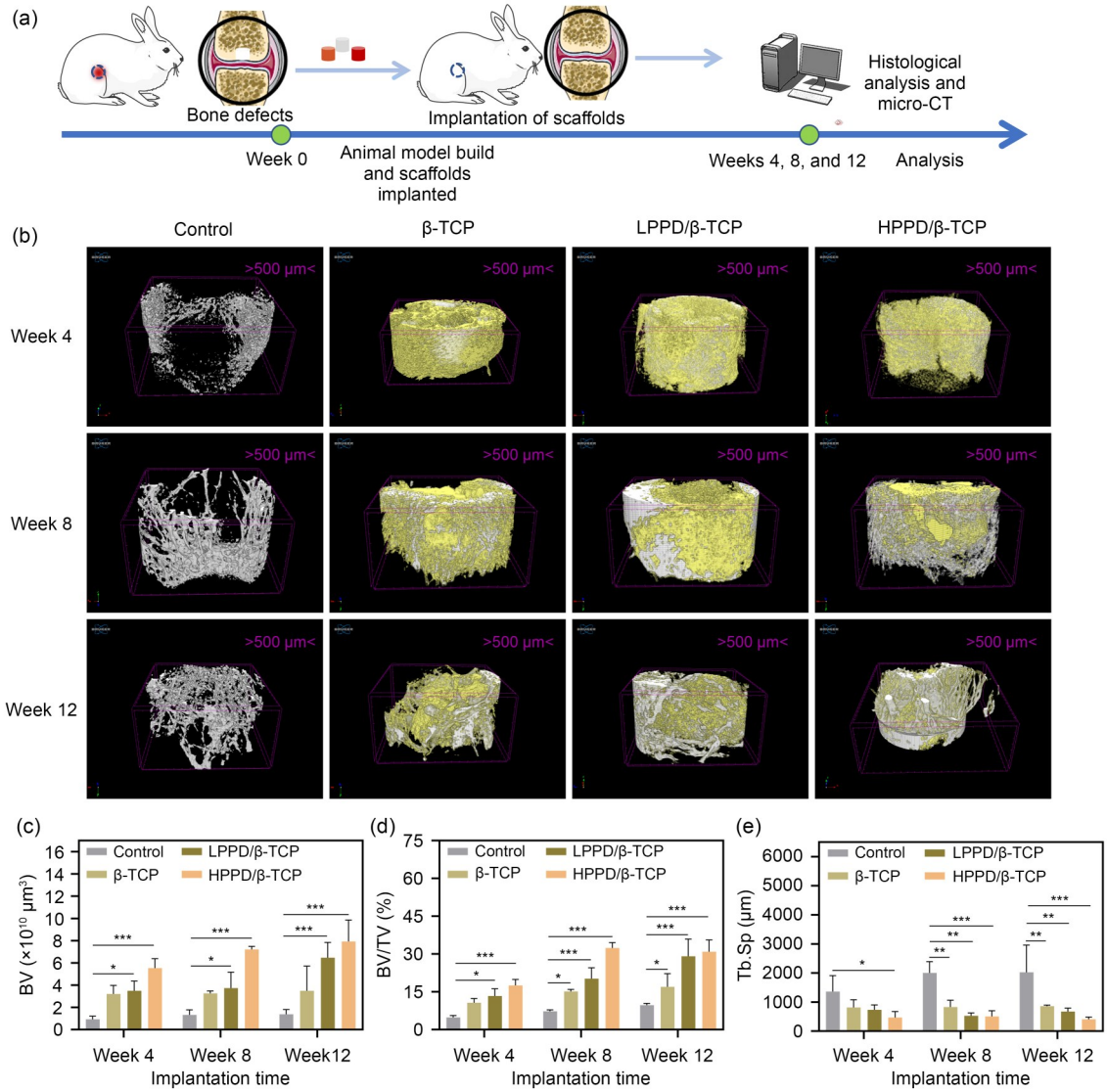

Fig. 5 Gross images and micro-computed tomography (micro-CT) analysis results of the repaired bone defects for the four groups at 4, 8, and 12 weeks after surgery. (a) Schematic illustration of the design of the animal study. (b) Three-dimensional (3D) reconstruction images of the new bone at the defect site on the scaffold. (c–e) Quantitative data of bone volume (BV), bone volume density (BV/TV), and (e) trabecular separation (Tb.Sp) for the four groups based on micro-CT images. All values (n=3) are demonstrated as mean±standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold.

confirmed that the scaffold prepared in this study promoted the repair of bone defects to a certain extent, and the addition of traditional Chinese medicine processed pyritum accelerated the bone repair process.

During the regeneration process, new bone tissue gradually grew toward the central region of the scaffold and entered most of its macropores. In Fig. 6a, the residual scaffold material (black arrow) is visible in the field of view, except for the control group without the implanted scaffold. The areas of the implanted scaffolds exhibit different degrees of trabecular hyperplasia, which is closely arranged and forms new bone tissues (red arrow). Osteoblasts and osteoclasts are distributed on the surface of bone trabeculae. With an increase in postoperative time, osteoblasts (gray arrow) gradually increased, and osteoclasts (blue arrow) decreased. New capillaries (purple arrow) can be observed in the trabecular space and margins, and bone blood vessels continued to form and increase over time. The drug-loaded implantation groups had more bone formation than the β-TCP group, and the pure β-TCP scaffold implantation groups had more bone formation than the control group. Bone formation in the HPPD/β-TCP group increased the most; the bone tissue was connected into a large area of new bone tissue; and the separation degree of the bone trabecular was reduced. These results were supported by the semi-quantitative H&E staining of new bone formation in the implant area (Fig. 6c).

Masson's trichrome staining (Fig. 6b) revealed greater new bone formation in the scaffold implantation groups. The longer the postoperative time, the more new bone tissue was formed. Semi-quantitative histology analysis of new bone formation in the implant area (Fig. 6d) revealed that the LPPD/β-TCP and HPPD/β-TCP groups had a greater increase in new bone formation compared with the control and β-TCP groups. The scaffold group with a high drug dose showed a significant increase compared with the lower dose group. These results followed the same trend as the H&E staining results, and the two results were mutually supportive.

The immunohistochemical staining results for Notch1, VEGF, and BMP-2 are shown in Fig. 7a, and the immunofluorescence staining results of VEGF, BMP-2, and OPN are shown in Fig. 8a. We observed the same trend in both experiments; that is, four weeks after scaffold implantation, the expression of angiogenic and osteogenic factors in the β-TCP group loaded with the traditional Chinese medicine PPD was essentially significantly higher than that in the pure β-TCP group. The semi-quantitative analysis results (Figs. 7b–7d and Figs. 8b–8d) verified the accuracy of the prediction results.

4 Discussion

The repair of large bone defects exceeding a certain critical size is an urgent problem in orthopedic clinics. The 3D-printing technology offers great potential for personalized regenerative repair in bone tissue engineering (Wang et al., 2024). In this study, a novel composite ceramic bone repair scaffold loaded with a traditional Chinese medicine PPD was developed based on 3D printing-assisted freeze-casting technology, and a composite ceramic scaffold promoting the repair of femoral defects in New Zealand white rabbits was prepared by combining PPD with β-TCP, a modern bone repair ceramic material. The fabricated scaffold demonstrated to have good physicochemical properties and biosafety. Moreover, the mechanical properties of the scaffold were significantly enhanced after loading it with PPD, which addresses the shortcomings of insufficient mechanical properties of pure β-TCP and other ceramic materials (Hao et al., 2023; Wang et al., 2024), providing the possibility of repairing the bone defects at the load-bearing bone. It was able to provide good support at the site of load-bearing bone defects rather than rapidly collapsing and fracturing. Based on the available literature (Wang et al., 2021), the mechanical strength of the composite scaffolds meets the clinical requirements for load-bearing bone repair and is at the lower end of the normal range. This level of mechanical strength is more conducive to the degradation and release of the scaffold after implantation as well as cellular infiltration, promoting vascularization and osteogenesis in the bone microenvironment. Pore structure directly affects osteogenic inducibility (Wu et al., 2024). An appropriate pore structure and porosity directly facilitate the cellular state of the bone microenvironment and cell infiltration, migration, and adhesion (Du et al., 2024), which in turn affects angiogenesis and osteogenesis. For instance, too low porosity of the scaffold hinders the entry of angiogenesis-related cells, while too high porosity in turn impairs the mechanical strength of the scaffold. The porosity of the composite scaffold in this study

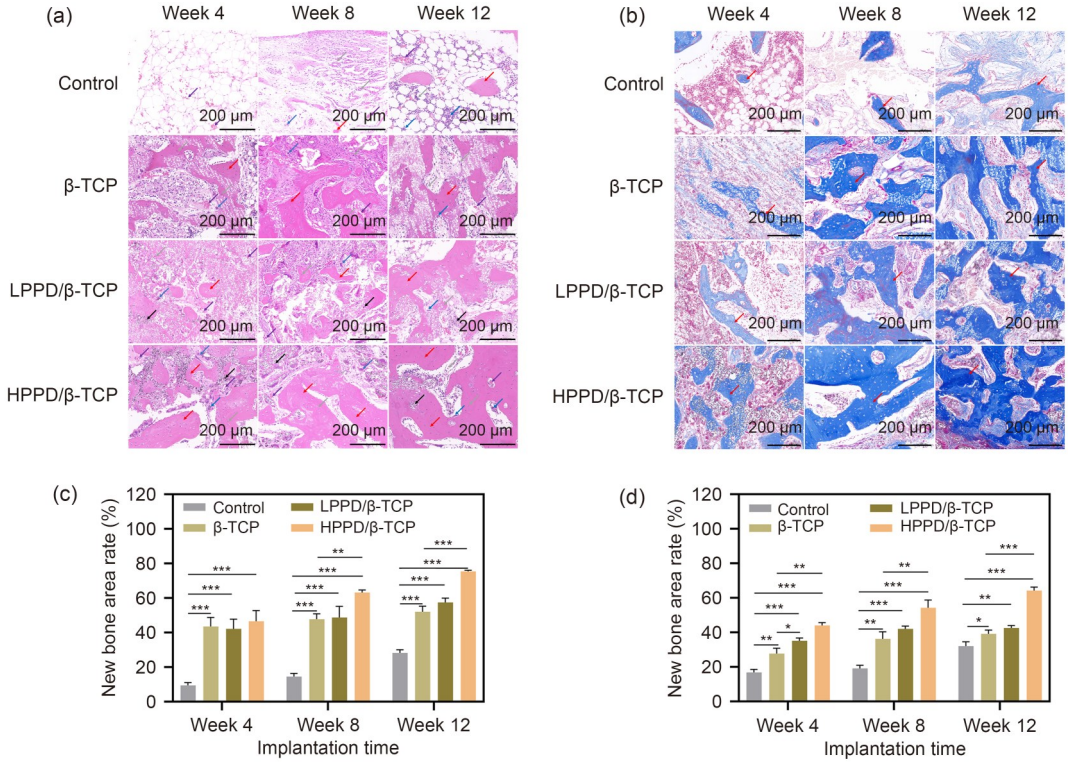

Fig. 6 Histomorphometric images and quantitative analysis of the decalcified sections. (a) Representative hematoxylin and eosin (H&E) staining images. (b) Representative Masson staining images. (c, d) Semi-quantitative analyses of new bone tissue: (c) H&E staining; (d) Masson staining. The red arrows represent new osteogenic tissue, the gray arrows represent osteoblasts, the blue arrows represent osteoclasts, the purple arrows represent new capillaries, and the black arrows represent undegraded scaffolds. All values (n=3) are demonstrated as mean±standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold.

was in a reasonable range (Joshi et al., 2020), which is conducive to the migration movement of HUVECs and accelerates angiogenesis and osteogenesis during bone defect repair. At the same time, it ensures that the composite scaffold has appropriate mechanical strength.

Bone is a highly vascularized tissue. Angiogenesis is essential for nutrient transport, exchange, and connectivity during bone repair and is closely related to the outcome of bone repair (Guo et al., 2023). VEGF, a key angiogenic factor, acts upstream of Notch1 (Grosso et al., 2023). After scaffold implantation in bone defects, the VEGF receptor is activated, leading to the release of VEGF. This stimulates the downstream Notch1 receptor to release Notch1, which in turn promotes bone vascularization. BMP is a member of the transforming growth factor-β (TGF-β) superfamily, of which BMP-2 has a highly efficient osteoinductive ability and promotes bone formation. OPN plays an important role in bone matrix mineralization, activates cell aggregation and adhesion, and is closely associated with bone resorption and formation (Zhu et al., 2024). In this study, animal experiments verified that PPD/β-TCP composite scaffolds significantly upregulated the expression of not only angiogenesis-related factors but also osteogenesis-related proteins through the angiogenesis–osteogenesis coupling of the VEGF-Notch1-BMP-2-OPN pathway. This effect greatly facilitated the process of bone repair in the induced rabbit bone defects.

5 Conclusions

In this work, PPD/β-TCP bone repair scaffolds loaded with PPD (a traditional Chinese medicine extract) were successfully prepared and extensively investigated for their biosafety, mechanical properties, and ability to facilitate bone repair. The scaffolds exhibited good physicochemical properties such as mechanical strength and biosafety. Cellular and animal

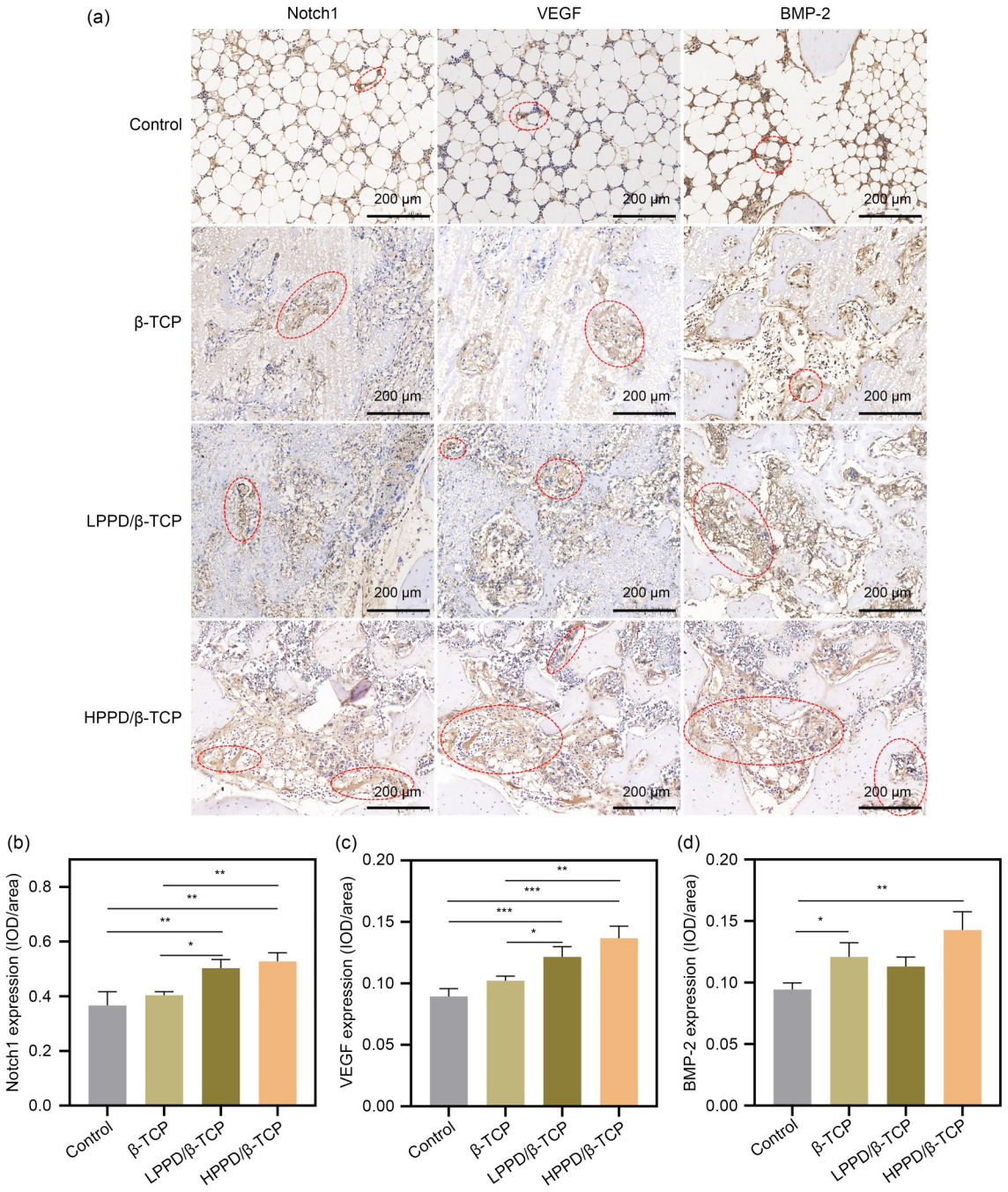

Fig. 7 Immunohistochemical analyses of neurogenic locus Notch homolog protein 1 (Notch1), vascular endothelial growth factor (VEGF), and bone morphogenetic protein-2 (BMP-2). (a) Images of immunohistochemical staining of Notch1, VEGF, and BMP-2 at Week 4. (b–d) Semi-quantitative analyses of the formation of new bone expressing Notch1 (b), VEGF (c), and BMP-2 (d) at Week 4. The circles represent the respective positive areas. All values (n=3) are demonstrated as mean±standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold; IOD: integrated optical density.

experiments demonstrated that the scaffold possessed the dual advantages of angiogenesis and osteogenesis, which in turn promoted bone regeneration and accelerated bone repair. This study provides a new method for the clinical treatment of bone defects. The scaffolds loaded with PPD have great potential for further development in clinical settings as a bone repair material.

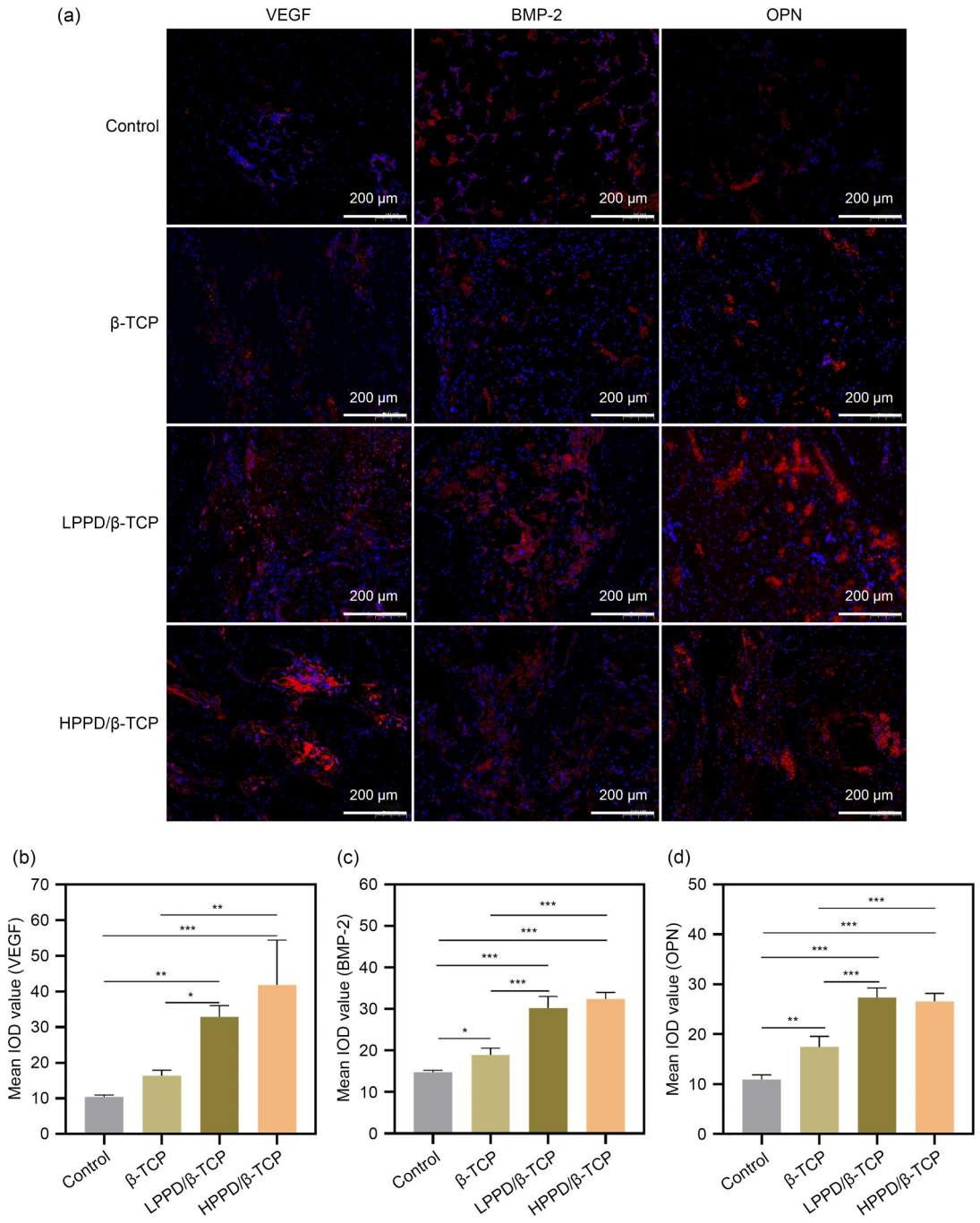

Fig. 8 Immunofluorescence analyses of vascular endothelial growth factor (VEGF), bone morphogenetic protein-2 (BMP-2), and osteopontin (OPN). (a) Immunofluorescence staining images of VEGF, BMP-2, and OPN at Week 4. (b–d) Semi-quantitative analyses of the formation of new bone expressing VEGF (b), BMP-2 (c), and OPN (d) at Week 4. All values (n=3) are demonstrated as mean±standard deviation (SD). * P<0.05; ** P<0.01; *** P<0.001. β-TCP: β-tricalcium phosphate; PPD: processed pyritum decoction; LPPD/β-TCP: 5% PPD and β-TCP scaffold; HPPD/β-TCP: 10% PPD and β-TCP scaffold; IOD: integrated optical density.

Data availability statement

All statistical data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Chenxu WEI, Zongan LI, and Xiaoyun LIANG contributed to the conceptualization, methodology, experimental operation, project design, data curation, writing – original draft, and writing – review & editing. Yuwei ZHAO, Xingyu ZHU, Haibing HUA, and Guobao CHEN contributed to the experimental operation. Kunming QIN and Zhipeng CHEN contributed to the writing – review & editing. Changcan SHI, Feng ZHANG, and Weidong LI contributed to the resources, project design, conceptualization, supervision, writing – review & editing, project administration, and funding acquisition. All authors have read and approved the final manuscript, and therefore, have full access to all the data in the study and take responsibility for the integrity and security of the data.

Compliance with ethics guidelines

Chenxu WEI, Zongan LI, Xiaoyun LIANG, Yuwei ZHAO, Xingyu ZHU, Haibing HUA, Guobao CHEN, Kunming QIN, Zhipeng CHEN, Changcan SHI, Feng ZHANG, and Weidong LI declare that they have no conflicts of interest.

All institutional and national guidelines for the care and use of laboratory animals were followed. The study was approved by the Nanjing University of Chinese Medicine Animal Ethics Committee (No. 202204A075), China.

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