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PROCESSAMENTO DE OSSOS ANIMAIS PARA A BIOECONOMIA CIRCULAR: MÉTODOS, PRODUTOS, APLICAÇÕES E REGULAÇÃO (REVISÃO 2020–2025)

ANIMAL BONE PROCESSING FOR A CIRCULAR BIOECONOMY: METHODS, PRODUCTS, APPLICATIONS, AND POLICY (2020–2025 REVIEW)

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Resumo

Ossos de origem animal são coprodutos abundantes da indústria de carnes e constituem fonte estratégica de cálcio, fósforo e proteínas (colágeno/gelatina). Esta revisão (2020–2025) sintetiza toda a cadeia de processamento—da preparação/limpeza às quatro rotas principais: (i) renderização para farinha/farelo de osso voltados a ração e fertilizantes fosfatados de liberação lenta; (ii) calcinação para cinza de osso com fases ajustáveis de HAp/β-TCP/α-TCP, adequadas a fertilizantes e biocerâmicos; (iii) processos hidrotérmicos/químicos para extração de colágeno/gelatina e produção de fosfatos solúveis (p.ex., DCP/MCP); e (iv) rotas biotecnológicas, incluindo micro-organismos solubilizadores de fosfato e tratamento hidrotérmico + digestão anaeróbia com recuperação de nutrientes (estruvita/DCP). Consolidamos janelas operacionais representativas (p.ex., ~700–950 °C para HAp; ~900–1050 °C para BCP; > 1125 °C para α-TCP; 120–180 °C para água subcrítica) e métricas de qualidade para tomada de decisão (XRD/FTIR para fases Ca-P, BET/porosidade, citrato/NAC ou DGT para disponibilidade de P, Bloom para gelatina). As aplicações industriais abrangem agricultura, alimentos, biomédica e energia; a seção regulatória resume salvaguardas sanitárias (ABP/príons) e vias de mercado (FPR/CMCs) para fertilizantes reciclados. Identificamos lacunas em padronização analítica, LCA/TEA de rotas eletrificadas/intensificadas, ensaios de campo de fertilizantes de osso e interoperabilidade regulatória. Concluímos que os ossos são um insumo circular de alto impacto, capaz de entregar benefícios ambientais,

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resiliência econômica e materiais avançados quando processados com controle de qualidade e conformidade regulatória.
Palavras-chave: osso animal; hidroxiapatita; carvão de osso; colágeno; gelatina; fosfato dicálcico (DCP); digestão anaeróbia; recuperação de fósforo; economia circular.

Abstract

Animal bones are abundant co-products of the meat industry and a strategic source of calcium and phosphorus alongside valuable proteins (collagen/gelatin). This review synthesizes advances (2020–2025) across the full processing chain—from preparation and cleaning to four principal routes: (i) rendering to bone meal/flour for feed and slow-release fertilizers; (ii) calcination to bone ash with tunable hydroxyapatite (HAp), β-tricalcium phosphate (β-TCP) and α-TCP for fertilizers and bioceramics; (iii) hydrothermal/chemical approaches for collagen/gelatin extraction and soluble phosphates (e.g., DCP/MCP); and (iv) biotechnological pathways, including phosphate-solubilizing microbes and hydrothermal treatment + anaerobic digestion with nutrient recovery. We consolidate operating windows (e.g., ~700–950 °C for HAp-rich ash; ~900–1050 °C for BCP; >1125 °C for α-TCP; 120–180 °C for subcritical-water extraction), decision points, and quality metrics (XRD/FTIR phase analysis, BET/porosity, citrate/NAC or DGT phosphorus availability, Bloom strength for gelatin). Industrial applications span agriculture (recycled P fertilizers), food (gelatin/collagen), biomedical (HAp/TCP biomaterials), and energy (bone char, biogas), with environmental and regulatory sections outlining sanitary safeguards (ABP categories, feed-ban rules) and EU fertilizer market entry (FPR/CMC pathways). We identify research gaps in harmonized QA/QC across routes, decision-grade LCA/TEA for electrified or intensified processing, field-scale agronomy for bone-derived P fertilizers, and regulatory interoperability to enable cross-border trade. Overall, bones represent a high-leverage circular feedstock; with fit-for-purpose processing and robust compliance, they can deliver environmental benefits, economic resilience, and advanced materials performance.
Keywords: animal bone; hydroxyapatite; bone char; collagen; gelatin; dicalcium phosphate (DCP); anaerobic digestion; phosphate recovery; circular economy.

1. Introduction

The meat industry generates a substantial amount of **animal bones** as by-products during slaughter and processing. Globally, bones represent around 9–10% of animal live weight and are frequently categorized as low-value residues. If improperly disposed, bone waste may cause serious environmental burdens, including methane emissions and local pollution (ALIBEKOV et al., 2024).

On the other hand, the valorization of animal bones aligns with circular economy principles, enabling the recovery of high-value compounds such as collagen, hydroxyapatite, gelatin, biochar, and calcium phosphate (PICCIRILLO et al 2023). Their utilization contributes to sustainable resource management, reducing the dependence on virgin raw materials and creating new economic opportunities

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(HART et al. 2022).

Recent studies have demonstrated applications of bone-derived materials in agriculture, catalysis, biomedicine, energy, and water treatment (LECOMPTE et al 2025). These findings reinforce the dual importance—economic and environmental—of adequately processing animal bones and integrating them into value chains.

1.1. General Objectives

The objective of this review is to:

- Summarize and critically assess the main methods (mechanical, thermal, chemical, biological) used to process animal bones.
- Review the key industrial and environmental applications of bone-derived materials.
- Highlight recent advances (2020–2025) in techniques and sustainability metrics.
- Identify research gaps and propose future directions for maximizing resource recovery from bone waste.

1.2. Methodology

This review used a structured narrative approach with a systematic search and transparent screening aligned with PRISMA 2020 reporting principles (PAGE et al., 2021). Searches (2020–2025) were run in Scopus, Web of Science, PubMed/MEDLINE, SciELO and ScienceDirect, combining terms for animal bones, processing/valorization (mechanical, thermal, chemical, biological) and applications (agriculture, food, biomaterials, water/energy). Strategies were documented per PRISMA-S (RETHLEFSEN et al., 2021).

Inclusion: peer-reviewed articles/reviews (English/Portuguese/Spanish) reporting processes, conditions, and outcomes for bone processing or applications. Exclusion: patents, theses, purely archaeological/forensic studies, and papers without sufficient methodological detail. Records were deduplicated, screened by title/abstract then full text by two reviewers; disagreements were resolved by consensus (PAGE et al., 2021).

Data extracted: bone source, pre-treatments, process conditions (T/°C, time, atmosphere/reagents, pH), products (e.g., hydroxyapatite, bone char, collagen/gelatin), performance metrics (e.g., adsorption capacity, mechanical

ISSN 2178-6925
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strength, agronomic response), and notes on environmental/economic aspects. Study quality was appraised with JBI tools and CASP checklists appropriate to design (JBI, 2020; CASP, 2022). Given heterogeneity, we used narrative synthesis supported by comparative tables and flow diagrams, prioritizing recent/high-quality evidence (PICCIRILLO, 2023; HART et al., 2022).

2. Literature Review

2.1. Organic constituents

Cortical bone is a hierarchical composite in which an organic matrix (≈30% by mass) and an inorganic phase (≈60–70%) are interlaced; the remaining fraction is water and bound ions (ŠROMOVÁ et al., 2023). Type I collagen accounts for ~85–90% of the organic matrix and forms the fibrillar scaffold that confers tensile strength, while non-collagenous proteins (e.g., osteocalcin, osteopontin, bone sialoprotein, proteoglycans) regulate nucleation, growth and remodeling at the collagen–mineral interface (ŠROMOVÁ et al., 2023; HONG et al., 2022). Species can influence collagen features (fibril diameter distribution, denaturation/thermal stability) and derived hydrolysates, with poultry bones often reported to yield collagen of favorable thermal and functional characteristics compared with bovine/porcine sources (JAYAPRAKASH et al., 2024). Processing intended for value-added recovery (e.g., collagen peptides) must account for these matrix differences (LI et al., 2021).

2.2. Inorganic constituents

The mineral phase is a carbonated, ion-substituted calcium phosphate whose idealized core structure is hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, intergrown with collagen and hydrated interfaces (IELO et al., 2022; VENKATESAN et al., 2024). Carbonate substitutes in A-type (OH^- sites) and B-type (PO_4^{3-} sites) positions, lowering crystallinity and stiffness and modulating solubility; these substitutions are key to the mechanical and dissolution behavior of bone-like apatites (WINGENDER et al., 2021). In addition to CO_3^{2-}, minor ions such as Mg^{2+}, Na^+, Sr^{2+} and F^- are ubiquitous and further tune lattice disorder and interfacial water structure (ŠROMOVÁ et al., 2023; VENKATESAN et al., 2024). Recent overviews reaffirm that bone minerals are best described as a nanocrystalline, carbonate-rich apatite with hydrated, ion-rich surface layers rather than a perfect stoichiometric crystal

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(SHAH et al., 2025).

2.3. Variability by species and age

Across animal species, bones share the same two-phase architecture but differ in mineral chemistry (e.g., Ca/P ratio), trace-ion content and thermal behavior, which has implications for processing routes and end-use applications of recovered biominerals. Reviews compiling waste-bone–derived apatites report Ca/P ratios and carbonate levels that vary with species (e.g., galline/chicken often showing lower effective Ca/P than bovine), and with calcination/sintering conditions (VENKATESAN et al., 2024; OKPE et al., 2024). Age (maturation) also shifts mineral chemistry: adult cortical femur typically exhibits higher crystallinity and lower relative carbonate than immature bone, reflecting maturation and remodeling history (LESKOVAR et al., 2024). Spectroscopic aging studies further show coordinated changes in carbonate-to-phosphate and amide-to-phosphate indices that can even be leveraged for age estimation (YU et al., 2022). Multiscale analyses summarize that aging increases mineral crystal size/crystallinity, alters collagen cross-linking, and modifies water at mineral interfaces—changes that matter for any processing aimed at mechanical or biochemical valorization (RAVAZZANO et al., 2024).

2.4. Preparation and Cleaning

2.4.1. Collection and pre-treatment (defatting and soft-tissue removal)

Fresh bones should be trimmed to remove residual muscle, connective tissue, and marrow, then washed and defatted to avoid rancidity and to standardize downstream processing. Conventional routes include hot-water washing and alkaline baths (mild NaOH) for surface proteins, while greener solvent-free defatting increasingly relies on supercritical CO_2 ($scCO_2$), which extracts lipids at near-ambient temperatures and preserves the trabecular microarchitecture—an advantage for biomedical or adsorbent applications (HART et al., 2022; KRIEGER et al., 2025).

2.4.2. Cleaning methods

Physical: mechanical scraping, high-pressure rinsing, sieving/grinding (when bone powder is needed) and controlled thermal steps (below collagen denaturation) to loosen adherent tissues. These operations are typically combined with chemical or enzymatic stages to limit damage to collagen and mineral phases (IELO et al.,

ISSN 2178-6925
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2022).

Chemical:

- Alkaline deproteinization (e.g., NaOH) to remove residual proteins before mineral recovery (e.g., hydroxyapatite, bone char).
- Acid demineralization (HCl or chelators like EDTA) when the target is collagen/gelatin extraction.

  Recent works on waste-bone hydroxyapatite explicitly document defatting → deproteinization sequences prior to milling/sintering, with process conditions tuned to species and desired crystal/porosity outcomes (OKPE et al., 2024; CAÑON-DÁVILA et al., 2024).

Enzymatic: Proteases (e.g., alcalase, pepsin, trypsin) selectively cleave residual proteins at moderate temperature and neutral/slightly acidic pH, improving purity without harsh chemistry. In bone-block grafts, $scCO_2$ followed by enzymatic post-treatment further reduces organic residues while maintaining mechanical integrity (SHIN et al., 2024/2025).

2.4.3. Sterilization

Sterilization is essential for food/biomedical use and for laboratory safety. Gamma irradiation (typically 25–35 kGy) is widely adopted for terminal sterilization of bone grafts; however, dose–response studies show collagen scission and reduced crack-growth resistance at standard doses, so parameters must balance sterility assurance with property retention (CROCKER et al., 2024; SHIN et al., 2024). Alternative or complementary routes include steam (autoclave)—effective but denaturing for collagen—and $scCO_2$-based sanitization/sterilization, which removes lipids/cells at low temperature and helps retain microstructure (ALATISHE et al., 2024; HSU et al., 2022).

2.4.4. Drying

Drying stabilizes the cleaned substrate and conditions the pore network. Freeze-drying (lyophilization) preserves porous architecture and interconnectivity—important for adsorption and scaffold performance—whereas oven/vacuum drying is simpler but may collapse fine porosity or denature collagen if overheated. Recent reviews highlight freeze-drying as a robust route to high-porosity matrices for bone-related applications (KATRILAKA et al., 2023; ANGRAINI et al., 2025).

Table 1 summarizes the preparation and cleaning workflow for animal bones—

ISSN 2178-6925
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from collection and sorting to drying and sizing—highlighting the purpose of each step, typical methods and operating windows, and expected impacts on collagen and mineral integrity. The staged approach supports two downstream routes: (A) demineralization for collagen/gelatin recovery and (B) deproteinization for hydroxyapatite/bone-mineral or bone-char production (HART et al., 2022; IELO et al., 2022; KATRILAKA et al., 2023; CROCKER et al., 2024; SHIN et al., 2024; OKPE et al., 2024; HSU et al., 2022; KRIEGER et al., 2025).

Table 1: Preparation & Cleaning workflow (animal bones)

Step	Purpose	Typical Methods	Typical Conditions
Collection & Sorting	Gather fresh bones; separate by species/part; minimize contamination	Cold chain; visual inspection; removal of gross contaminants	≤4 °C transport; process within 24–48 h
Trimming & Washing	Remove residual tissues and blood; standardize substrate	Mechanical trimming/scraping; high-pressure rinsing; sieving of fragments	Water 20–50 °C; short exposure
Defatting	Remove lipids/marrow; prevent rancidity; improve purity	Hot water/alkaline wash (mild NaOH); supercritical CO_2 ($scCO_2$) extraction	50–70 °C (hot wash) or $scCO_2$ ~31–45 °C, 10–30 MPa
Deproteinization (optional)	Remove residual proteins before mineral recovery (HAp/bone char)	Alkaline treatment (NaOH); controlled mild thermal assist	0.1–1.0 M NaOH; 25–60 °C; minutes–hours
Enzymatic Cleaning (optional)	Selective protein removal under mild conditions	Proteases (alcalase, pepsin, trypsin) post-defatting	pH 6–8 (enzyme-dependent); 30–55 °C
Demineralization — collagen/gelatin route	Dissolve mineral to recover collagen/gelatin	HCl or chelators (e.g., EDTA) after defatting/cleaning	≤1 M HCl; 4–25 °C; hours–days; rinse to neutrality
Sterilization	Ensure biosafety for biomaterials /food	Gamma irradiation; steam autoclave; $scCO_2$ sanitization	Gamma 25–35 kGy; Steam 121–134 °C; $scCO_2$ low-T/high-P
Drying	Stabilize substrate; condition porosity	Freeze-drying (lyophilization); oven/vacuum drying	Lyophilization: –40 to –55 °C (primary); Oven: 40–80 °C
Sizing / Milling (as needed)	Set particle size for downstream routes	Cutting, crushing, ball milling; classification/sieving	Dry milling; control temperature rise
Ready for downstream	Branch to target routes	Route A: Demineralization → collagen/gelatin;	—

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Step	Purpose	Typical Methods	Typical Conditions
		Route B: Deproteinization → HAp/bone-mineral/bone char	

Abbreviations: $scCO_2$ = supercritical CO_2; HAp = hydroxyapatite. **Sources:** HART et al., 2022; IELO et al., 2022; KATRILAKA et al., 2023; CROCKER et al., 2024; SHIN et al., 2024; OKPE et al., 2024; HSU et al., 2022; KRIEGER et al., 2025.

2.5. Processing Routes

Animal bone valorization typically follows four main routes: (i) production of bone meal/flour by rendering and milling, (ii) calcination/carbonization to obtain bone ash or bone char (Ca- and P-rich adsorbents/fertilizers), (iii) hydrothermal/chemical routes targeting hydroxyapatite or collagen/gelatin, and (iv) biotechnological conversions (e.g., composting, biochar, enzymatic hydrolysis). Selection depends on target product (feed ingredient, fertilizer, biomaterial) and regulatory constraints (ALIBEKOV et al., 2024; HART et al., 2022).

2.5.1. Bone meal/flour (rendered) uses as feed additive and phosphate fertilizer

Process outline

In the rendering route, cleaned bones (Section 3) are thermally processed to inactivate pathogens and separate fat/protein fractions, then milled to produce bone meal/flour. EU “Method 1” pressure-sterilization (reference for stringent treatment) corresponds to particle size ≤ 50 mm, 133 °C for 20 min at ≥ 3 bar, widely cited in current guidance for animal by-products (ESPP/SAFOSO, 2024). Rendering definitions and composition descriptors for meat-and-bone meal (MBM) are standardized in AAFCO’s Official Publication (2024) (ALATISHE et al., 2024; AAFCO, 2024). (ALATISHE et al., 2024; AAFCO, 2024; ESPP/SAFOSO, 2024).

Regulatory note (feed use)

Use of processed animal proteins in feed remains regulated. In the EU, 2021 changes partially lifted the long-standing feed ban, re-authorizing PAPs from pigs for poultry and from poultry for pigs, while ruminant feed restrictions remain (EFSA, 2021; EUROPEAN COMMISSION, 2021). AAFCO provides the prevailing US definitions/labeling for MBM (EFSA, 2021; EUROPEAN COMMISSION, 2021; AAFCO, 2024).

ISSN 2178-6925
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(A) Feed additive

Rendered bone meal/MBM is used primarily in non-ruminant diets as a mineral and protein source where permitted, with formulation subject to species-specific legislation and avoidance of intra-species recycling (EFSA, 2021; EUROPEAN COMMISSION, 2021). Quality hinges on upstream cleaning/defatting and validated heat treatment (EFSA, 2021; EUROPEAN COMMISSION, 2021; ESPP/SAFOSO, 2024; AAFCO, 2024).

(B) Phosphate fertilizer

Bone meals contain phosphorus predominantly as hydroxyapatite, giving slow-release behavior; plant availability is often evaluated by citric/neutral ammonium citrate extractions and pot trials (KIANI et al., 2024; NAPOLITANO et al., 2025). Thermo-converted MBM (bone-meal biochar) can reduce mineral fertilizer requirements and improve soil properties in field/greenhouse tests (PIASH et al., 2023). Process optimization (e.g., mild pyrolysis, co-composting, acidulation) increases P solubility while keeping contaminant risks low (PIASH et al., 2023; KIANI et al., 2024; NAPOLITANO et al., 2025).

Practical takeaways.

For feed, compliance with PAP/MBM rules and validated sterilization is decisive (EFSA/EC). For fertilizer, the agronomic value of (steamed) bone meal depends on particle size and chemical activation; MBM-biochar shows the most consistent yield benefits among recent studies (PIASH et al., 2023), while new waste-to-fertilizer formulations leverage bone-derived hydroxyapatite as a controlled-release P source (NAPOLITANO et al., 2025).

Figure 1 summarizes the bone meal/flour route from rendering to milling, followed by a decision node that directs product either to FEED (MBM)—subject to species restrictions, labeling and microbiological compliance—or to FERTILIZER, where steamed bone meal or MBM-biochar is formulated as a slow-release P source. Quality controls differ by branch: FEED emphasizes protein/ash and Ca–P specs plus hygiene (AAFCO, 2024; EFSA, 2021; EUROPEAN COMMISSION, 2021), whereas FERTILIZER focuses on P_2O_5/CaO content, citrate/NAC solubility and heavy-metal limits, with mild pyrolysis or co-composting often improving agronomic response (PIASH et al., 2023; KIANI et al., 2024).

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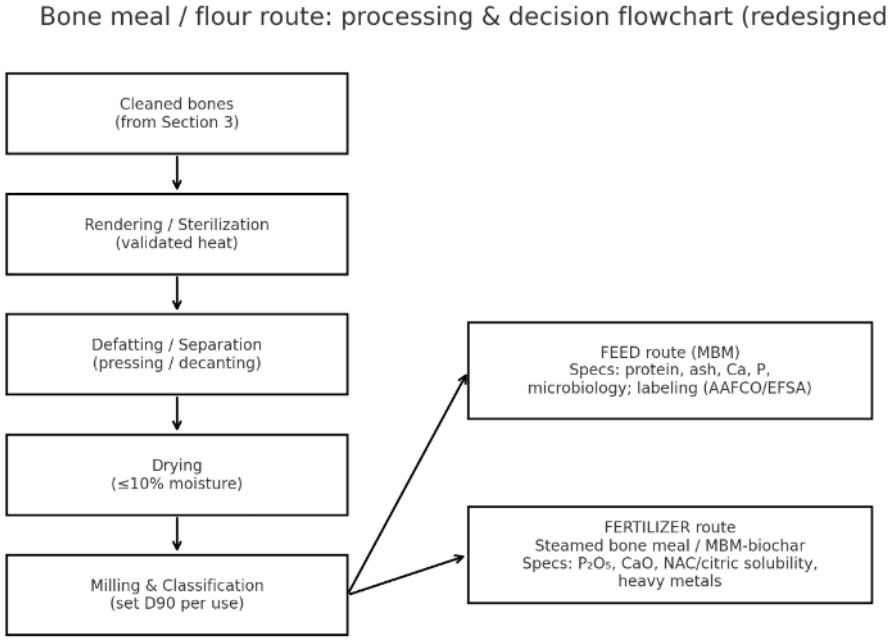


Figure 1: Bone meal / flour route: processing & decision flowchart

2.5.2. Calcination and production of bone ash

Calcination converts defatted bone into an inorganic, carbon-free ash in which the mineral fraction is largely hydroxyapatite (HAp) with variable carbonate content; the exact phase assemblage depends on atmosphere, temperature, dwell time and the Ca/P ratio (OKPE et al., 2024; ETINOSA et al., 2024). In air, heating in the ~700–950 °C window removes organics and CO_2, increases crystallinity, and yields low-carbon bio-HAp suitable for downstream processing (KOWALSKI et al., 2023). Prolonged or higher-temperature treatments promote dehydroxylation (oxyapatite formation near ~1000 °C in dry/vacuum conditions) and progressive HAp decomposition to β-tricalcium phosphate (β-TCP); the β→α-TCP transition occurs above ~1125 °C (BULINA et al., 2023; EKNAPAKUL et al., 2024; BÖHME et al., 2022). Thus, by tuning the calcination profile it is possible to obtain phase-pure HAp, β-TCP or biphasic calcium phosphate (BCP, HAp+β-TCP) tailored for end-use (OKPE et al., 2024; EKNAPAKUL et al., 2024).

Target products and applications.

• Tri-calcium phosphate (TCP) & hydroxyapatite (HAp). β-TCP obtained at >~750–900 °C (below the β→α transition) is resorbable and often blended with HAp to form

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BCP granules or scaffolds; α-TCP (>1125 °C) is used as a reactive phase in calcium-phosphate cements (CPCs). Bone-derived HAp/TCP have been widely applied as bone-graft substitutes, 3D-printed ceramics, and implant coatings, with performance governed by phase fraction, porosity and sintering schedule (VENKATESAN et al., 2024; TRZASKOWSKA et al., 2023; EKNAPAKUL et al., 2024).

- Cement and construction materials. Bone ash (or milled bone powder pre-calcination) can partially replace Portland cement (typically ~10 % by mass) without compromising 28-day strength in moderate-strength concretes, offering a valorization route for slaughterhouse residues; bone ash also improves properties of clay bricks at elevated firing temperatures (PALOMINO-GUZMÁN et al., 2024; BIH et al., 2022).
- Ceramics & glass-ceramics. Bone ash (bioapatite) remains a functional raw material in ceramic slips and specialty porcelains; recent assessments emphasize its role as a low-CO_2 secondary raw material for the industry (GARCÍA-TEN et al., 2024; JACERS 2023).
- Process notes. Industrially, air calcination below ~950 °C minimizes sulfate-related issues and retains phosphate value, whereas inert-atmosphere pyrolysis yields bone char (carbon + apatite) for adsorption uses rather than ash; ramp rates and water-vapor partial pressure modulate dehydroxylation/rehydroxylation during cool-down and thereby the final HAp/oxyapatite/TCP balance (KOWALSKI et al., 2023; BULINA et al., 2023).
- **Figure 2** presents a temperature × atmosphere map for bone calcination/pyrolysis, highlighting typical windows: bone char (HAp + C) under inert gas (≈400–700 °C), HAp-rich ash in air (≈700–950 °C), BCP—HAp+β-TCP in air (≈900–1050 °C), and α-TCP (> 1125 °C). The diagram guides the thermal profile selection according to the target product (adsorbent, fertilizer, bioceramic, or calcium-phosphate cement) (KOWALSKI et al., 2023; EKNAPAKUL et al., 2024; TRZASKOWSKA et al., 2023; OKPE et al., 2024; BULINA et al., 2023).

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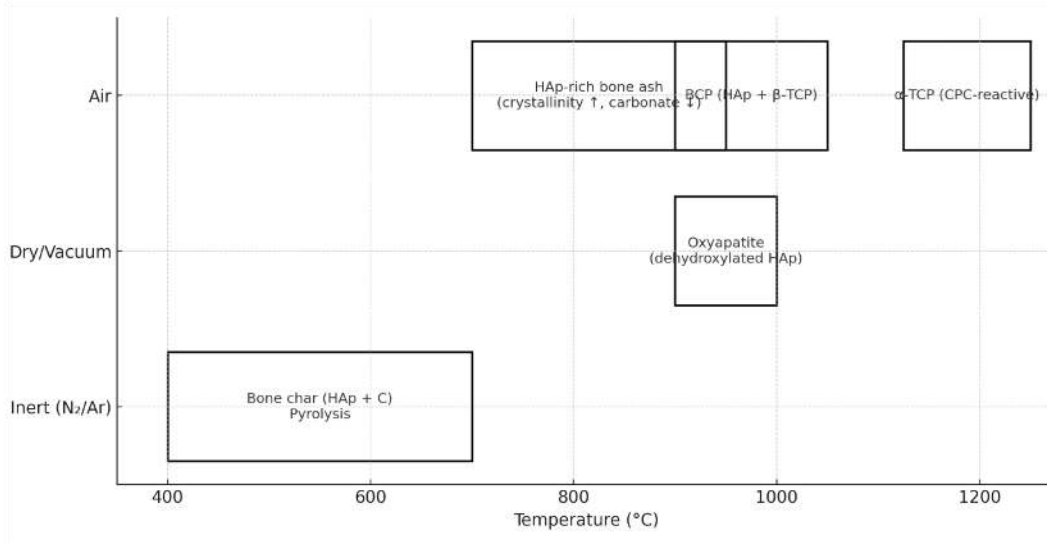


Figure 2: Calcination / Pyrolysis Outcomes vs. Temperature and Atmosphere (schematic, de-overlapped)

- Overlapping windows depend on Ca/P, carbonate, and moisture; humidity drives rehydroxylation and shifts apparent thresholds (BULINA et al., 2023).
- Higher temperature/time ↑ crystallinity but ↓ surface area trade-off between adsorption/fertilizer reactivity vs implant stability (KOWALSKI et al., 2023; TRZASKOWSKA et al., 2023).
- For P fertilizers, less-crystalline HAp and fine milling raise citrate/NAC solubility; BCP can enhance P bioavailability (KOWALSKI et al., 2023).
- For biomaterials, the HAp/β-TCP ratio governs resorption; α-TCP is desired for CPCs, but > 1200 °C risks over-densification (EKNAPAKUL et al., 2024; TRZASKOWSKA et al., 2023).
- Inert atmospheres yield bone char for adsorption; air is preferable for mineral ash/bioceramics (OKPE et al., 2024).
- Minimum QC per batch: XRD (HAp/β-TCP/α-TCP), FTIR (OH^-/CO_3^{2-}), BET/porosity, particle size; for fertilizers, citrate/NAC P-solubility (KOWALSKI et al., 2023; TRZASKOWSKA et al., 2023).

2.6. Hydrothermal and chemical processes: collagen/gelatin extraction and soluble phosphate recovery

Collagen/gelatin.

Bones are a dual matrix of collagen (organic) and carbonated hydroxyapatite (inorganic); most protein valorization routes begin by loosening or removing the

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mineral phase, then extracting collagen/gelatin via heat, pressure and/or catalysis. Conventional sequences include de-fatting → acid or alkali demineralization (e.g., HCl or NaOH/EDTA) → hot-water extraction (50–70 °C) → filtration and drying. Reviews focused on bovine sources show that acid + pepsin pretreatments raise yield and shorten extraction times compared with acid alone, while helping preserve molecular weight distribution desirable for gel strength (SAMATRA et al., 2022). Green "intensification" options include steam-explosion (1.5–2.5 MPa, 10–30 min), which disrupts the bone matrix and boosts protein recovery (≈60% at 2.0 MPa/30 min), and subcritical-water hydrolysis (≈120–180 °C, pressurized) that uses water's auto-ionization as the catalyst to generate collagen peptides with fewer chemical residues (ZHANG et al., 2023; TADESSE et al., 2024). Supercritical CO_2–acidified water has also been trialed at moderate T/P as a greener solvent system for skin/bone streams in fish processing (PHON et al., 2023). Collectively, these hydrothermal and chemical variants trade off yield, peptide size, and energy/chemical footprints; enzymatic aids (e.g., pepsin, bromelain) can be combined with mild hydrothermal steps to fine-tune functionality while reducing salt loads from neutralization (XU et al., 2023; SAMATRA et al., 2022). (SAMATRA et al., 2022; ZHANG et al., 2023; TADESSE et al., 2024; PHON et al., 2023; XU et al., 2023; HART et al., 2022).

Soluble phosphates.

Chemical routes can redirect the mineral fraction to fertilizer-grade soluble calcium phosphates. Two common pathways are

- **Acidulation/precipitation**—after cleaning/calcination, bone mineral is reacted with phosphoric acid under controlled pH (≈4.5–6.0) and moderate temperatures (≈50–70 °C), precipitating dicalcium phosphate (DCP/DCPA), while mother liquors can be recycled. Recent fish-bone studies report high-purity DCP at ~3 M H_3PO_4, pH ≈ 5 and 60 °C/60 min, with nanometric crystallites (NGO et al., 2025). Process fundamentals and phase control across MCP/DCP/HAp are well described for aqueous precipitation systems, highlighting the critical roles of pH and Ca/P in targeting soluble phases (NIKOLENKO et al., 2020).
- **Thermochemical + mild leaching**—pyrolysis/incineration yields bone char/ash with hydroxyapatite-rich P that is more plant-available than phosphate rock but slower-release than triple superphosphate; agronomic studies in tropical soils

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confirm intermediate solubility and efficacy, improvable via organic acids, sulfur or bio-augmentation (CASTRO et al., 2024; AMIN, 2024; ROBINSON & LEINWEBER, 2023). For benchmarking methods to predict P availability of such side-stream fertilizers, recent work shows DGT soil tests outperform several conventional extractants when correlating to short- and long-term plant uptake (KIANI & YLIVAINIO, 2024). (NGO et al., 2025; NIKOLENKO et al., 2020; CASTRO et al., 2024; AMIN, 2024; ROBINSON & LEINWEBER, 2023; KIANI & YLIVAINIO, 2024).

Table 2 synthesizes the hydrothermal and chemical routes for animal-bone valorization toward two targets: (i) collagen/gelatin and (ii) soluble phosphates. For each step, it compiles representative operating windows, expected outputs, and QC metrics to support method selection and benchmarking across studies (SAMATRA et al., 2022; XU et al., 2023; NIKOLENKO et al., 2020; KIANI; YLIVAINIO, 2024; TADESSE et al., 2024). Conditions are indicative and should be adapted to species, bone part, and target specifications.

Table 2: Hydrothermal & Chemical Processes — Summary

Objective (branch)	Key step / unit op.	Typical conditions	Main outputs	QC / metrics
Collagen/Gelatin	Demineralization (acid or chelator)	HCl ≤ 1.0 M or EDTA; 4–25 °C; hours–days	Mineral removed; collagen-rich matrix	Ash < 1–2%; neutral pH after rinsing
Collagen/Gelatin	Hot-water extraction	50–70 °C; 2–8 h; S/L 1:5–1:10	Gelatin solution → dried gelatin	Gel strength (Bloom); viscosity
Collagen/Gelatin	Enzymatic assistance (pepsin, alcalase, etc.)	pH 2–8 (enzyme-dependent); 30–55 °C	Gelatin/collagen peptides (target Mw)	Mw distribution (SDS-PAGE/GPC); N recovery
Collagen/Gelatin	Subcritical-water hydrolysis	120–180 °C; autogenous pressure; 10–90 min	Peptides with low salt burden	Degree of hydrolysis; peptide profile
Collagen/Gelatin	Steam-explosion (pretreatment)	1.5–2.5 MPa; 10–30 min; rapid depressurization	Matrix disruption → higher extraction rate	Protein yield (%)
Collagen/Gelatin	Clarification → drying	Filtration; evaporation; spray/freeze-drying	Gelatin powder / collagen peptides	Moisture; ash; microbiology

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Objective (branch)	Key step / unit op.	Typical conditions	Main outputs	QC / metrics
Soluble phosphates	Acidulation & precipitation (DCP/MCP)	H_3PO_4; pH 4.5–6.0; 50–70 °C; 30–90 min	DCP/DCPA crystals	Phase purity (XRD/FTIR); P_2O_5; citrate/NAC solubility
Soluble phosphates	Thermochemical + mild leaching	Bone ash/char → organic or mild acid leach	Soluble P fraction	P recovery (%); solubility; metals screening
Soluble phosphates	Crystallization/ aging → drying	Aging at set pH; 40–80 °C; filtration; drying	DCP/MCP powder	Particle size; free acidity; moisture
Soluble phosphates	Granulation / pelletizing (optional)	Pan drum; binder; low T	Granular fertilizer	Size distribution; crush strength

Abbrev.: S/L = solid-to-liquid ratio; Mw = molecular weight; DCP/DCPA = dicalcium phosphate (anhydrous); MCP = monocalcium phosphate; NAC = neutral ammonium citrate.

2.7. Biotechnological processing: fermentation, bio-extraction of nutrients, and biogas production

Bio-extraction of phosphorus (P) from bone/char.

Microbial routes mobilize P from bone mineral and bone-derived chars via secretion of organic acids (e.g., gluconic/oxalic), chelation, and proton release by phosphate-solubilizing microbes (PSM). Fungal systems such as *Aspergillus niger* have released PO_4^{3-} from fish-bone char in soil, lowering Pb phytoavailability while increasing soluble P (field-pot evidence), demonstrating concurrent nutrient release and risk mitigation (TAUQEER et al., 2022). Encapsulating phosphate-solubilizing bacteria (e.g., *Pseudomonas rhodesiae*) together with bone char (“bio-beads”) enhances P release from the char and drives in situ formation of Pb-phosphates; the same mechanism underpins bioactivation of bone char as a slow-release P source (LI et al., 2023). Recent agronomic syntheses converge that bone char’s fertilizer effectiveness depends on soil pH and microbial activity—biological activation (PSM inoculation/composting) increases plant-available P relative to passive application (AMIN, 2024; HEYL et al., 2023). Hydrothermal/chemical leaching can be combined with PSM pre- or post-steps when faster, higher-yield P recovery is the priority (DU et al., 2020).

Fermentation/composting bone-rich residues.

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As an aerobic biotechnology, MBM-assisted composting (meat-and-bone meal as N/P/Ca co-substrate) prolongs the thermophilic phase, increases microbial diversity, suppresses plant pathogens, and yields a stabilized organic matrix that can carry PSM into soils—useful as a biofertilizer base or as a pre-activation step for bone-derived P (LIU et al., 2022).

Biogas from process waters and co-substrates

Bones themselves are largely mineral and poorly biodegradable, but bone-containing residues (e.g., MBM process waters, dissolved organics released by pretreatments) support anaerobic digestion (AD) when appropriately formulated. A chicken meat-and-bone meal platform coupling hydrothermal treatment (HTT) with AD solubilized >95% of P and nearly all N into the aqueous phase (enabling struvite/apatite recovery) and achieved 250–300 mL $CH_4 \cdot g^{-1}$ COD_added with up to ~75% COD removal in batch AD—showing viable energy recovery plus nutrient capture (SARRION et al., 2023). At plant scale, co-digestion enriched with bovine bone meal increased biogas output and produced digestates suited to biofertilization when C/N and buffering were balanced (HADIDI et al., 2023). Practical notes: keep lipids/proteins below inhibitory thresholds, favor mesophilic–thermophilic staging, and integrate struvite or DCP precipitation to close the P loop.

Integration & selection.

- Goal: fertilizer P → bioactivation of bone char with PSM (seed on char or co-compost), or HTT+AD to recover energy and precipitate struvite/DCP; tailor to soil pH and crop demand. (AMIN, 2024; HEYL et al., 2023; DU et al., 2020; SARRION et al., 2023).
- Goal: risk reduction + nutrient reuse → PSM-assisted systems (PSB/PSF) mobilize P while immobilizing metals as phosphates; consider bio-beads or compost matrices for field deployment. (LI et al., 2023; TAUQEER et al., 2022).

Table 3 summarizes the biotechnological routes for valorizing bone-derived residues—ranging from microbial P-solubilization and composting to HTT+anaerobic digestion and struvite/DCP recovery. For each route, it lists representative operating windows, main outputs, and QC metrics to guide method selection; conditions are indicative and should be adjusted to feedstock and target specifications.

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Table 3: Biotechnological processing — summary

Biotech route	Feedstock	Mechanism / unit op.	Main outputs	QC / metrics
P-solubilization with phosphate-solubilizing microbes (PSM)	Bone char / bone ash (milled)	Organic acids, chelation, proton release; inoculation in slurry or soil	Dissolved PO_4^{3-}; bio-activated char	Soluble P (mg L^{-1}); pH drop; metals immobilization check
Bio-beads / inoculated bone char	Char + alginate-encapsulated PSB/PSF	Entrapment of microbes; controlled field deployment	Enhanced P release; in-situ Pb immobilization	P release rate (mg P kg^{-1} d^{-1}); bead integrity; microbial viability
Composting / co-composting with MBM	Organic residues + meat-and-bone meal (MBM)	Aerobic thermophilic composting	Stabilized compost; PSM enrichment	Maturity (GI); pathogens; C/N; moisture
Hydrothermal treatment (HTT) + anaerobic digestion (AD)	Process waters; organics from bone processing; MBM slurries	HTT solubilizes organics/nutrients; AD converts COD → CH_4	Biogas (CH_4); nutrient-rich liquor (NH_4^+, PO_4^{3-})	CH_4 yield (mL g^{-1} COD); COD removal; VFA; NH_4^+; PO_4^{3-}
Struvite (MAP) / DCP precipitation from liquors	Digestate or HTT liquor	Crystallization: Mg:NH_4:P ≈ 1:1:1 (struvite) or Ca:P ≈ 1:1 (DCP)	MAP crystals (struvite) or DCP powder	P recovery (%); phase purity (XRD/FTIR); metals
Co-digestion with MBM / process waters	Manure, food waste + MBM/processing liquors	Anaerobic digestion (CSTR or batch)	Higher biogas output; stabilized digestate	OLR/HRT; CH_4 yield; stability (alk/acid ratio)

Abbrev.: PSM = phosphate-solubilizing microbes; PSB/PSF = phosphate-solubilizing bacteria/fungi; S/L = solid-to-liquid ratio; PSD = particle-size distribution; MBM = meat-and-bone meal; HTT = hydrothermal treatment; AD = anaerobic digestion; COD = chemical oxygen demand; VFA = volatile fatty acids; MAP = magnesium ammonium phosphate (struvite); DCP = dicalcium phosphate; CSTR = continuous stirred-tank reactor; OLR = organic loading rate; HRT = hydraulic retention time; GI = germination index.

2.8. Industrial applications

2.8.1. Agriculture — phosphate fertilizers

Bone-derived products span steamed bone meal, bone ash (HAp-rich), and bone-char/MBM-biochar. In weathered or acidic soils, they act as slow-release P sources with agronomic performance typically intermediate between phosphate rock and fully

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soluble triples (TSP), and can be bio-activated (e.g., with P-solubilizing microbes) to increase plant-available P. For compliance and benchmarking, recent work recommends DGT-based tests to predict both short- and long-term P availability of side-stream fertilizers more reliably than several conventional extractants. (CASTRO et al., 2024; HEYL et al., 2023; PIASH et al., 2023; KIANI; YLIVAINIO, 2024).

2.8.2. Food — gelatin, collagen and supplements

Demineralized bone and bone-rich residues are processed into gelatin and collagen peptides for food, nutraceuticals, and specialty ingredients. Process intensification routes (acid/pepsin pretreatment, steam-explosion, subcritical-water or enzymatic hydrolysis) allow tuning of molecular-weight distributions and gel strength, enabling application-specific functionality in confectionery, beverages, and supplement capsules. (SAMATRA et al., 2022; ZHANG et al., 2023; XU et al., 2023).

2.8.3. Biomedical — grafts, HAp/TCP biomaterials

Calcined bone yields biogenic hydroxyapatite (HAp) and calcium phosphates (β-/α-TCP, BCP) used in bone-graft substitutes, porous scaffolds, and implant coatings. Properties relevant to clinical performance (resorption, osteoconductive, mechanical strength) are governed by phase composition, crystallinity, porosity and grain size, which can be tailored via calcination/sintering schedules and post-processing. Recent reviews and experimental studies confirm competitive performance of natural HAp-based nano/macro-composites in bone tissue engineering. (VENKATESAN et al., 2024; TRZASKOWSKA et al., 2023; EKNAPAKUL et al., 2024; OKPE et al., 2024).

2.8.4. Energy — bone char and bioenergy

Thermochemical and biochemical routes enable energy valorization. Vacuum/inert pyrolysis of MBM/bone streams produces a combustible bio-oil, syngas, and bone char (P-rich), while incineration of MBM is already used at industrial scale for process heat/steam; hydrothermal treatment + anaerobic digestion of bone-processing liquors or MBM slurries delivers biogas with parallel nutrient recovery (e.g., struvite/DCP). Selection depends on local energy needs, emissions control, and by-product markets for the residual P-rich ash/char. (HART et al., 2022; KOWALSKI et al., 2022; SARRION et al., 2023; MACAVEI et al., 2024).

ISSN 2178-6925
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Table 4 consolidates the current industrial use of bone-derived products and the closest measurable market lenses for 2024–2025 across four segments—agriculture (bone char/ash, DCP), food (gelatin, collagen peptides), biomedical (hydroxyapatite), and energy (biogas, with MBM as an upstream proxy). Values are triangulated from recent industry trackers and should be read as order-of-magnitude guides rather than bone-only submarket totals: biochar/bone-char within the broader biochar market; DCP within the global DCP market; gelatin/collagen peptides as ingredient markets; hydroxyapatite as the biomaterials market; biogas as the overall AD market; and MBM as a rendering-sector proxy. Sources: Grand View Research (biochar, gelatin, hydroxyapatite; collagen peptides), Fortune Business Insights (biochar, biogas), Straits Research (DCP, phosphate fertilizers), Market Research Future (phosphate fertilizers), and The Business Research Company (MBM).

Table 4: Industrial applications of animal-bone processing: current use & market value (2024–2025)

Segment	Main bone-based products / use cases	Closest market lens & 2024/25 value (USD)	Growth / outlook
Agriculture (fertilizers)	Bone char / bone-ash (slow-release P); DCP/MCP made from bone mineral	Biochar (proxy for bone-char niche): $0.76–0.88B (2024); proj. ≈ $1.35B by 2030. • Dicalcium phosphate (DCP): $0.93–0.96B (2024). • Phosphate fertilizers (TAM): $52–73B (2024).	Biochar ~13–14% CAGR to 2030; DCP ~5–6% CAGR; phosphate fertilizers ~~5% CAGR mid-term.
Food (ingredients)	Gelatin (capsules, confectionery); collagen peptides for nutraceuticals	Gelatin: $7.05B (2024) (alt est. $3.20B). • Collagen peptides: $2.2–2.3B (2023/24).	Gelatin: ~7–11% CAGR to 2030–2032; collagen peptides ~11% CAGR.
Biomedical (biomaterials)	Biogenic HAp/BCP powders; porous scaffolds; coatings	Hydroxyapatite (HAp): $2.54B (2024); ~7.5% CAGR to 2030.	Demand tied to dental/orthopedic implants; biogenic HAp competes with synthetic.
Energy (thermo/biochemical)	Bone-char as solid fuel co-product; HTT + anaerobic digestion (AD) of process water & MBM slurries →	Biogas (overall): $68–161B (2024) depending on scope/method; typical projection to 2030 $88–191B. Meat-and-bone meal (MBM) market (feed/fuel input proxy): $5.95B (2024)	Biogas: ~4–5% CAGR mid-term

ISSN 2178-6925
DOI: 10.61164/0q52sj86

Segment	Main bone-based products / use cases	Closest market lens & 2024/25 value (USD)	Growth / outlook
	biogas	→ $6.18B (2025).	

2.9. Environmental and regulatory aspects

2.9.1. Reducing environmental liabilities

Valorizing bones diverts pathogen-susceptible residues from landfilling, recovers P and Ca into fertilizers/biomaterials, and integrates with bioenergy systems—fully aligned with circular-economy priorities that foster markets for recycled nutrients (EUROPEAN COMMISSION, 2020). In Brazil, the PNRS establishes a hierarchy that prioritizes prevention, reuse, recycling and treatment over disposal, creating policy support for upgrading slaughterhouse by-products (BRASIL, 2010; BRASIL, 2022).

2.9.2. Sanitary norms (prion/zoonosis control)

Animal by-products are classified by risk categories and must undergo validated processing (time/temperature/pressure), traceable collection and restricted end-uses under the ABP framework (EUROPEAN COMMISSION, 2009; EUROPEAN COMMISSION, 2011). The EU's 2021 amendment to the "feed ban" re-authorised certain non-ruminant processed animal proteins only in cross-species feeds (porcine↔poultry), while maintaining ruminant safeguards (EUROPEAN COMMISSION, 2021). In the U.S., FDA rules continue to prohibit mammalian proteins in ruminant feed and ban specified high-risk cattle materials from all animal feed (FDA, 2024a; FDA, 2024b). International prion-disease standards and surveillance are articulated in the WOAH Terrestrial Code (WOAH, 2024.

2.9.3. Circular-economy and fertilizer-market rules

To place bone-derived products on the EU market as CE-marked fertilizers, operators must meet the EU Fertilizing Products Regulation (FPR) 2019/1009 (safety limits, labelling) and fit an eligible Component Material Category, notably precipitated phosphate salts/derivatives (CMC 12) and pyrolysis/gasification materials (CMC 14) introduced by the 2021 delegated acts—while also complying with ABP rules for inputs and processing (EUROPEAN COMMISSION, 2019; EUROPEAN

ISSN 2178-6925
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COMMISSION, 2021a; EUROPEAN COMMISSION, 2021b). Governance analyses emphasize that bone char/ash can qualify only where ABP category, process validation and contaminant caps are demonstrably satisfied (HEYL; GARSKE; EKARDT, 2023).

2.10. Future perspectives

2.10.1. Low impact, "green" processing.

Expect broader adoption of electrified heat and intensified reactors to decarbonize unit operations now dominated by fossil heat. Lessons from adjacent minerals/cement show that electrified calcination can substantially cut process CO_2 (with resistance/induction heating and renewable power)—a pathway that is technically transferable to bone-ash/HAp kilns (BARBHUIYA et al., 2024; LAURINI et al., 2024). Microwave-assisted hydrothermal routes are also maturing for rapid, low-solvent synthesis of carbonated HAp from bone/shell calcium sources, reducing time and chemicals versus conventional hydrothermal processing (IRFA'I et al., 2024). On the protein side, subcritical-water and steam-explosion pretreatments can shrink chemical footprints in gelatin/collagen extraction while preserving functionality (JOY et al., 2024).

2.10.2. Biorefinery valorization.

Integrated "bone biorefineries" can co-produce collagen/gelatin peptides, bio-HAp/TCP for biomaterials, fertilizer salts (e.g., DCP/struvite), and energy (HTT + anaerobic digestion) from process liquors—closing C–N–P loops and improving plant economics (SARRION et al., 2023; MUÑOZ et al., 2024). Standardized DGT-based P-availability tests will help specify fertilizer performance for bone char/ash streams within circular markets (KIANI; YLIVAINIO, 2024.

2.10.3. Bioeconomy & advanced materials.

Demand growth in tissue-engineering and medical-grade composites favors biogenic HAp/gelatin platforms, including bioinks and 3D-printable scaffolds that leverage the collagen–apatite synergy (CHITICARU et al., 2024; LIU et al., 2025; ZHAO et al., 2024). Future work should couple phase-controlled bio-HAp (tunable HAp/β-TCP/α-TCP) with green synthesis to meet both clinical performance and sustainability criteria (OKPE et al., 2024).

ISSN 2178-6925
DOI: 10.61164/0q52sj86

2.10.4. Policy signals and market pull.

The EU's 2023 Critical Raw Materials list includes phosphate rock and phosphorus, reinforcing the case for recycled P from bones as a strategic complement to mined inputs (EUROPEAN COMMISSION, 2023). In parallel, CE-mark routes under the EU Fertilizing Products Regulation already accommodate precipitated phosphate salts and pyrolysis/gasification materials, helping bone-derived P reach the single market when ABP and contaminant rules are met (HEYL et al., 2023).

2.10.5. What's still missing (R&D priorities).

- Harmonized QC across value chains—XRD/FTIR phase metrics for bio-HAp, DGT/citrate solubility for P fertilizers, and functional tests for gelatin/peptides—so results are comparable across studies and plants (KIANI; YLIVAINIO, 2024).
- (ii) Decision-grade LCA/TEA for end-to-end trains (bone to biomaterial/fertilizer/energy) to guide siting and heat-source choices; recent biochar LCAs highlight the sensitivity to energy mix and kiln design (OSMAN et al., 2024). (iii) Digitalization (inline spectroscopy, soft sensors) to control Ca/P phase evolution and peptide size in real time. (iv) Regulatory alignment for cross-border trade (ABP categories + FPR/feed rules) to unlock scale while maintaining prion/zoonosis safeguards (HEYL et al., 2023).

3. Conclusion

This review mapped the full value chain for animal-bone processing—from preparation/cleaning to four complementary routes:

- rendering → bone meal/flour for feed or slow-release P fertilizers.
- calcination to bone ash with tunable HAp/β-TCP/α-TCP phase assemblages for fertilizers and bio ceramics.
- hydrothermal/chemical routes yielding collagen/gelatin and soluble phosphates (e.g., DCP/MCP); and
- biotechnological conversions, including phosphate-solubilizing microbes and HTT+anaerobic digestion with nutrient recovery. Selecting among these options is a decision on target product, regulatory pathway (ABP categories, feed-ban rules, fertilizer CMCs), and local market pull, supported by upstream quality controls on lipid removal, demineralization, sterilization, and particle sizing (HART et al., 2022;

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EKNAPAKUL et al., 2024; OKPE et al., 2024).

Environmentally, bone valorization diverts a pathogen-sensitive residue from disposal while recycling strategic phosphorus and calcium into agriculture and biomaterials—consistent with circular-economy goals. Properly designed thermal or biological trains can cut emissions (e.g., electrified calcination, biogas from liquors) and close C–N–P loops, provided sanitary barriers are maintained (CASTRO et al., 2024; SARRION et al., 2023; HEYL et al., 2023). Economically, diversified product slates—gelatin/collagen, bio-HAp/BCP, bone-char/ash fertilizers, and biogas + struvite/DCP—allow plants to hedge commodity cycles and regional regulations. Technologically, recent advances enable phase-controlled bio-apatites, greener protein extraction (subcritical water, steam-explosion, enzymatic aids), and decision-grade testing of fertilizer performance (e.g., DGT, citrate/NAC solubility) (TRZASKOWSKA et al., 2023; KIANI; YLIVAINIO, 2024; VENKATESAN et al., 2024).

Research gaps and opportunities.

- **Harmonized QC & standards** across routes: routine XRD/FTIR for HAp/β-TCP/α-TCP, BET/porosity and grain size for ceramics, **DGT/citrate** metrics for P fertilizers, and functional assays for gelatin/peptides to make results comparable across studies and plants (KIANI; YLIVAINIO, 2024; TRZASKOWSKA et al., 2023).
- **Process intensification with low impact:** scale-ready, electrified or microwave-assisted calcination and subcritical-water extraction to reduce energy and chemical loads while preserving performance (HART et al., 2022; VENKATESAN et al., 2024).
- **Integrated biorefineries:** co-production schemes coupling collagen/gelatin, bio-HAp, fertilizer salts and energy (HTT+AD) with real-time analytics and soft sensors for Ca/P phase control and peptide size distribution (SARRION et al., 2023; OKPE et al., 2024).
- **Long-term field/clinical evidence:** multi-season agronomy for bone-char/ash in varied soils and **in vivo** validation of biogenic HAp/BCP scaffolds to solidify claims on efficacy and safety (CASTRO et al., 2024; VENKATESAN et al., 2024).
- **Regulatory interoperability:** clearer bridges between ABP rules, FPR component categories, and feed legislation to unlock cross-border trade without

relaxing prion/zoonosis safeguards (HEYL et al., 2023).

In sum, bones are a strategic circular feedstock. With fit-for-purpose processing and robust QA/QC, they can deliver environmental benefits (waste and P recovery), economic resilience (diverse, higher-value products), and technological advances (bio-HAp and tailored peptides). Closing the remaining gaps will move bone processing from opportunistic recycling to a mature biorefinery platform embedded in the bioeconomy.

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