processes

MDPI

*Review*

# A Comprehensive Review of Porous Materials Derived from Animal Bone Waste

**Chi-Hung Tsai [1,*] and Wen-Tien Tsai [2,*]**

[1] Department of Resources Engineering, National Cheng Kung University, Tainan 701, Taiwan
[2] Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung 912, Taiwan
* Correspondence: n48091089@gs.ncku.edu.tw (C.-H.T.); wttsai@mail.npust.edu.tw (W.-T.T.)

**Abstract**

As the global population grows and living standards rise, the demand for meat is increasing rapidly, inevitably generating about 100 million metric tonnes of animal bone waste (ABW). This biomass residue is mainly composed of organic collagen and inorganic hydroxyapatite. Therefore, ABW may cause environmental pollution if it is not properly treated, but it can also serve as a valuable resource for the circular economy if appropriately valorized. This comprehensive review aims to focus on thermochemical processes for converting ABW into porous hydroxyapatite-based materials and further summarize their value-added applications (e.g., environmental adsorbents, catalysts or their supports, biomedical materials for bone grafting and tissue engineering, and electrode materials for energy storage). Therefore, the four topics will be covered to echo the targets of this review paper, including the sources and characteristics of ABW, processes for transforming ABW into porous materials, pore property determinations for porous materials derived from ABW, and value-added applications of porous materials derived from ABW. Based on the information gathered in this review, the valorization of ABW and its derived pore materials may facilitate a practical circular economy case in which animal bones are reused as an available resource to produce newly porous materials for a variety of novel and high-value applications like medicine and energy fields.

**Keywords:** animal bone waste; valorization; thermochemical process; bone ash; bone char; porous material; pore property; value-added application

Check for updates

Academic Editor: Satyanarayana Narra

Received: 31 August 2026
Revised: 24 October 2026
Accepted: 4 November 2026
Published: 6 November 2026

**Copyright:** © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

## 1. Introduction

Agrifood systems accounted for approximately one-third of global greenhouse gas (GHG) emissions in terms of carbon dioxide equivalent ($CO_{2eq}$) [1,2], thus resulting in regional climate extremes caused by global warming. Carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) are the major GHGs associated with the activities of residential and non-residential sectors, such as crop/livestock production and food waste after consumption or during processes. According to the GHG inventory guideline reports by the Intergovernmental Panel on Climate Change (IPCC) [3,4], the sectors of agriculture, forestry and other land use (AFOLU) and waste management should be responsible for anthropogenic GHG emission sources. On the other hand, food loss reduction and waste management can closely connect SDG-12 (Responsible Consumption and Production) and SDG-2 (Zero Hunger) under the United Nations (UN) Sustainable Development Goals (SDGs) [5]. In this regard, food waste valorization should be a circular economy roadmap for sustainable agrifood systems [6].

Among the food waste sources, animal bone waste (ABW) has been estimated to be generated annually at about 100 million metric tons from slaughterhouses, meat processing plants, commercial markets/wholesalers, and domestic food consumption [7–9]. More importantly, it implies some environmental and resource issues due to its main composition of organic components (mainly consisting of collagen protein) and inorganic components (mainly including hydroxyapatite) [8,10–12]. Obviously, ABW will cause some environmental pollution problems if not properly treated or indiscriminately disposed of, including odor, pathogens, GHG emissions, and soil and water pollution. On the other hand, ABW may be representative of one of the value-added resources, especially for phosphorus (P), calcium (Ca) and other valuable substances. Therefore, there are many review papers for the valorization of ABW (or its resulting bone char or bone ash) and/or meat and bone meal (MBM) [8–10,12–22]. However, they mostly focused on the traditional fields or applications such as organic fertilizers (or soil amendments), animal feeds, and environmental adsorbents (or environmental materials for pollutant removal). It seemed that there is no comprehensive review covering the production of porous materials from ABW and/or MBM and their higher value-added applications. On the other hand, the hydrochar-based materials and their applications in environmental remediation have been recently studied using other feedstocks such as fish bone biomass [23] and winery waste [24], compared to the porous animal-bone-derived materials.

This work focused on the porous animal-bone-derived materials and their value-added applications, thus highlighting distinct differences in structural properties, chemical compositions, and performance metrics compared to animal manure-derived porous carbon-rich materials. The bones of the animal's skeleton vary in the forms of shape, size, function, and structure, depending on their species. Herein, the study on animal bone and its valorization will focus on the sources of livestock animals (i.e., cattle, pig, sheep) and poultry animals (i.e., chicken, duck), excluding fish. In addition, the context of this comprehensive review only covers the conversion processes or technologies by thermochemical methods (i.e., combustion, pyrolysis, and gasification) due to the practical purposes for producing porous materials and their potential applications. Furthermore, this work reviews the pore property determinations of porous materials from the viewpoints of materials science, environmental and chemical engineering.

To approach these aims, we first searched the scientific databases such as ScienceDirect, Web of Science, MDPI, Google, and Google Scholar. By entering the relevant keywords (e.g., review, animal bone, animal bone waste, meat and bone meal, bone char, bone ash, valorization) into the search fields (i.e., title, field, or topic) and also combining them (i.e., and, or), the relevant papers can be identified in the list. After the initial screening of the title and abstract, the initial search yielded approximately 150–200 articles. Finally, we further examined their targets and/or scopes in the experiments and main findings, further reducing the articles to about 100 in this work, including review papers, research papers, important reports, and available websites. In brief, the following topics will be reviewed to echo the paper's title:

- Sources and characteristics of animal bone waste (ABW).
- Processes for transforming ABW into porous materials.
- Pore property determinations for porous materials derived from ABW.
- Value-added applications of porous materials derived from ABW.

## 2. Sources and Characteristics of Animal Bone Waste (ABW)

### *2.1. Sources*

As defined above, ABW refers to the discarded skeletal parts (or fragments) and leftover bone-containing biomass which are often generated from the main meat (i.e., livestock:

cattle, pigs, sheep, goats; poultry: chickens, ducks, geese, turkeys) processing factories and markets [8]. In this regard, the sources of ABW include slaughterhouses, meat processing plants, and commercial markets like supermarkets and wholesalers. Because ABW is generated by industrial and commercial activities, it can be classified as non-residential waste. In contrast, ABW generated by households can be classified as residential waste. On the other hand, ABW can also originate from residential households and be discarded by humans without reuse. Therefore, this bone-attached waste may be added to residential trash because of its difficulty in recycling, finally forming so-called municipal solid waste (MSW) or urban waste. In other words, ABW cannot be processed as food waste (or kitchen waste) because it does not shred easily in standard composting facilities or pig-feed farms [25]. Therefore, it could be treated in large-scale MSW incineration plants or sanitary landfills in most developed countries.

It was reported that the global slaughter (or meat/food-processing) industries generated about 100 million metric tons of ABW every year [7]. This mass amount was mainly based on approximately 15–20 wt% of the total weight of a slaughtered animal [26]. Other relevant core statistics included the meat market statistics (approx. 370 million metric tonnes by carcass weight equivalent) by the Food and Agriculture Organization (FAO) [27], and the dressing percentage (e.g., 47 wt% for cattle, 50 wt% for sheep, and 70 wt% for pigs). Herein, the dressing percentage of livestock/poultry animals is defined by the ratio of hot carcass weight to live weight expressed as a percentage. According to the annual statistics by the FAO [28], the largest ABW-generating countries should be China, followed by the United States, Brazil and India. Furthermore, the projected ABW generation is expected to increase in the coming years due to population growth and rising living standards for global meat protein demand. This massive ABW amount not only poses a severe environmental protection problem but also gives rise to the utilization value of biomass resources. Due to the richness in organic components (i.e., collagen-based proteins) and inorganic compounds (especially calcium phosphate like hydroxyapatite), improper disposal and/or illegal dumping could lead to greenhouse gas (GHG) emissions, foul odors, and soil/water body/groundwater contamination because of microbial degradation [8].

### 2.2. Characteristics

On average, ABW contains valuable materials. It was reported that it consists of 30–35% organic components and 65–70% inorganic components [8,12,29], depending on the animal bone sources. The former mainly contains collagen (90–95%), followed by other proteins (up to 5%), with the rest being polysaccharides (e.g., chondroitin) and lipids. The latter is rich in a natural apatite-rich material, which is mostly composed of the inorganic substance calcium phosphate (approximately 65–70 wt%, mainly hydroxyapatite). Table 1 briefly summarizes the nutritional components of main ABW sources [30]. This natural inorganic mineral has a molecular formula $Ca_{10}(PO_4)_6(\text{-}OH)_2$, denoting its crystal unit cell with two entities. Theoretically, hydroxyapatite, a naturally occurring white powder, consists of approximately 39.89 wt% calcium, 41.41 wt% oxygen, 18.50 wt% phosphorus, and 0.20 wt% hydrogen. However, other colors (e.g., brown, yellow, or green) are often found in naturally occurring apatite due to the presence of other elements like fluorine, chlorine, and other inorganic elements. Regarding the elemental compositions of animal bones, it was found to contain the data in order [31–33]: 53 wt% calcium (Ca), 24 wt% phosphorus (P), 8 wt% boron (B), 6 wt% silicon (Si), 3 wt% sodium (Na), 2 wt% chlorine (Cl), 1.7 wt% sulfur (S), 1.6 wt% potassium (K), and 1.4 wt% magnesium (Mg). Other trace elements (less than 0.4 wt% for each element) include aluminum (Al), iron (Fe), zinc (Zn), manganese (Mn), titanium (Ti), and copper (Cu). Obviously, ABW or meat and bone meal (MBM) can be

traditionally reused as an efficient, slow-release, high Ca/P fertilizer for agricultural and food applications [34–39].

**Table 1.** Nutrition components of raw ABW categorized by main sources [1].

| Bone Source | Nutrition Component (wt%, Dry Basis) | | | |
|---|---|---|---|---|
| | Protein | Fat | Calcium | Ash Content [2] |
| Cattle bones | 30.4 | 18.5 | 12.4 | 38.7 |
| Pig bones | 33.0 | 25.7 | 9.7 | 38.6 |
| Sheep bones | 33.5 | 25.2 | 9.2 | 32.1 |
| Chicken bones | 47.4 | 40.7 | 2.9 | 9.0 |

[1] Reference [30]. [2] Mainly consisting of phosphorus.

## 3. Processes for Transforming ABW into Porous Materials

As described above, ABW or animal bones on a dry basis, typically consist of approximately 65–70% inorganic minerals (primarily hydroxyapatite), 30–35% organic components (majorly collagen-type proteins, minorly fats and polysaccharides). To convert them into porous materials (i.e., bone char, bone ash, or minerals mainly containing hydroxyapatite), the processes involve removing organic components by using thermal, chemical, or physical treatment methods [8,9,15,40–48], thereby leaving the inorganic minerals behind. However, the pretreatment procedures (i.e., washing and degreasing by hot water, alkaline sodium hydroxide solution, or acidic solution) must be performed to remove residual impurities like meat, fats, and blood [8]. Some advanced pretreatment processes adopt a mix of enzymatic (e.g., protease and lipase) and physical (e.g., ultrasound) approaches to break down attached organic matrices without the use of acid/alkali chemicals [49–51]. Figure 1 simply depicts three thermochemical routes for producing bone char and other resulting products and their potential applications. Furthermore, Table 2 summarizes a brief comparison of processes for converting ABW or MBM into porous materials and other valuable materials.

**Table 2.** Comparison of processes for converting ABW/MBM into porous materials and other valuable materials.

| Treatment Process | Principle/Mechanism | Main Products/Solid Carbon Content | Main Applications |
|---|---|---|---|
| Calcination (or combustion) | Complete oxidation of organic components | Steam, bone ash/~ 0% | Energy recovery, Ca/P fertilizer |
| Pyrolysis | Oxygen-limited decomposition at moderate temperature | Pyrolytic gas/liquid, bone char/10–20% | Ca/P fertilizer, porous adsorbent, catalyst |
| Gasification | Oxygen/water-limited decomposition at high temperature | Syngas, bone char/10–20% | Gas fuel, Ca/P fertilizer |
| Activation | Oxygen-limited pyrolysis of biomass with activating agents or gases | Bone activated char/10–15% | Porous adsorbent, catalyst |
| Supercritical $CO_2$ | Solvent-mediated lipid and protein extraction | Bone mineral scaffold/(Retained) | Biocompatible tissue engineering scaffolds |
| Steam-explosion | High-pressure mechanical destruction | Bone mineral scaffold/(Retained) | Functional food additives, specialty fertilizers |

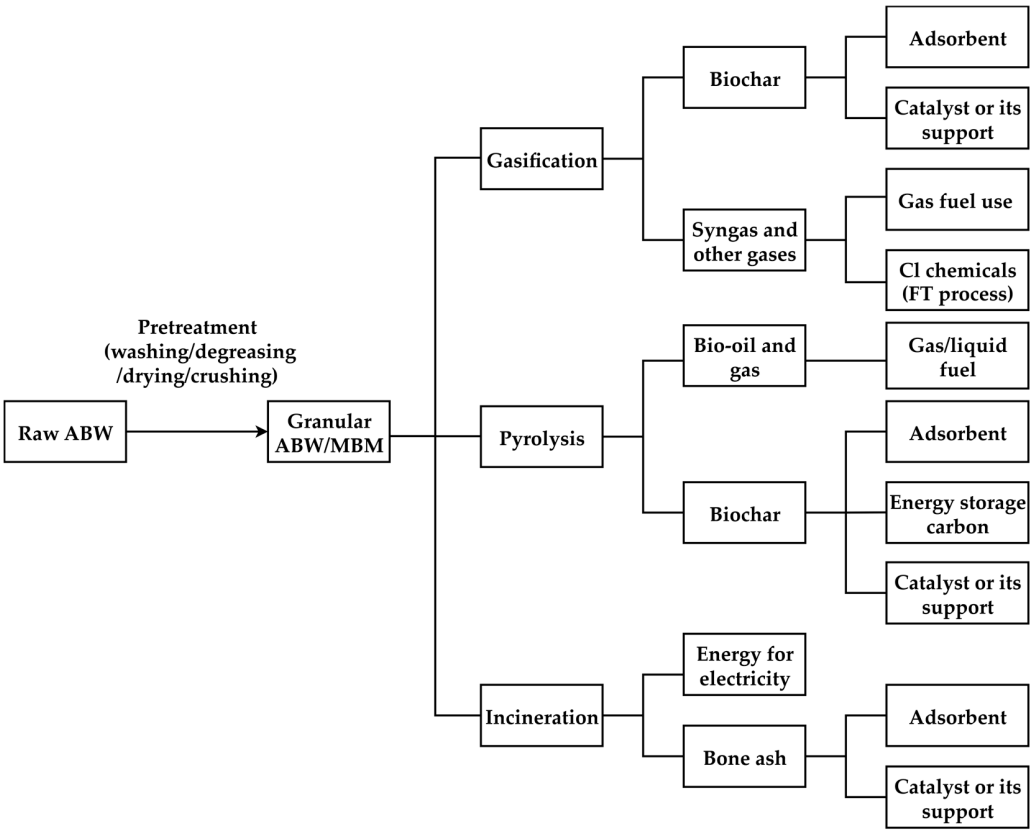



**Figure 1.** Thermochemical processes for producing bone char/ash and its potential applications.

### *3.1. Gasification Processes*

The main purposes of thermal/gasification processes are to produce various energy forms, including high-temperature steam by the combustion (or incineration) method and syngas (one of the gas fuels) by the gasification route. Due to the inorganic components present in ABW/MBM, bone ash or residual solids will be generated incidentally at the bottom of the process system. In the combustion process, it may be the most commonly used method to treat animal slaughter-derived waste and dead body animals at high temperatures (>850 °C). Depending on the excess air percentage, process temperature and the acidic organic elements (i.e., chlorine, sulfur, and even nitrogen) present in poultry/livestock animal waste, the emissions of sulfur dioxide ($SO_2$) and hydrogen chloride (HCl) may increase in the exhaust gases [52]. Practically, these animal waste and its bones are often mixed with urban waste and totally treated by a so-called municipal solid waste (MSW) incineration plant. Therefore, bone ash is not recovered due to the complicated bottom ash and fly ash.

The water content of residual animal bones can promote the gasification process at higher temperatures for converting ABW into gas-rich products [10], including hydrogen ($H_2$), carbon monoxide, methane ($CH_4$), carbon dioxide, and so on. The gasification efficiency is affected by the process parameters, including temperature, pressure, heating rate, gasifying gas (oxygen or moisture), feedstock composition (e.g., inorganics) and morphology (e.g., particle size), and catalysts added. By using a proper catalyst, it is possible to not only produce more $H_2$-rich and/or $CH_4$-rich gaseous products at moderate temperatures, but also reduce tar formation [53], thus improving overall process efficiency. Currently, the commonly used catalysts for enhancing the gasification process include alkali and alkaline earth catalysts, transition metal catalysts, Ni-based catalysts, carbon-based catalysts, natural mineral catalysts, and catalysts derived from waste byproducts [54–56].

### 3.2. Pyrolysis Process

Pyrolysis is a process for decomposing organic materials (e.g., biomass or organic waste) at low-moderate temperatures in the absence of oxygen. During the process, the pyrolytic products will include solid-formed char, gas-formed volatiles and water [53]. The latter may be further categorized into condensed liquid solution and non-condensed gas when chilling. In general, the liquid product mainly contains water, organic acids (e.g., acetic acid), phenols, and other oxygen-containing hydrocarbons. By contrast, the non-condensed gas commonly consists of hydrogen, carbon monoxide, carbon dioxide, methane, and $C_2$ hydrocarbons (e.g., ethylene). In this regard, the gas product can be used as a fuel for energy use, such as power generation. The solid char is a carbon-rich material that can be considered as a carbon sequestration, organic fertilizer or soil conditioner by providing nutritional elements such as N, P and Ca. In addition, the solid char can be further upgraded by activation treatment to produce activated char with high porosity, which will be described in the later subsection.

Regarding the pyrolysis process for ABW/MBM treatment, several studies have been reported in the literature [16,19,39,57–65]. Similar to the gasification process, several parameters will affect the yields of resulting pyrolysis products and their chemical compositions. They include temperature, residence time, heating rate, chemical/physical properties of feedstock, feedstock pretreatment, pyrolysis reactor types, and catalysts added [66–71]. In general, the resulting biochar or char develops a more porous structure at higher process temperatures [72–74]. It should be noted that fast pyrolysis is not a suitable process for producing higher char yields [75,76]. On the other hand, gaseous nitrogen compounds (especially for ammonia) have been detected during the pyrolysis of MBM, owing to the presence of nitrogen-containing proteins. These nitrogen-containing gases include ammonia ($NH_3$), hydrogen cyanide (HCN) and isocyanic acid (HNCO) [60], which are the precursors of nitrogen oxides (NOx) in the ambient atmosphere.

### 3.3. Activation Process

The activation process aims to further improve the pore properties of the resulting biochar derived from the pyrolysis (or carbonization) of biomass precursor. Regarding the production process of activated carbon, activated char, or activated biochar, there are usually two methods [77–80]. One is to adopt physical (or thermal) activation by passing gasification gas (i.e., carbon dioxide or steam) at higher temperatures (above 700 °C), thus creating more micropores (pore diameter or width smaller than 2 nm) and giving higher textural characteristics such as surface area and pore volume. Another is to perform chemical activation at lower process temperatures. However, this process features the impregnation of chemical agents (i.e., zinc chloride, phosphoric acid, potassium salts like potassium oxide KOH and potassium carbonate $K_2CO_3$) with biomass precursor or its resulting biochar before activation by pyrolysis (or carbonization), thus causing environmental pollution problems from the release of wastewater containing toxic components (e.g., zinc) when finishing the chemical activation process. In this regard, commercial activated carbon is commonly manufactured by the physical activation process.

Using the activation process for producing activated biochar from ABW/MBM, limited studies were reported in the literature [41,81–84]. Also similar to the pyrolysis process, the main process parameters affecting the pore and chemical properties include temperature, residence time, feedstock nature, and activation agents. Iriarte-Velasco et al. performed the chemical activation for producing microporous hydroxyapatite-based biochars by using three activating agents (namely, NaOH, KOH, $K_2CO_3$) [41]. At the proper temperature (about 800 °C) and impregnation ratio (or activating agent concentration of 10 mmol $K_2CO_3$/g), $K_2CO_3$ seemed to be the most effective agent for increasing the surface area of

activated biochar up to 234 $m^2/g$ (or being increased by 30%) when compared to that of the non-alkali-impregnated sample. In the study by Wang et al. [81], it was found that the pore properties of the biochar derived from waste pig MBM were increased significantly by about threefold (e.g., surface area 142.6 $m^2/g$ to 430.5 $m^2/g$) by chemical activation treatment with potassium hydroxide (KOH). Xie et al. employed animal bone as a precursor for producing hierarchical porous carbon (high surface area of about 1245 $m^2/g$) by KOH activation [82], which was used as a cathode material in a lithium–selenium battery. The efficient activated bone char adsorbent was produced from waste bovine bone at a pyrolysis temperature of 450 °C, followed by treatment with $H_3PO_4$ for surface modification and activation by $K_2CO_3$ [83]. The main findings focused on a new hierarchical material with a total pore volume of 2.807 $cm^3/g$ and toluene adsorption capacity of about 13.03 mmol/g. To use the resulting porous biochar as a support for a nickel-based catalyst for the water-gas shift (WGS) reaction, the authors Iriarte-Velasco et al. [84] further investigated the effects of $K_2CO_3$ and sulfuric acid ($H_2SO_4$) on the properties of activated char derived from pork chop bones.

## 4. Pore Property Determinations for Porous Materials Derived from ABW

This review paper focuses on the production of porous material from ABW and/or MBM. Therefore, its pore properties will determine the potential applications in a variety of fields. These physical properties often involve the measurement principles of gas (i.e., nitrogen) adsorption–desorption isotherms, mercury porosimetry and helium displacement for calculating surface area, pore volume, pore size distribution, true density, particle density, and porosity.

### *4.1. Pore Property by Nitrogen Adsorption–Desorption Isotherms*

The porous structure of a porous material is closely related to its surface area (or referred to as specific surface area due to the notation by gram), pore volume, pore size distribution, and average pore diameter. These properties play a vital role in the interface behaviors and potential applications. According to the International Union of Pure and Applied Chemistry (IUPAC) classification [85], the diameter boundary between mesopores and macropores is set at 50 nm, but 2 nm represents the boundary between micropores and mesopores. In words, micropores are characterized by diameters less than 2.0 nm, macropores are characterized by diameters larger than 50.0 nm, and mesopores range from 2.0 to 50.0 nm in diameter. For most porous materials, they often contain both microporous and mesoporous structures simultaneously. Furthermore, the IUPAC defines six types of physical adsorption–desorption isotherms that closely correlate with the following pore structures of solid materials:

- Type I: It features a sharp rise at low relative pressure (<0.05) and then reaches a horizontal plateau. Theoretically, it is characteristic of microporous materials (pore diameter or width < 2 nm), such as activated carbon or activated biochar, due to the high adsorption potential in narrow pores.
- Type IV: It is characteristic of a hysteresis loop to have capillary condensation at medium-to-high relative pressures (>0.4). It is closely relevant to mesoporous materials (pore diameter or widths between 2 and 50 nm) with strong interactions between adsorbate gas and pore wall.

In general, nitrogen ($N_2$) adsorption–desorption isotherms at −196 °C are the standard experimental methods for determining the pore properties of porous materials such as surface area, pore volume, and pore size distribution. Furthermore, the pore structures can be evaluated by their corresponding curves of adsorption–desorption isotherms over a wide relative pressure range from 0.000 to 0.995, where multilayer physical adsorption by van der

Waals interactions and capillary condensation at higher relative pressures (up to 1.0) will occur. Thereafter, the adsorbed amount of probe gas (i.e., $N_2$) will decrease as relative pressure is reduced during the desorption process. Based on the data of adsorption–desorption isotherms and the use of several equations or models like Langmuir, Harkins and Jura and Brunauer–Emmett–Teller (BET), we can calculate the pore properties of the tested material [86,87].

1. Specific surface area (SSA):

Generally speaking, the specific surface area of a non-porous spherical material increases with decreasing particle size by a proportionally inverse relationship [88]. In addition, the specific surface area will also increase when the particles have irregular shapes or porous surfaces. For a porous material, its specific surface area is closely related to the physical changes and chemical reactions in the industrial processes. Among the pore properties of a porous material, specific surface area may be the most important one because it determines the extent of surface available for interaction when using it as a catalyst and adsorbent. Therefore, a larger specific surface area is indicative of greater activity or reactivity on the surface of the material. The specific surface area of a porous material can be determined by several models and their equations. Among them, the BET theory of multilayer adsorption should be the most widely used one. In this model, the amounts of physical adsorption by nitrogen molecules onto the material surface are usually measured in a limited relative pressure range (0.05–0.35), which will yield a linear plot relevant to monolayer coverage. Using the data on the slope and intercept of the BET linear plot, the monolayer volume is thus calculated. The total surface area can be further determined from the monolayer volume and the cross-sectional area of the adsorbate nitrogen molecule (0.162 $nm^2$). Finally, the specific surface area based on the BET model can be obtained by dividing the total surface area by the sample weight. For a microporous material, the Rouquerol criteria, a set of consistency rules [89], should be used to correctly select the narrow relative pressure ($P/P_0$) range for calculating the specific surface area using the BET theory. A negative value of the BET parameter C would violate physical constraints.

2. Pore volume:

Herein, pore volume only refers to total pore volume, excluding micropore volume or mesopore volume. For a porous material, its total pore volume is commonly determined by nitrogen adsorption isotherm data at high relative pressure (very close to 1.0, like 0.995). Under the high saturation condition, capillary condensation will occur because all accessible open pores are filled with adsorbed nitrogen in the liquid form. Then, the adsorbed amount (denoted as the number of moles) at near saturation was converted to a mass of adsorbate per sample weight by using the ideal gas law. The total pore volume can be thus estimated by dividing this value by the liquid nitrogen density (i.e., 0.806 $g/cm^3$). The gas adsorption analysis is available for all porous materials containing both micropores and mesopores. However, for macroporous materials (or those containing fewer mesopores), the mercury intrusion porosimetry may be more appropriate [87]. Its principle is based on the relationship (or Washburn equation) between the pore diameter and the amount of mercury forced into the porous structure under various applied external pressures. Due to the limitations in applied pressure (up to 440 MPa, for example), this method can measure a wide pore size range from 3.2 nm (assuming a contact angle of 140° between mercury and the sample surface at 440 MP) to 1110 μm (assuming a contact angle of 150° at 14 hPa). Under the Minamata Convention, this method has been recently banned or phased out because of the high hazard of toxic mercury vapor if released during the measurement.

3. Average pore size:

If all pores (total number n) of porous material (total mass $m_p$) are independent, non-intersecting cylindrical (dimensions of diameter D and length L), the average pore diameter ($D_p$) can thus be estimated from its BET surface area ($S_{BET}$) and total pore volume ($V_t$) by the cylindrical pore model [88]:

$$m_p \times S_{BET} = (\pi \times D \times L) \times n$$

$$m_p \times V_t = [\pi \times (D/2)^2 \times L] \times n$$

$$\rightarrow D_p = 4 \times (V_t/S_{BET})$$

4. Pore size distribution:

As mentioned above, the pore size distribution of a porous material can be determined by mercury intrusion porosimetry. However, the most commonly used method is to use the data on $N_2$ adsorption–desorption isotherms at −196 °C based on relations like Halsey, Kelvin, Barrett–Joyner–Halenda (BJH) [87]. For mesoporous materials (pore diameter or width ranging from 2 to 50 nm), the BJH method is commonly adopted by using the isotherm data on the desorption route. As compared to the data on the adsorption route, it can provide a more reliable estimation of pore core size during meniscus formation and capillary evaporation. In contrast, several models or theories have been applied to measure the pore size distribution for microporous materials (pore diameter or width less than 2 nm). These relations include the Horváth-Kawazoe (HK) model, corrected HK Model (Rege-Yang) [90], and 2D-NLDFT-HS (Two-Dimensional Non-Local Density Functional Theory for Heterogeneous Surfaces) model [91]. Depending on the pore shape (e.g., slit-shaped pores), it should be done carefully when adopting the proper model to determine the pore size distribution of microporous materials.

### *4.2. Porosity by Helium Pycnometry*

The porosity can be defined as the fraction of open pore space inside a porous material compared to its total volume. Although several available methods can be used to determine the porosity ($\varepsilon_p$) of a porous material [86], the methods by helium pycnometry for true density ($\rho_s$) and mercury pycnometry for particle density ($\rho_p$) may be commonly adopted by the following equation:

$$\varepsilon_p = 1 - (\rho_p/\rho_s)$$

As defined, the true density of a porous material should be the mass of the solid material divided by its exact solid volume, excluding all open pores and closed (or confined) pores. In this regard, the "true" density of material is not easy to measure because some confined pores may be present inside the sample and are not accessible from outside. Despite this inherent limitation, the most commonly used method is based on helium displacement theory for determining true density by a pycnometer. Obviously, helium is an inert gas with a very small molecular size that diffuses into all open pores without interacting with the probe molecule. Regarding the particle density of a porous material, it is similarly defined by the sample mass divided by its external (or apparent) volume. Traditionally, its measurement was carried out by mercury pycnometry due to the liquid mercury nature (e.g., high surface tension without penetration into the material inside under normal conditions). As stated above, mercury pycnometry for particle density measurement has been phased out in recent years due to the health and environmental hazards of exposing mercury vapor or releasing mercury liquid. To estimate the true density of a porous material, another available method is to use the data on the true density ($\rho_s$) and total pore volume ($V_t$).

According to the definition of particle density ($\rho_p$) for a porous material, it can be calculated by using the following equation [86,88]:

$$\rho_p = 1/[V_t + (1/\rho_s)]$$

Following that, the porosity of a porous material ($\varepsilon_p$) can be calculated from the data on the $N_2$ adsorption isotherm and helium displacement.

## 5. Value-Added Applications of Porous Materials Derived from ABW

Based on the features of porous structure and hydroxyapatite-based composition, the resulting materials mainly derived from the thermochemical conversion processes of animal bones like ABW or MBM have potential practical applications in the review papers [8,10], not traditional fields like agriculture (e.g., organic fertilizer, soil amendment, animal feed) and food (e.g., food additive, nutritious food) [9,15,92–94]. When using porous animal-bone-derived materials (e.g., bone biochar, hydroxyapatite-based materials), the operational performance and reliability are heavily constrained by their mechanical and chemical stability. For example, the ABW-derived materials are sensitive to acidic environments, possibly leaching the ions of calcium and phosphate from hydroxyapatite and thus weakening the porous structure [95].

The following subsections will briefly address the value-added fields, including environmental applications, medical applications, catalyst applications, energy storage applications, and other applications.

### *5.1. Environmental Applications*

In recent years, several review papers or book chapter focused on the production of porous materials (or bone char) from ABW or MBM in the environmental protection [21,96–98]. They are used as adsorbents for removing pollutants from the aqueous stream or gaseous stream due to their available adsorption capacities. The target pollutants include a variety of types like heavy metals (e.g., Cr(VI)) [99], ionic molecules (e.g., fluoride) [100], volatile organic compounds (e.g., xylene) [101,102], carbon dioxide [103,104], dyes (e.g., Acid Yellow 34, tannery dye) [105,106], emerging organic compounds (e.g., triclosan) [107], and pesticides (e.g., organophosphorus pesticides) [108].

### *5.2. Medical Applications*

Based on the naturally occurring composition (i.e., hydroxyapatite) of ABW or MBM, the resulting bone char has been investigated in biomedical applications like bone grafting and tissue engineering because of its properties of high biocompatibility, excellent bioactivity and osteoconductivity [12,42,109–115]. On the other hand, the commercial scaffolds, regenerative materials or chemically synthesized materials are usually expensive and do not possess a well-defined interconnected and three-dimensional porous texture. Therefore, hydroxyapatite-based bone char produced from ABW or MBM can be considered an available alternative.

### *5.3. Catalyst Applications*

It is well known that catalysts play a vital role in the chemical process industries, including chemicals, fuels, acids, polymers, and so on. They provide an efficient route for promoting chemical reactions, thus lowering energy costs and even reducing the production of byproducts and undesired products. In recent years, some studies have reported using the mesoporous hydroxyapatite-based materials from animal bones (ABW or MBM) as a heterogeneous catalyst [10,116–121]. In addition, the bone-derived char material also contains metal oxides like CaO, MgO, $SiO_2$, $Na_2O$, and $K_2O$. As a result, the bone-derived

char has been used as a green catalyst for different chemical reaction applications [8], including transesterification for biodiesel production and hydrogen production, organic reduction reaction (ORR), synthesis of bioactive compounds, pyrolysis of plastic, and degradation of pollutants by photocatalytic reaction.

### 5.4. Energy Storage Applications

The uses of energy storage devices (e.g., lithium-ion batteries and supercapacitors) are becoming more and more popular around the world due to the growing adoption of electric vehicles, electricity grid-scale storage, and portable electronics like mobile phones [119,122–125]. Therefore, an electrified society not only brings many conveniences to daily life, but also reduces the emissions of GHG from fuel-driven engines. Regarding the performance of these devices or equipment, their electrodes must meet several specifications, especially for large surface areas and excellent electrical conductivity. Up to now, porous carbon materials with large specific surface area and high porosity may be suitable for charge storage batteries and supercapacitors. However, they are almost entirely derived from fossil fuel carbon sources that consume non-renewable energy and thus emit air pollutants. In contrast, carbon materials from biomass are renewable and environmentally friendly. In recent years, there have been several studies on producing ABW-based porous materials and further reusing them as novel electrode materials in energy storage devices [125]. To facilitate electron ion mobility, the high-surface-area bone-derived carbons were usually pyrolyzed at higher temperature and further activated by using thermal activation by gasification gas $CO_2$.

### 5.5. Other Applications

Since animal bone is a resource which is rich in elements such as calcium and phosphorus, it or its resulting products (e.g., bone ash, bone biochar, bone char, or activated biochar) can be used in various other value-added applications, including as additives in low-carbon cement [33,126], and other value-added products [127,128].

## 6. Conclusions and Prospects

Valorizing hydroxyapatite/collagen-based resources from animal bone waste has proven to be a valuable route, not only resolving environmental loadings, but also promoting a circular economy. Using thermochemical processes (i.e., combustion, pyrolysis, and gasification), animal bone waste can be converted into functionally porous materials. These Ca/P-rich materials have excellent pore and chemical properties, including high specific surface area (or pore volume), mesoporous structures, and Ca/P/O-containing functional groups. Due to these features, they can be applied to various value-added fields/industries for being used as environmental adsorbents and catalysts for removing pollutants from water and soils, catalysts and their supports for chemical synthesis or other reactions, biomedical uses in bone grafting and tissue engineering, and electrode materials for energy storage. However, the porous animal-bone-derived materials (e.g., bone biochar, hydroxyapatite-based materials) are sensitive to acidic environments, possibly causing the widening and collapse of the porous structures due to the leaching/dissolution of calcium and phosphate ions from the hydroxyapatite matrix.

This comprehensive review demonstrates that the thermochemical treatment of animal bone waste through pyrolysis and gasification will be preferred to producing porous materials like bone char and bone biochar. Although the combustion (or calcination) process can produce bone ash for agricultural use and heat for energy use, this bone-attached waste could often be added to residential trash for further treatment by municipal solid waste (MSW) incineration plants without the utilization of bottom ash. To increase the pore

properties of bone char (or biochar) and its value-added applications (like energy storage materials), the chemical or physical process should be performed in the post-pyrolysis operation. Depending on the final application purposes, these thermochemical processes have their own pros and cons from the viewpoint of energy and material production. The production of porous materials should be prioritized based on an assessment of their economic benefits because hydroxyapatite is a valuable resource in the biomedical materials and chemical process industry. In addition, phosphorus contained in hydroxyapatite is also a valuable resource for soil fertility.

**Author Contributions:** Conceptualization, W.-T.T.; data collection, C.-H.T.; data analysis, C.-H.T.; writing—original draft preparation, W.-T.T.; writing—review and editing, W.-T.T.; supervision, W.-T.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F.N.; Leip, A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2021**, *2*, 198–209. [CrossRef] [PubMed]
2. Tubiello, F.N.; Rosenzweig, C.; Conchedda, G.; Karl, K.; Gütschow, J.; Xueyao, P.; Obli-Laryea, G.; Wanner, N.; Qiu, S.Y.; De Barros, J.; et al. Greenhouse gas emissions from food systems: Building the evidence base. *Environ. Res. Lett.* **2021**, *16*, 065007. [CrossRef]
3. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/ (accessed on 30 August 2026).
4. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (accessed on 30 August 2026).
5. Take action for the Sustainable Development Goals. Available online: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed on 30 August 2026).
6. Manzoor, S.; Fayaz, U.; Dar, A.H.; Dash, K.K.; Shams, R.; Bashir, I.; Pandey, V.K.; Abdi, G. Sustainable development goals through reducing food loss and food waste: A comprehensive review. *Future Foods* **2024**, *9*, 100362. [CrossRef]
7. Nassar, H.N.; Ismail, A.R.; El-Salamony, R.A.; Aboelazayem, O.; Abu Amr, S.A.; El-Gendy, N.S. Animal bone affluence in environmental reclamation: Biodiesel production, petro-diesel biodesulfurization and wastewater photo-treatment. *Biofuels Bioprod. Biorefin.* **2021**, *15*, 770–792. [CrossRef]
8. Hart, A.; Ebiundu, K.; Peretomode, E.; Onyeaka, H.; Nwabor, O.F.; Obileke, K. Value-added materials recovered from waste bone biomass: Technologies and applications. *RSC Adv.* **2022**, *12*, 22302–22330. [CrossRef] [PubMed]
9. Ghorbani, M.; Azarnejad, N.; Brown, R.W.; Chadwick, D.R.; Loppi, S.; Lones, D.L. Sustainable resource management with bone char—Challenges and opportunities for enhancing soil health and phosphorus stocks. *Biochar* **2026**, *8*, 34. [CrossRef] [PubMed]
10. Macavei, M.G.; Gheorghe, V.-C.; Ionescu, G.; Volceanov, A.; Pătrașcu, R.; Mărculescu, C.; Magdziarz, A. Thermochemical conversion of animal-derived waste: A mini-review with a focus on chicken bone waste. *Processes* **2024**, *12*, 358. [CrossRef]
11. Angela, S.; Barrow, C.J. A review of the processing, analysis and application of animal bone-derived collagen. *Food Hydrocoll.* **2026**, *175*, 112499. [CrossRef]
12. Mkhitaryan, L.; Baghdasaryan, L.; Nazaretyan, K.; Khachatryan, Z.; Khachatryan, A.; Torosyan, M.; Aghayan, M.; Rodríguez, M.A.; Rstakyan, V. Valorization of bone waste: Effect of animal bone origin on hydroxyapatite structure and properties. *Environ. Sci. Pollut. Res.* **2026**, *33*, 2921–2935. [CrossRef] [PubMed]
13. Jayathilakan, K.; Sultana, K.; Radhakrishna, K.; Bawa, A.S. Utilization of byproducts and waste materials from meat, poultry and fish processing industries: A review. *J. Food Sci. Technol.* **2012**, *49*, 278–293. [CrossRef] [PubMed]
14. Vamvuka, D.; Dermitzakis, S.; Pentari, D.; Sfakiotakis, S. Valorization of meat and bone meal through pyrolysis for soil amendment or lead adsorption from wastewaters. *Food Bioprod. Process.* **2018**, *109*, 148–157. [CrossRef]

15. Ahmed, M.; Nigussie, A.; Addisu, S.; Belay, B.; Sato, S. Valorization of animal bone into phosphorus biofertilizer: Effects of animal species, thermal processing method, and production temperature on phosphorus availability. *Soil Sci. Plant Nutr.* **2021**, *67*, 471–481. [CrossRef]
16. Azeem, M.; Shaheen, S.M.; Ali, A.; Jeyasundar, P.G.S.A.; Latif, A.; Abdelrahman, H.; Li, R.; Almazroui, M.; Niazi, N.K.; Sarmah, A.K.; et al. Removal of potentially toxic elements from contaminated soil and water using bone char compared to plant- and bone-derived biochars: A review. *J. Hazard. Mater.* **2022**, *427*, 128131. [CrossRef] [PubMed]
17. Ahmed, M.; Nigussie, A.; Addisu, S.; Belay, B.; Lehmann, J.; Sato, S. Valorization of animal bone waste for agricultural use through biomass co-pyrolysis and bio-augmentation. *Biomass Conv. Bioref.* **2023**, *13*, 12823–12832. [CrossRef]
18. Castillo, N.A.M.; González-Fernández, L.A.; Thiodjio-Sendja, B.; Aguilera-Flores, M.M.; Leyva-Ramos, R.; Reyes-López, S.Y.; de León-Martínez, L.D.; Dias, J.M. Bone char for water treatment and environmental applications: A review. *J. Anal. Appl. Pyrolysis* **2023**, *175*, 106161. [CrossRef]
19. Piccirillo, C. Preparation, characterisation and applications of bone char, a food waste-derived sustainable material: A review. *J. Environ. Manag.* **2023**, *339*, 117896. [CrossRef] [PubMed]
20. Amin, A.E.E.A.Z. Using bone char as a renewable resource of phosphate fertilizers in sustainable agriculture and its effects on phosphorus transformations and remediation of contaminated soils as well as the growth of plants. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 6980–6998. [CrossRef]
21. Li, Y.; Liu, J.; Wei, B.; Zhang, Z.; Liu, X.; Han, L. A comprehensive review of bone char: Fabrication procedures, physicochemical properties, and environmental application. *Sci. Total Environ.* **2024**, *954*, 176375. [CrossRef] [PubMed]
22. Shi, H.; Wang, J.; Kim, W.K. Interactive effects of calcium, phosphorus, and exogenous phytase on growth performance and bone ash in broilers under Eimeria or necrotic enteritis infections: A systemic review and meta-analysis. *J. Appl. Poult. Res.* **2024**, *33*, 100422. [CrossRef]
23. Castro-Cárdenas, M.; Medellín-Castillo, N.A.; González-Fernández, L.A.; Leyva-Ramos, R.; Gómez-Duran, C.F.A.; Gariepy, Y.; Pou, K.R.J.; Raghavan, V. Innovative solution for invasive species and water pollution: Hydrochar synthesis from pleco fish biomass. *Processes* **2024**, *12*, 1158. [CrossRef]
24. Petrović, J.; Koprivica, M.; Milenković, M.; Ercegović, M.; Lazarević-Pašti, T.; Terzić, T.; Milanković, V.; Simić, M. Sustainable hydrochars from winery waste for the efficient removal of organophosphorus pesticides and synthetic dye. *Int. J. Mol. Sci.* **2026**, *27*, 2984. [CrossRef] [PubMed]
25. Vigil, J.M.; DeAtley, K.L. PSXII-12 Effects of compost environment on bone degradation of livestock mortality compost. *J. Anim. Sci.* **2024**, *102*, 727. [CrossRef]
26. Hussain, F.; Alshahrani, S.; Abbas, M.M.; Khan, H.M.; Jamil, A.; Yaqoob, H.; Soudagar, M.E.M.; Imran, M.; Ahmad, M.; Munir, M. Waste animal bones as catalysts for biodiesel production; A mini review. *Catalysts* **2021**, *11*, 630. [CrossRef]
27. Food and Agriculture Organization (FAO). *MEAT MARKET REVIEW-Overview of Global Market Developments in 2023*; FAO: Rome, Italy, 2024.
28. World Food and Agriculture—Statistical Yearbook 2025. Available online: https://www.donorplatform.org/post/publications/fao-statistical-yearbook-2025-world-food-and-agriculture/ (accessed on 24 August 2026).
29. Malla, K.P.; Regmi, S.; Nepal, A.; Bhattarai, S.; Yadav, R.J.; Sakurai, S.; Adhikari, R. Extraction and characterization of novel natural hydroxyapatite bioceramic by thermal decomposition of waste ostrich bone. *Int. J. Biomater.* **2020**, 1690178. [CrossRef] [PubMed]
30. Animal Bones Protein Market Research. Available online: https://www.meat-machinery.com/meat-processing-insight/animal-bone-processing-industry-analysis.html (accessed on 26 August 2026).
31. Genisel, M.; Erdal, S.; Turk, H.; Dumlupinar, R. The availability of bone powder as inorganic element source on growth and development in wheat seedlings. *Toxicol. Ind. Health* **2012**, *28*, 458–462. [CrossRef] [PubMed]
32. Bih, N.L.; Mahamat, A.A.; Chinweze, C.; Ayeni, O.; Bidossèssi, H.J.; Onwualu, P.A.; Boakye, E.E. The effect of bone ash on the physio-chemical and mechanical properties of clay ceramic bricks. *Buildings* **2022**, *12*, 336. [CrossRef]
33. Duvallet, T.Y.; Jewell, R.B. Recycling of bone ash from animal wastes and by-products in the production of novel cements. *J. Am. Ceram. Soc.* **2023**, *106*, 3720–3735. [CrossRef]
34. Bøen, A.; Haraldsen, T.K. Meat and bone meal and biosolids as slow-release phosphorus fertilizers. *Agri. Food Sci.* **2013**, *22*, 235–246. [CrossRef]
35. Heyl, K.; Garske, B.; Ekardt, F. Using bone char as phosphate recycling fertiliser: An analysis of the new EU Fertilising Products Regulation. *Environ. Sci. Eur.* **2023**, *35*, 109. [CrossRef]
36. Piash, M.I.; Uemura, K.; Itoh, T.; Iwabuchi, K. Meat and bone meal biochar can effectively reduce chemical fertilizer requirements for crop production and impart competitive advantages to soil. *J. Environ. Manag.* **2023**, *336*, 117612. [CrossRef] [PubMed]
37. Gil, F.; Skrzypczak, D.; Wijatkowska, A.; Taf, R.; Chojnacka, K. Waste-to-fertilizer strategy for circular nutrient recovery from meat and bone meal: Optimization of organo-mineral fertilizer production. *J. Environ. Chem. Eng.* **2025**, *13*, 118708. [CrossRef]

38. Ciurli, A.; Sciubba, L.; Biase, G.D.; Mazzon, M.; Ciavatta, C.; Cavani, L. The degree of hydrolysis of meat and bone meals fertilizers drives carbon mineralisation and the availability of nitrogen and phosphorus in soil. *J. Environ. Manag.* **2026**, *413*, 130354. [CrossRef] [PubMed]
39. Skrzypczak, D.; Wijatkowska, A.; Gil, F.; Pstrowska, K.; Mazur–Nowacka, A.; Chojnacka, K. Thermochemical conversion of meat and bone meal into biochar: Effect of pyrolysis temperature on nutrient retention and fertilizer potential. *Biomass Bioenergy* **2026**, *215*, 109592. [CrossRef]
40. Iriarte-Velasco, U.; Ayastuy, J.L.; Zudaire, L.; Sierra, I. An insight into the reactions occurring during the chemical activation of bone char. *Chem. Eng. J.* **2014**, *251*, 217–227. [CrossRef]
41. Iriarte-Velasco, U.; Sierra, I.; Zudaire, L.; Ayastuy, J.L. Conversion of waste animal bones into porous hydroxyapatite by alkaline treatment: Effect of the impregnation ratio and investigation of the activation mechanism. *J. Mater. Sci.* **2015**, *50*, 7568–7582. [CrossRef]
42. Ramesh, S.; Loo, Z.Z.; Tan, C.Y.; Kelvin Chew, W.J.; Ching, Y.C.; Tarlochan, F.; Chandran, H.; Krishnasamy, S.; Bang, L.T.; Sarhan, A.A.D. Characterization of biogenic hydroxyapatite derived from animal bones for biomedical applications. *Ceram. Int.* **2018**, *44*, 10525–10530. [CrossRef]
43. Liu, K.F.; Chen, R.F.; Li, Y.T.; Lin, Y.N.; Hsieh, D.J.; Periasamy, S.; Lin, S.D.; Kuo, Y.R. Supercritical carbon dioxide decellularized bone matrix seeded with adipose-derived mesenchymal stem cells accelerated bone regeneration. *Biomedicines* **2021**, *9*, 1825. [CrossRef] [PubMed]
44. Sierra, I.; Ayastuy, J.L.; Gutiérrez-Ortiz, M.A.; Iriarte-Velasco, U. A study on the impact of the reaction mechanism of the thermochemical activation of bone char (by pyrolysis and carbonization). *J. Anal. Appl. Pyrolysis* **2023**, *171*, 105973. [CrossRef]
45. Kong, X.; Qiu, X.; Li, P.; Li, Y.; Zhang, Y.; Guo, X.; Kong, F. Enhancement of nutrient bioaccessibility and functional property of chicken bone powder through steam explosion. *J. Agric. Food Res.* **2024**, *15*, 100941. [CrossRef]
46. Okpe, P.C.; Folorunso, O.; Aigbodion, V.S.; Obayi, C. Hydroxyapatite synthesis and characterization from waste animal bones and natural sources for biomedical applications. *J. Biomed. Mater. Res. B Appl. Biomater.* **2024**, *112*, e35440. [CrossRef] [PubMed]
47. Ma, Y.; Zhang, C.; Hai, D.; Wang, T.; Bai, G.; Zhang, Y.; Meng, S.; Zhao, J.; Song, L.; Huang, X. Quality change of chicken bone residue treated by steam explosion and its application in meatballs. *LWT* **2025**, *237*, 118725. [CrossRef]
48. Rota, S.; Sicard, L.; Perarnaud, J.; Agniel, R.; Bardonnet, R.; Chaussain, C.; Boissière, M.; Pauthe, E.; Gorin, C. Purified bone xenografts: A novel and efficient animal bone substitute derived from an optimized supercritical $CO_2$ treatment. *Mater. Today Bio* **2025**, *31*, 101619. [CrossRef] [PubMed]
49. Yao, Y.; Wang, M.; Liu, Y.; Han, L.; Liu, X. Insights into the improvement of the enzymatic hydrolysis of bovine bone protein using lipase pretreatment. *Food Chem.* **2020**, *302*, 125199. [CrossRef] [PubMed]
50. Ionescu, G.; Macavei, M.; Pătrascu, M.; Volceanov, A.; Pătrascu, R.; Werle, S.; Mlonka-Mędrala, A.; Coman, A.E.; Mărculescu, A.M.C. New integrated processing of chicken bone waste using an enzymatic pretreatment and slow pyrolysis to produce green chemicals. *Energy Convers. Manag.* **2025**, *323*, 119281. [CrossRef]
51. Zhang, Y.; Yu, S.; Liu, C.; Jiang, S.; Wang, H.; Cheng, Y.; Guo, Y.; Qian, H. Optimizing enzymatic processes for enhanced nutritional and organoleptic properties of chicken bones. *Foods* **2025**, *14*, 1217. [CrossRef] [PubMed]
52. Poskrobko, S. Identification and stabilization of combusting animal waste with active participation of bone material—Emission of $SO_2$ and HCl. *Fuel Process. Technol.* **2013**, *113*, 20–27. [CrossRef]
53. Kirtania, K. Thermochemical conversion processes for waste biorefinery. In *Waste Biorefinery: Potential and Perspectives*; Bhaskar, T., Pandey, A., Mohan, S.V., Lee, D.J., Khanal, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 129–156.
54. Alptekin, F.M.; Celiktas, M.S. Review on catalytic biomass gasification for hydrogen production as a sustainable energy form and social, technological, economic, environmental, and political analysis of catalysts. *ACS Omega* **2022**, *7*, 24918–24941. [CrossRef] [PubMed]
55. Niu, Y.H.; Chi, Z.Y.; Li, M.; Du, J.Z.; Han, F.T. Advancements in biomass gasification and catalytic tar-cracking technologies. *Mater. Rep. Energy* **2024**, *4*, 100295. [CrossRef]
56. Jothiprakash, G.; Balasubramaniam, P.; Sundaram, S.; Ramesh, D. Catalytic biomass gasification for syngas production: Recent progress in tar reduction and future perspectives. *Biomass* **2025**, *5*, 37. [CrossRef]
57. Purevsuren, B.; Avid, B.; Narangerel, J.; Gerelmaa, T.; Davaajav, Y. Investigation on the pyrolysis products from animal bone. *J. Mater. Sci.* **2004**, *39*, 737–740. [CrossRef]
58. Cascarosa, E.; Boldrin, A.; Astrup, T. Pyrolysis and gasification of meat-and-bone-meal: Energy balance and GHG accounting. *Waste Manag.* **2013**, *33*, 2501–2508. [CrossRef] [PubMed]
59. Cascarosa, E.; Gea, G.; Arauzo, J. Thermochemical processing of meat and bone meal: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 942–957. [CrossRef]
60. Feng, Y.; Wan, L.; Wang, S.; Yu, T.; Chen, D. The emission of gaseous nitrogen compounds during pyrolysis of meat and bone meal. *J. Anal. Appl. Pyrolysis* **2018**, *130*, 314–319. [CrossRef]

61. Zaharioiu, A.M.; Şandru, C.; Ionete, E.I.; Marin, F.; Ionete, R.E.; Soare, A.; Constantinescu, M.; Bucura, F.; Niculescu, V.-C. Eco-friendly alternative disposal through the pyrolysis process of meat and bone meal. *Materials* **2022**, *15*, 6593. [CrossRef] [PubMed]
62. State, R.N.; Ionescu, G.; Volceanov, A.; Coman, A.E.; Magdziarz, A.; Marculescu, C. Combined valorization of bone waste as feedstock and support material for ex-situ catalytic pyrolysis. *J. Environ. Chem. Eng.* **2025**, *13*, 119091. [CrossRef]
63. Alshdoukhi, I.F.; Al-Ahmary, K.M.; Al-Mhyawi, S.R.; Alnawmasi, J.S.; Alqahtani, Z.; AlMohamadi, H.; Alrashood, J.S.; Kola, O.E. Valorization of chicken bone waste into biochar adsorbent for methyl red adsorption from aqueous systems. *Sci. Rep.* **2026**, *16*, 19482. [CrossRef] [PubMed]
64. Wang, X.; Zhang, S.; Wang, B.; Gao, M.; Peng, Y.; Zhao, R.; Li, J. Recent advances in the valorization of agricultural waste-derived biochar: From preparation strategies and structural regulation to intelligent design. *J. Anal. Appl. Pyrolysis* **2026**, *198*, 107907. [CrossRef]
65. Odoi-Yorke, F.; Agyekum, E.B.; Al-Maaitah, M.I.; Ribeiro, J.X.F.; Seepana Praveenkumar, S. Conversion of food waste to biochar via pyrolysis: Production processes, material properties, and environmental applications. *Talanta* **2027**, *311*, 130237. [CrossRef] [PubMed]
66. Chun, Y.; Lee, S.K.; Yoo, H.Y.; Kim, S.W. Recent advancements in biochar production according to feedstock classification, pyrolysis conditions, and applications: A review. *BioResources* **2021**, *16*, 6512–6547. [CrossRef]
67. Devi, M.; Rawat, S.; Sharma, S. A comprehensive review of the pyrolysis process: From carbon nanomaterial synthesis to waste treatment. *Oxf. Open Mater. Sci.* **2021**, *1*, itab014. [CrossRef]
68. Jerzak, W.; Acha, E.; Li, B. Comprehensive review of biomass pyrolysis: Conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis. *Energies* **2024**, *17*, 5082. [CrossRef]
69. Mengesha, T.T.; Ancha, V.R.; Sundar, L.S.; Pollex, A. Review on the influence of pyrolysis process parameters for biochar production with minimized polycyclic aromatic hydrocarbon content. *J. Anal. Appl. Pyrolysis* **2024**, *182*, 106699. [CrossRef]
70. Talwar, P.; Agudelo, M.A.; Nanda, S. Pyrolysis process, reactors, products, and applications: A review. *Energies* **2025**, *18*, 2979. [CrossRef]
71. Zhang, X.; Zhang, Y.; Zhang, S.; Yao, L.; Hao, Y. Lignocellulosic biomass pyrolysis: A review on the pretreatment and catalysts. *Fuel Process. Technol.* **2025**, *279*, 108352. [CrossRef]
72. Keiluweit, M.; Vico, P.S.; Johnson, M.G.; Kleber, M. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environ. Sci. Technol.* **2010**, *44*, 1247–1253. [CrossRef] [PubMed]
73. Chia, C.H.; Downie, A.; Munroe, P. Characteristics of biochar: Physical and structural properties. In *Biochar for Environmental Management: Science, Technology and Implementation*, 2nd ed.; Lehmann, J., Joseph, S., Eds.; Routledge: New York, NY, USA, 2015; pp. 89–109.
74. Mukome, F.N.D.; Parikh, S.J. Chemical, physical, and surface characterization of biochar. In *Biochar: Production, Characterization, and Applications*; Ok, Y.S., Uchimiya, S.M., Chang, S.X., Bolan, N., Eds.; CRC Press: Boca Raton, FL, USA, 2016; pp. 67–96.
75. Basu, P. *Biomass Gasification, Pyrolysis and Torrefaction*, 3rd ed.; Academic Press: San Diego, CA, USA, 2018.
76. Zhang, Y.; Ma, Z.; Yan, J. Influence of pork and bone on product characteristics during the fast pyrolysis of pig carcasses. *Waste Manag.* **2018**, *75*, 352–360. [CrossRef] [PubMed]
77. Marsh, H.; Rodriguez-Reinoso, F. *Activated Carbon*; Elsevier: Amsterdam, The Netherlands, 2006.
78. Sakhiya, A.K.; Anand, A.; Kaushal, P. Production, activation, and applications of biochar in recent times. *Biochar* **2020**, *2*, 253–285. [CrossRef]
79. Panwar, N.L.; Pawar, A. Influence of activation conditions on the physicochemical properties of activated biochar: A review. *Biomass Conv. Bioref.* **2022**, *12*, 925–947. [CrossRef]
80. Hai, A.; Wan Daud, W.M.A.; Abdul Patah, M.F.; Bharath, G.; Almohamadi, H.; Tang, D.Y.Y.; Show, P.L.; Banat, F. A comprehensive insight on activated carbon production from agricultural biomass: Parametric analysis, challenges, future recommendations & machine learning modelling. *Resour. Conserv. Recycl. Adv.* **2025**, *2*, 100041. [CrossRef]
81. Wang, S.; Yuan, H.; Wang, Y.; Shan, R. Transesterification of vegetable oil on low cost and efficient meat and bone meal biochar catalysts. *Energy Convers. Manag.* **2017**, *150*, 214–221. [CrossRef]
82. Xie, L.S.; Yu, S.X.; Yang, H.J.; Yang, J.; Ni, J.L.; Wang, J.L. Hierarchical porous carbon derived from animal bone as matric to encapsulated selenium for high performance Li–Se battery. *Rare Met.* **2017**, *36*, 434–441. [CrossRef]
83. Yang, Y.; Sun, C.; Lin, B.; Huang, Q. Surface modified and activated waste bone char for rapid and efficient VOCs adsorption. *Chemosphere* **2020**, *256*, 127054. [CrossRef] [PubMed]
84. Iriarte-Velasco, U.; Sierra, I.; Gutiérrez-Ortiz, M.A.; Ayastuy, J.L. Bioapatite derived from animal bones as support for environmentally concerned catalysts: WGS with suppressed methanation activity. *J. Environ. Chem. Eng.* **2023**, *11*, 110677. [CrossRef]
85. Gregg, S.J.; Sing, K.S.W. *Adsorption, Surface Area and Porosity*, 2nd ed.; Academic Press: London, UK, 1982.
86. Suzuki, M. *Adsorption Engineering*; Elsevier: Amsterdam, The Netherlands, 1990.

87. Lowell, S.; Shields, J.E.; Thomas, M.A.; Thommes, M. *Characterization of Porous Solids and Powders: Surface Area, Pore Size and Density*; Springer: Dordrecht, The Netherlands, 2006.
88. Smith, J.M. *Chemical Engineering Kinetics*, 3rd ed.; McGraw-Hill: New York, NY, USA, 1981.
89. Rouquerol, J.; Llewellyn, P.; Rouquerol, F. Is the BET equation applicable to microporous adsorbents? *Stud. Surf. Sci. Catal.* **2007**, *160*, 49–56. [CrossRef]
90. Rege, S.U.; Yang, R.T. Corrected Horváth-Kawazoe equations for pore-size distribution. *AIChE J.* **2000**, *46*, 734–750. [CrossRef]
91. Jagiello, J.; Ania, C.; Parra, J.B.; Cook, C. Dual gas analysis of microporous carbons using 2D-NLDFT heterogeneous surface model and combined adsorption data of $N_2$ and $CO_2$. *Carbon* **2015**, *91*, 330–337. [CrossRef]
92. Iskakov, R.; Sugirbay, A. Technologies for the rational use of animal waste: A Review. *Sustainability* **2023**, *15*, 2278. [CrossRef]
93. Huyen, D.T.; Long, D.H.; Nguyen, H.C.; Khoa, B.D.D. Investigation of characteristics and application of food waste-derived bone char on plant growth. *J. Environ. Chem. Eng.* **2024**, *12*, 113446. [CrossRef]
94. Stępień, A.; Wojtkowiak, K.; Kolankowska, E.; Pietrzak-Fiećko, R. Organochlorine contaminants in maize fertilized with meat and bone meal derived from animal by-products. *Appl. Sci.* **2025**, *15*, 5620. [CrossRef]
95. Cui, H.; Yi, Q.; Yang, X.; Wang, X.; Wu, H.; Zhou, J. Effects of hydroxyapatite on leaching of cadmium and phosphorus and their availability under simulated acid rain. *J. Environ. Chem. Eng.* **2017**, *5*, 3773–3779. [CrossRef]
96. Medellin-Castillo, N.A.; Aguilera-Flores, M.M.; Sendja, B.T. Removal of pollutants from water by adsorbents prepared from animal bone wastes. In *Porous Materials. Engineering Materials*; Moreno-Piraján, J.C., Giraldo-Gutierrez, L., Gómez-Granados, F., Eds.; Springer Nature: Cham, Switzerland, 2021; pp. 273–314.
97. Martini, S.; Afroze, S. Current development of sorbents derived from plant and animal waste as green solution for treating polluted aqueous media. *J. Teknol.* **2021**, *83*, 175–191. [CrossRef]
98. Njewa, J.B.; Dzoujo, H.T.; Nyairo, W.; Shikuku, V.O. Application of bone chars for the removal of chemical contaminants from water resources: A review. *Discov. Chem.* **2025**, *2*, 214. [CrossRef]
99. Liu, K.; Li, F.; Tian, Q.; Nie, C.; Ma, Y.; Zhu, Z.; Fang, L.; Huang, Y.; Liu, S. A highly porous animal bone-derived char with a superiority of promoting nZVI for Cr(VI) sequestration in agricultural soils. *J. Environ. Sci.* **2021**, *104*, 27–39. [CrossRef] [PubMed]
100. Aung, T.R.; Chun, M.; Choi, S.; Ojulo, O.M.; Jung, J.; Choi, D. Sustainable valorization of post-consumer bone waste into calcium-rich bone char via HCl-induced partial phase transformation for enhanced fluoride removal. *J. Environ. Chem. Eng.* **2026**, *14*, 124337. [CrossRef]
101. Dobrzyńska, J.; Jankovská, Z.; Matějová, L. Chicken cartilage-derived carbon for efficient xylene removal. *Int. J. Mol. Sci.* **2023**, *24*, 10868. [CrossRef] [PubMed]
102. Jankovská, Z.; Peikertová, P.; Tokarský, J.; Matějová, L.; Bojko, J.; Saksa, P. Waste animal bone as a low-cost precursor for bone char in xylene adsorption. *J. Environ. Chem. Eng.* **2026**, *14*, 122827. [CrossRef]
103. Gil-Lalaguna, N.; Navarro-Gil, A.; Carstensen, H.H.; Ruiz, J.; Fonts, I.; Ceamanos, J.; Murillo, M.B.; Gea, G. $CO_2$ adsorption on pyrolysis char from protein-containing livestock waste: How do proteins affect? *Sci.Total Environ.* **2022**, *846*, 157395. [CrossRef] [PubMed]
104. Jeong, H.; Lim, J.; Yun, Y.; Ryu, Y.; Kim, J. Novel waste bone recovery system for $CO_2$ and SOx utilization in cement plants using microbubble carbonation reactor. *J. Environ. Chem. Eng.* **2024**, *12*, 111729. [CrossRef]
105. Bangash, F.K.; Alam, S. Removal of Acid Yellow 34 from aqueous solution by activated charcoal of animal bones. *Tenside Surf. Det.* **2006**, *43*, 299–309. [CrossRef]
106. Chagtmi, R.; Trabelsi, A.B.H.; Haddad, K.; Maaoui, A.; Lopez, G.; Santamaria, L.; Cortazar, M.; Khedira, H.; Chaden, C.; Olazar, M. Biochar derived from animal bone waste as an alternative bioadsorbent for an industrial tannery dye removal. *Biomass Convers. Biorefin.* **2022**, *14*, 27461–27475. [CrossRef]
107. Cisneros-Ontiveros, H.G.; Medellín-Castillo, N.A.; Flores-Rojas, A.I.; Cruz-Briano, S.A. Removal of fluoride, cadmium and triclosan from water using bone chars from an invasive species: Optimization, equilibrium and adsorption mechanisms. *Sustain. Chem. Environ.* **2024**, *8*, 100182. [CrossRef]
108. Supri, S.; Lim, T.W.; Rahman, M.N.A.; Tridtitanakiat, P.C.; Rovina, K. Sustainable valorization of chicken bone waste into high-performance activated carbon for efficient removal of organophosphorus pesticides. *Discov. Chem.* **2025**, *2*, 283. [CrossRef]
109. Barua, E.; Das, A.; Pamu, D.; Deoghare, A.B.; Deb, P.; Lala, S.D.; Sushovan Chatterjee, S. Effect of thermal treatment on the physico-chemical properties of bioactive hydroxyapatite derived from caprine bone bio-waste. *Ceram. Int.* **2019**, *45*, 23265–23277. [CrossRef]
110. Balu, S.K.; Andra, S.; Jeevanandam, J.; Vidyavathy, S.M.; Sampath, V. Emerging marine derived nanohydroxyapatite and their composites for implant and biomedical applications. *J. Mech. Behav. Biomed. Mater.* **2021**, *119*, 104523. [CrossRef] [PubMed]
111. Tarafdar, A.; Gaur, V.K.; Rawat, N.; Wankhade, P.R.; Gaur, G.K.; Awasthi, M.K.; Sagar, N.A.; Sirohi, R. Advances in biomaterial production from animal derived waste. *Bioengineered* **2021**, *12*, 8247–8258. [CrossRef] [PubMed]

112. Ielo, I.; Calabrese, G.; De Luca, G.; Conoci, S. Recent advances in hydroxyapatite-based biocomposites for bone tissue regeneration in orthopedics. *Int. J. Mol. Sci.* **2022**, *23*, 9721. [CrossRef] [PubMed]
113. Venkatesan, J.; Anchan, R.V.; Murugan, S.S.; Anil, S.; Kim, S.K. Natural hydroxyapatite-based nanobiocomposites and their biomaterials-to-cell interaction for bone tissue engineering. *Discov. Nano.* **2024**, *19*, 169. [CrossRef] [PubMed]
114. Liu, W.; Cheong, N.; He, Z.; Zhang, T. Application of hydroxyapatite composites in bone tissue engineering: A review. *J. Funct. Biomater.* **2025**, *16*, 127. [CrossRef] [PubMed]
115. Diansari, V.; Idroes, R.; Sunarso, S.; Fitriyani, S. A systematic review on the transformation of bone waste into valuable dental biomaterials. *Malacca Pharm.* **2026**, *4*, 15–33. [CrossRef]
116. Nasrollahzadeh, M.; Soheili Bidgoli, N.S.; Shafiei, N.; Soleimani, F.; Nezafat, Z.; Luque, R. Low-cost and sustainable (nano)catalysts derived from bone waste: Catalytic applications and biofuels production. *Biofuels Bioprod. Bioref.* **2020**, *14*, 1197–1227. [CrossRef]
117. Qiu, Q.; Meng, F.; Li, X.; Li, S.; Tang, Y. Effect of bone char catalyst on the pyrolysis behavior and crystal structure of cotton stalks. *Renew. Energy* **2024**, *236*, 121504. [CrossRef]
118. Liu, J.; Li, Y.; Deng, W.; Wu, Y.; Chen, D.; Zhang, X.; Liu, X.; Han, L. Study on a potential bone char catalyst for high efficiency catalytic pyrolysis of polypropylene plastic. *Fuel* **2025**, *381*, 133625. [CrossRef]
119. Kim, M.; Lee, S.; Lee, T.; Lee, C.G.; Lee, J.; Kwon, E.E. Biodiesel production through thermally induced transesterification from waste cooking oil using calcium phosphate catalyst. *Fuel* **2026**, *415*, 138491. [CrossRef]
120. Petcu, G.; Patrascu, M.; Gheorghe, V.C.; Ionescu, G.; Radoiu, M.; Magdziarz, A.; Mărculescu, C. Synthesis of hydroxyapatite—Containing catalysts from bone waste—Conventional route versus microwaves. *Catal. Today* **2026**, *462*, 115538. [CrossRef]
121. Tang, Y.; Zhu, R.; Meng, F.; Li, X.; Liu, S. Waste-derived bone char catalysts for enhanced tar conversion and syngas production: A comparative study of K-modification and coupled pyrolysis processes. *React. Chem. Eng.* **2026**, *11*, 2747–2756. [CrossRef]
122. Huang, W.; Zhang, H.; Huang, Y.; Wang, W.; Wei, S. Hierarchical porous carbon obtained from animal bone and evaluation in electric double-layer capacitors. *Carbon* **2011**, *49*, 838–843. [CrossRef]
123. Niu, J.; Shao, R.; Liu, M.; Zan, Y.; Dou, M.; Liu, J.; Zhang, Z.; Huang, Y.; Wang, F. Porous carbons derived from collagen-enriched biomass: Tailored design, synthesis, and application in electrochemical energy storage and conversion. *Adv. Funct. Mater.* **2019**, *29*, 1905095. [CrossRef]
124. Tarimo, D.J.; Oyedotun, K.O.; Sylla, N.F.; Mirghni, A.A.; Ndiaye, N.M.; Manyala, N. Waste chicken bone-derived porous carbon materials as high performance electrode for supercapacitor applications. *J. Energy Storage* **2022**, *51*, 104378. [CrossRef]
125. Ngoy, K.R.; Lukong, V.T.; Yoro, K.O.; Makambo, J.B.; Chukwuati, N.C.; Ibegbulam, C.; Eterigho-Ikelegbe, O.; Ukoba, K.; Jen, T.C. Lithium-ion batteries and the future of sustainable energy: A comprehensive review. *Renew. Sustain. Energy Rev.* **2025**, *223*, 115971. [CrossRef]
126. Palomino-Guzmán, E.R.; González-López, A.; Olmedo-Montoya, J.; Sanchez-Echeverri, L.A.; Tovar-Perilla, N.J. A Sustainable approach using beef and pig bone waste as a cement replacement to produce concrete. *Sustainability* **2024**, *16*, 701. [CrossRef]
127. Mozhiarasi, V.; Natarajan, T.S. Slaughterhouse and poultry wastes: Management practices, feedstocks for renewable energy production, and recovery of value added products. *Biomass Conv. Bioref.* **2025**, *15*, 1705–1728. [CrossRef] [PubMed]
128. Ashilenje, D.; Ashour, F.; Barz, M.; Belandria, V.; Borello, A.; Bostyn, S.; Boushaki, T.; Branciari, R.; Bwapwa, J.K.; Cerza, E.; et al. A literature review of slaughterhouse waste valorisation: Techniques, environmental, and economic implications. *Resour. Conserv. Recycl.* **2026**, *224*, 108571. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.