

Review

Thermochemical Conversion of Animal-Derived Waste: A Mini-Review with a Focus on Chicken Bone Waste

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Abstract: Food waste, particularly animal-derived waste, presents a significant challenge globally, prompting the need for sustainable management strategies. In 2022, the amount of food waste per capita reached 131 kg/capita in the EU (European Union), which is why the search for environmentally friendly ways to manage food waste through thermochemical conversion processes has gained momentum in recent years. Animal-derived waste is a good source of organic matter (proteins, lipids, and polysaccharides) and mineral compounds (calcium phosphate, mostly hydroxyapatite). This composition makes animal-derived waste valuable for the extraction of chemical compounds, such as hydroxyapatite (HAp), which constitutes up to 70 wt% of animal bones; keratin; collagen; and hyaluronic acid (HA), to produce pharmaceutical, medical, or industrial by-products. The thermochemical conversion of chicken bones through pyrolysis and gasification creates a new opportunity to valorize this type of waste by reintroducing valuable by-products into the economy and thus achieving sustainable waste management objectives. The results of this study showcase the multiple applications of the pyrolysis of chicken bone waste products (as adsorbents in aqueous mediums, catalysts, fertilizers, and biomedical applications) and the necessity of a better exploration of the gasification process of chicken bone waste. Therefore, this study explores the properties of animal-derived waste and discusses the pyrolysis and gasification of chicken bone waste, the influence of process conditions on product yields, and the catalytic enhancement of these thermochemical processes.

Keywords: animal-derived waste; chicken bone waste; food waste; pyrolysis; gasification



Citation: 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. <https://doi.org/10.3390/pr12020358>

Academic Editor: Antoni Sanchez

Received: 9 January 2024

Revised: 1 February 2024

Accepted: 6 February 2024

Published: 8 February 2024



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1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) estimates that each year, one third of the total food produced worldwide for human consumption is wasted [1]. In 2019, more than 931 million tonnes of food waste was generated only at the distribution and consumption level of the food chain [2]. Out of this total, households were responsible for 61%, food services were responsible for 26%, and the retail sector was responsible for 13% [2], as presented in Figure 1. Meat production increased from 234 million tonnes in 2001 to 357.4 million tonnes in 2021 [3], and by 2030, livestock and fish production are expected to grow by approximately 14% [4]. Consequently, the generation of animal-derived waste will increase considerably in the next few years. These statistics highlight the urgent need to tackle the food waste problem and explore sustainable approaches for its reduction.

From meat-processing industries to individual households, this waste requires an effective disposal management strategy because of the substantial environmental and

health risks it poses [5]. Currently, the primary disposal method for this organic waste is landfilling [6]; thus, waste valorization fits into the prospect of a circular economy.

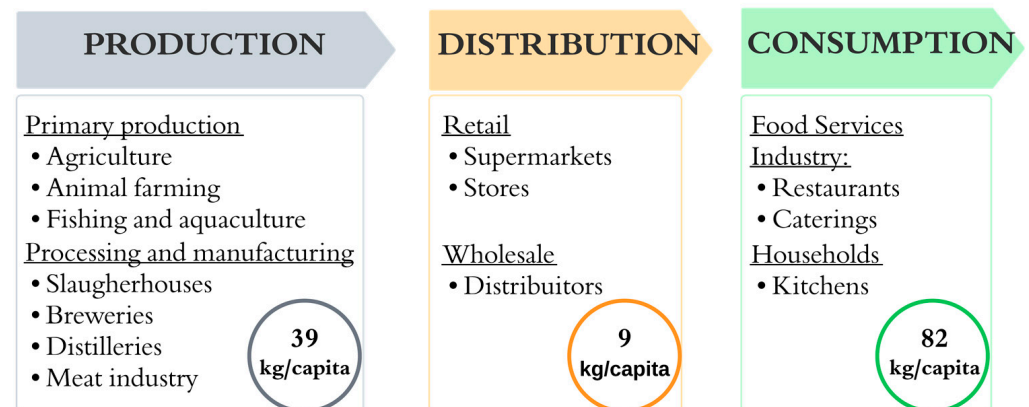


Figure 1. Food waste supply chain with examples of the entities involved at each level and the amount of waste produce in EU-27 in 2021, expressed in kg/capita [7].

According to the FAO [8], food waste contributes 3.3 billion metric tons of CO₂ equivalent emissions globally. To this carbon footprint, meat production contributes 21% of the total CO₂ emissions, and the fish and seafood industry contributes 4%, while the main contributor is the agricultural sector via growing cereals (34%) [8].

In 2021, the EU generated approximately 58 million tonnes of food waste, estimated to amount to a total cost of EUR 132 billion [7,9]. Table 1 presents the most recent statistical data regarding food waste generation in the three phases of this process: the production and manufacturing of food products, distribution, and the consumption of food. It can be observed that over half of this waste is produced in the consumption stage, accounting for 63% of the total. In this stage, the highest waste producers are households, contributing 54%, and the food services industry, contributing 9%. At the distribution stage, the retail sector produces approximately 4 million tonnes of food waste, equivalent to 7% of the total waste. The production stage, which involves the primary production and food-processing sectors, generates approximately 18 million tonnes, contributing to 30% of the overall amount of food waste. Globally, the estimated cost of the total 931 million tonnes of food waste generated in the distribution and consumption stages is approximately EUR 897 billion [10].

Table 1. Statistics regarding the food waste generated at different stages of the supply chain in the EU-27, United States of America (USA), and worldwide.

			Production		Distribution	Consumption		Total	Reference
			Primary Production	Processing	Retail	Food Services	Households		
EU-27, 2021	Food Waste	(million tonnes)	5.1	12.4	4.2	5.4	31.3	58.4	[7,9]
		(kg/capita)	11.0	28.0	9.0	12.0	70.0	130.0	
	Estimated costs	(EUR billion)	-	-	-	-	-	132.0	
USA, 2019	Food Waste	(million tonnes)	17	11	10	13	30	81.0	[11]
		(kg/capita) *	55.0	35.6	32.3	42.0	97.0	261.9	
	Estimated costs	(EUR billion)	14	35	37	164	37	287.0	
Global, 2019	Food Waste	(million tonnes)	-	-	118	244	569	931	[2,10]
		(kg/capita)	-	-	15	32	74	121	
	Estimated costs	(EUR billion)	-	-	-	-	-	896.5	

* Calculated according to the population level during the respective year.

There is a current movement underway around the world to achieve more sustainable waste management [12]. In the EU, the Waste Framework Directive (2008/98/EC) establishes the legislative framework for waste management. One of the key points of this directive is the formulation of the waste hierarchy for food, which prioritizes strategies that prevent, reduce, reuse waste over recycling, and recover policies. In a circular economy, waste that cannot be prevented becomes a resource that should be valorized through the aforementioned strategies and reintroduced into the economy. Figure 2 illustrates the predominant techniques used for the valorization of food waste. These include extraction methods, composting, and thermochemical conversion, such as pyrolysis, gasification, and hydrothermal processes.

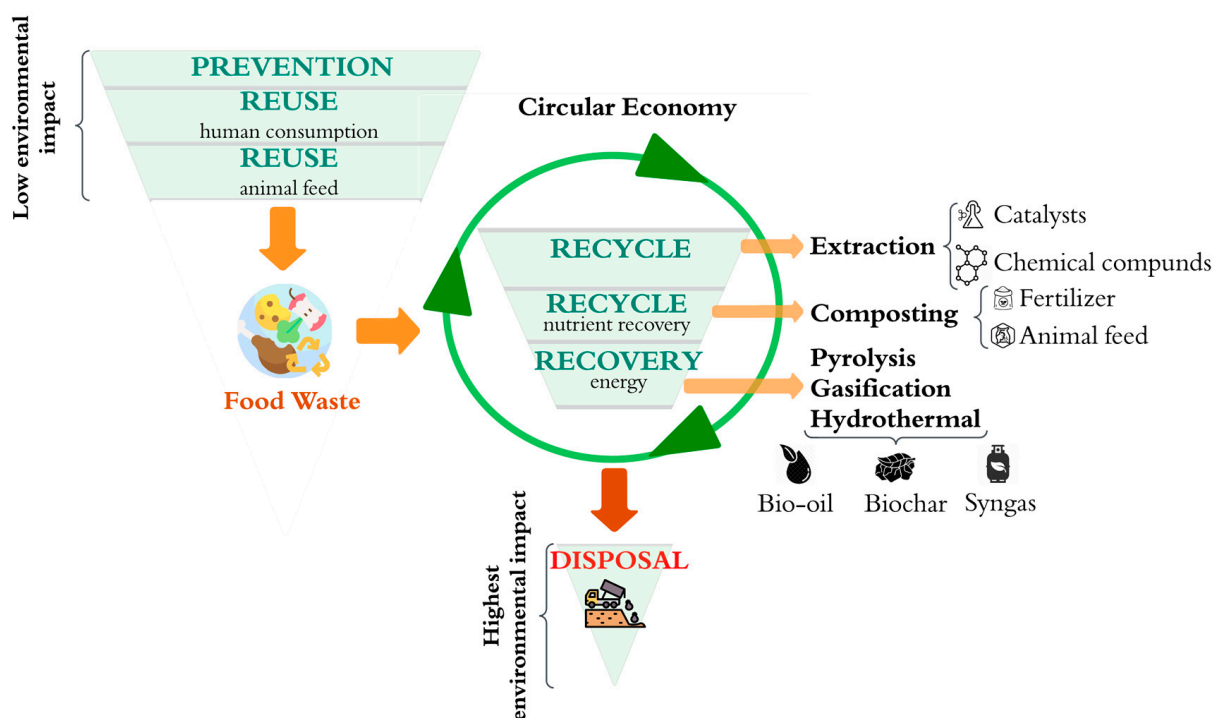


Figure 2. Waste strategies hierarchy adapted from the Waste Framework Directive 2008/98/EC and potential recycling strategies.

Among the various types of food waste, animal-derived waste has emerged as a promising feedstock because of its high mineral content and potential for valorization. For example, the general composition of bone waste consists of 65–70% minerals, mainly represented by calcium and phosphorus, and 30–35% organic matter, of which up to 90% is represented by protein collagen [13,14].

According to the current literature on food waste management, there is a gap in exploring the potential of animal-derived waste [15–17]. The current strategies focus primarily on waste prevention and reduction, frequently ignoring the potential of value-added products that can be obtained [18,19]. This underscores the critical necessity of exploring the valorization pathways specifically for animal-derived waste.

Therefore, this study aims to identify existing and emerging methods for valorizing animal-derived waste, specifically chicken bone waste, and its thermochemical conversion. It highlights its importance of waste management and energy recovery and their contribution to closing the loop in a circular economy.

At first glance, most reviews on animal-derived waste valorizations focused on a wide range of feedstocks such as meat, poultry, and fish [5], considering various waste generation streams (litter, manure, bones, feathers, shells, hatcheries, and abattoirs) [20]. The various type of animal-derived waste streams analyzed in former review papers emphasized their properties (e.g., mineral density [14]); potential conversion via biological and

thermochemical treatment [20,21]; utilization as catalysts for biodiesel production [6,22]; use in tissue engineering; use in cosmetic, medical, and pharmaceutical applications [23,24]; and use as fertilizer [25]. The originality of the current mini-review lies in its identification of the existing and emerging methods for valorizing animal-derived waste, focusing on chicken bone waste and its thermochemical conversion. This study is completed with a comprehensive analysis of food waste management and valorization within the circular economy context. In addition, the identified benefits and gaps are discussed. This study also highlights recommendations for future work on chicken bone waste mainly in regard to pyrolysis and gasification.

2. Methodology

2.1. Food Waste Definitions

Many definitions of food waste have been developed due to disagreements on what constitutes food waste. This issue was highlighted by Schneider [26], who explained the current irregularity of the definitions. For example, the FAO defines food waste as food that has been removed from the retail and consumer level, while food loss occurs at the production and processing level. This mini-review will follow the definition of “food” and “food waste” provided by the FUSION definitional framework and accepted by EU Directive 2008/98/EC and the UNEP in the Food Waste Index Report 2021 [2]. For the purposes of this study, the following definitions were produced:

1. Herein, food is any substance or product (solid or liquid) intended for human consumption, regardless of its processed status (processed, partially processed, or unprocessed).
2. Food waste refers to any “food” or inedible parts of food removed from the supply chain that can be recovered and disposed of.
3. Inedible parts refer to any parts associated with food that humans cannot consume (e.g., bones, pits, peels, seeds, and hooves).

2.2. Literature Review Method

The first step was to identify the state of the art in the valorization of food waste, including peer-reviewed studies and technical reports in the process. Thus, we performed an electronic search using different scientific database platforms: ScienceDirect, Web of Science Database, Scopus, MDPI, and Google Scholar. We adjusted the search process based on the indications made by Moher et al. [27] and Dessie et al. 2020 [28]. Therefore, we removed irrelevant publications with respect to the current research topic, as well as duplicates, and divided the systematic search into three areas: research-type articles, review-type articles, and technical reports and documents. The search terms and connecting words used in the current research were “food/animal/meat/fish/marine/bone/kitchen/food/abattoir/slaughterhouse” and connecting words “waste” or “waste and pyrolysis/gasification” or “pyrolysis/gasification”. Another selection criterion was the year of the study, maintaining a high level of relevance. As a result, we identified 306 relevant publications in the databases searched. After an initial screening, 63 records were excluded from the survey, reducing the number of publications to 243. After thorough examination, 84 more research articles, 30 review papers, and 2 reports were excluded from this analysis (Figure 3) because they were not related to the scope of our study. In conclusion, 128 eligible and relevant studies and reports were included in this mini-review.

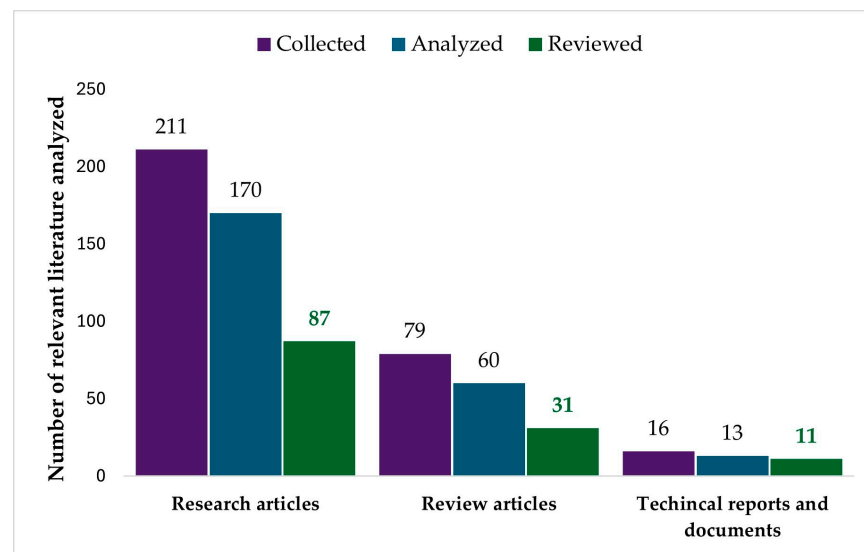


Figure 3. The number of publications identified initially, and the final number of journal articles and technical reports used in this study.

3. Characteristics of Animal-Derived Waste

The composition of food waste is complex, diverse, and heterogeneous in structure [29]. Its composition varies around the world and is influenced by various factors, such as lifestyle, dietary practices, climate, environment, geographical position, culture, and economic status [30]. In a meta-study on food waste characteristics, Fisgativa et al. [31] concluded that 24% of the variability of food samples can be attributed to the geographic origin of the waste in question. Su et al. [30] congregated the main constituents of the heterogeneous mix of food waste from various studies and obtained an average content of 23–65% for vegetables and fruits, 19–44.23% for animal-derived waste, and 16–32.69% for cereals.

Generally, food waste is characterized by high organic matter and high moisture content (74–90%) and a high percentage of volatile solids to total solids ratio (80–97%) [29,32]. Its macronutrient profile consists of 41–62% carbohydrates, 15–25% proteins, and 13–30% lipids [22].

Animal-derived waste is a significant component of the food waste mixture at all supply chain levels. The main source of animal-derived waste in the production and manufacturing stage is slaughterhouses, while that for the consumption phase is individual households. This type of waste is a rich source of organic components such as proteins, collagens, polysaccharides [24], lipids [33], and inorganic compounds primarily in the form of calcium phosphate (57.35%) [24,34]. For example, animal bone contains 53% calcium (Ca), 24% phosphorus (P), 8% boron (B), 6% silicon (Si), 3% sodium (Na), 2% chlorine (Cl), 1.7% sulfur (S), 1.6% potassium (K), and 1.4% magnesium (Mg), while aluminum (Al), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are present at less than 0.4% each [35].

This endows animal waste with good applicability as fertilizer [23,25] and animal feed, in different industrial by-products (such fats and oils) [36], or as catalysts [6,22].

Animal-derived waste from slaughterhouses

Meat production in a slaughterhouse involves various steps [21] whereby a specific type of animal-derived waste is produced. After the monetizable meat has been removed, multiple parts such as bones (which can account for 18% of the living animal's weight) [6] and other animal-derived products (e.g., skin, blood, offal, horns, teeth, feathers, combs, hooves, feet, and shells) are left as waste. The estimated annual global slaughterhouse production of bone waste exceeds 130 billion kg, making it one of the most significant contributors to animal-derived wastes [37]. This number is reflected in the estimated livestock population, consisting of 4.89 billion bovines, caprine and ovine animals, and swine and 27.88 billion

poultry animals [38]. Given these numbers, chicken farming is one of the most prominent animal industries, producing more than 100,000 tonnes of meat yearly [39].

Animal-derived waste from fishing and aquaculture

Marine waste consists of various waste-derived components, such as jellyfish, bones, shellfish, crustacea, shrimps, and skin [40]. The global production of seafood from aquaculture and fisheries reached 214 million tonnes in 2020 [41]. In the EU, up to 10 million tonnes of fish is estimated to be discarded each year [42]. These materials offer the opportunity to extract valuable chemical compounds through different chemical, biological, and thermochemical processes. HAp, calcium carbonate, chitin, collagen, omega-3 fatty acids [43], and polysaccharides [40] are the main chemical compounds that can be obtained. For example, shrimp shells are an essential source of protein (48%), chitin (38%), and other minerals (14%) [44].

Animal-derived waste from kitchens

This study discusses kitchen waste generated in residential households and restaurant kitchens. This waste, which includes leftovers and cooking residue, stems from food preparation and consists of the waste from cooking and leftovers. Kitchen waste provides a complex mixture of animal-derived waste, dairy products, various plant components (cereals, fruits, vegetables, roots, etc.) [33], and seafood obtained from households and restaurants. This composition creates an organic environment rich in proteins, carbohydrates, and lipids [45].

3.1. Composition of Animal-Derived Waste

Table 2 presents the elemental and proximate compositions of different samples used in the literature, including pig bones, bone meal, meat meal, and meat and bone meal (MBM). The table highlights the differences in the organic content of these animal-derived waste types. Although pork is a high source of carbon, its carbon content can vary from 27% up to 63% [46]. The elemental analysis shows the different chemical structures of the feedstocks analyzed. The hydrogen (H₂) concentration also varies but maintains an average value below 10%. The highest oxygen (O₂) concentration is present in cattle bone (~56%), while the lowest is in the pig bones studied by Zhang et al. [46]. These wastes have low sulfur content, varying from 0.3% to 1.4%. Regarding the proximate analysis, the main constituent of this waste is the volatile matter concentration, which is as high as 91% for pork. MBM char has a composition different from the rest of the centralized MBMs, containing the maximum amount of fixed carbon due to the conversion of char. The compositions vary significantly because of differences in the waste types, pretreatment procedures, and geographical regions. These differences have an important influence on the elemental and proximate characteristics of the various feedstock sources examined in the literature.

Table 2. Elemental analyses, proximate analyses, and high heating values (HHVs) of animal-derived waste.

Feedstock	d.b/ a.r/ d.a.f	Elemental Analysis (%)					Proximate Analysis (%)				HHV (MJ/kg)	References
		C	H	O	N	S	VM	W	FC	Ash		
Pork	d.b	63.2	9.8	16.6	4.2	0.6	90.9	4.1	3.5	1.5	-	[46]
Pig bones	d.b	37.9	5.4	9.3	7.0	0.2	57.3	0.9	2.6	39.3	-	
Pork	d.b.	43.6	8.1	33.9	9.8	1.0	83.6	-	12.6	3.8	19.6	[47]
Cattle bones	d.b.	32.9	8.0	55.9	3.2	-	28.9	4.1	-	64.7	-	[48]
Mix bones	d.b.	37.3	5.6	24.4	6.1	0.3	54.1	3.7	2.9	39.3	16.9	[49]
Mixed bones	d.b.	29.2	4.1	20.2	3.3	0.3	52.9	4.8	3.4	39.0	11.9	
Mixed meat and bones	d.b.	37.1	5.5	32.9	5.7	-	70.5	-	10.7	18.8	-	[50]
Meat Meal	a.r d.a.f	57.2	10.3	23.8	8.1	0.4	84.3	8.1	5.5	2.2	25.2	[51]
Meat Meal	m.a.b	42.5	6.6	-	9.1	0.0	71.7	1.0	5.4	21.5	18.1	[52]
Bone Meal	m.a.b	27.0	4.0	-	4.6	0.0	65.3	1.0	3.7	30.0	9.5	

Table 2. Cont.

Feedstock	d.b/ a.r/ d.a.f	Elemental Analysis (%)					Proximate Analysis (%)				HHV (MJ/kg)	References
		C	H	O	N	S	VM	W	FC	Ash		
Bone Meal	a.r d.a.f.	58.8	9.0	22.0	9.7	0.3	49.1	4.2	7.3	39.5	5.8	[51]
MBM	a.r d.a.f.	57.8	9.8	23.1	8.7	0.3	54.1	5.5	15.3	25.1	4.3	
MBM	d.b.	45.9	6.4	38.4	8.9	0.4	71.5	1.4	9.7	17.5	-	[53]
MBM	d.b.	46.3	6.6	36.4	9.7	1.0	73.8	4.5	7.8	18.3	17.1	[54]
MBM	d.b.	41.5	6.5	20.9	4.3	0	67		7	28		[55]
MBM	d.b.	43.1	6.0	15.6	9.2	1.3	63.3	2.5	12.7	23.9	18.6	[56]
MBM	d.a.f.	60.7	5.5	24.9	7.5	1.4	58.4	2.5	30.1	9.0	-	
MBM char	d.a.f.	64.1	6.1	24.0	5.1	0.7	2.3	1.3	77.3	20.1	-	[57]

d.b. = dry basis; a.r. = as received; d.a.f. = dry and ash-free; m.a.b. = moisture ash basis.

3.2. Extractable Valuable Chemical Compounds from Animal-Derived Waste

Recovering materials by using bone waste as a resource can help promote environmental and resource sustainability by facilitating the design of value-added products and materials that are more reusable and recyclable. The physicochemical properties of bone-derived materials such as bone char and HAp have shown that they possess a high surface area, mesoporous microstructures, acid–base properties, good ion-exchange characteristics, and surface functional groups such as hydroxyl (OH^-), carbonate (CO_3^{2-}), and phosphate (PO_4^{2-}) groups. Due to these textural features, materials derived from bone waste have found applications in diverse fields (Figure 4). These include their use as adsorbents for wastewater and flue gas treatment, catalysts and catalyst supports, hierarchical porous carbon for energy storage electrodes, phosphate sources for soil remediation, and HAp materials for biomedical applications. Using valorization techniques, namely, calcination, pyrolysis, gasification, hydrothermal hydrolysis processes, subcritical water processes, and solvent extraction, value-added products and materials such as HAp, calcium oxide, bone char, bone ash, β -tricalcium phosphate, and phosphate can be recovered from these types of wastes [15].

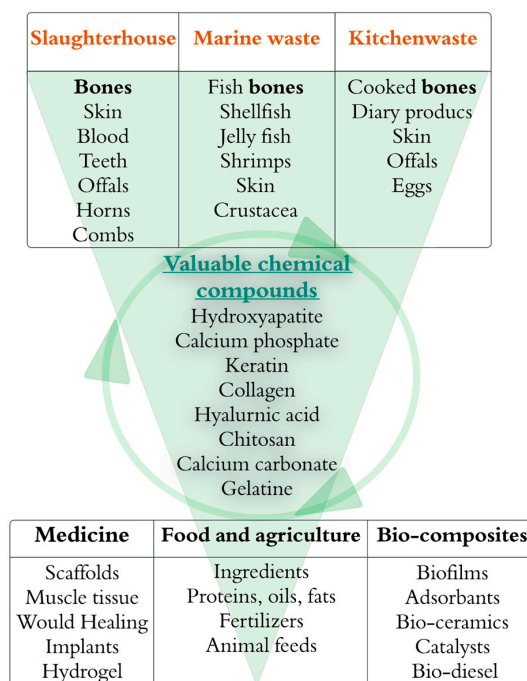


Figure 4. The main chemical compounds that can be extracted from different types of animal-derived waste and their potential applications.

When considering the potential applications of animal bones, the most common are the extraction of HAp, keratin, collagen, and HA to produce pharmaceutical, medical, or industrial products [58–61].

3.2.1. Hydroxyapatite (HAp)

The most common synthesized compound is HAp, a crystalline inorganic mineral composed of calcium and phosphate ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) [62] that is present in 70% of vertebrates' bones in terms of dry weight [63]. Using various techniques that remove moisture and organic matter from waste, HAp can be obtained [24] at different levels of purity. The most common HAp extraction method is calcination at temperatures above 700 °C [64]. This is in line with the findings of Khoo et al. [65], who analyzed the production and extraction of HAp in a calcination process at 700 °C and concluded that these parameters are optimal for the extraction of HAp, allowing for the organic content to be removed and a highly crystalline structure to be formed [65]. Many studies have demonstrated the effectiveness of the synthesis of HAp from marine waste such as scales, bones, shells, and skins [66,67]. These studies applied ultrasound technologies to obtain a highly adsorbent HAp enriched with another chemical compound (3-mercaptopropyl trimethoxysilanes) [66]. Elsewhere, Athinarayanan et al. [67] employed conventional heating to obtain nano-HAp with a very high surface area ($112.36 \text{ m}^2\text{g}^{-1}$) [68]. Other studies have obtained HAp by calcinating eggshells and other CaCO_3 -rich wastes, such as bones [69].

3.2.2. Keratin

Keratin is the most abundant structural protein [70] found in animal hair, nails, feathers, horns, and hooves. Animal-derived waste offers the possibility of converting feathers, hair, ears, horns, nails, and wool, which otherwise would have been disposed, into keratin at a relatively low cost [40]. Keratin makes up 90% of feathers and 95% of wool [71]. Therefore, the demand for keratin recovery from animal-derived waste is increasing yearly, contributing to the sustainability goals. Kakkar et al. [72] studied the extraction of keratin from bovine hoofs, further demonstrating its potential in various tissue-engineering applications [40,72]. In another comparative study by Nisar Abdulla et al. [70], the authors successfully recovered up to 89% of keratin from bovine hooves and up to 53% from chicken feathers using various chemical extraction methods. There has also been an increase in research on converting keratin-rich waste into carbonous materials via pyrolysis [71]. However, the unique challenges presented by these wastes still hinders the efficiency of keratin extraction.

3.2.3. Hyaluronic Acid

The main animal-derived types of waste from which HA can be extracted are rooster combs, containing 7500 $\mu\text{g}/\text{mL}$ [73], and bovine tissues [40]. The literature on using rooster combs and other animal tissues as sources of HA is very well established [74–76]. One of the downsides of the extraction of HA from animal tissue is related to the high operational cost, the amount of time required, and the complexity of the processes involved (ranging from tissue collection to the creation of the purified final product, HA) [74].

4. Thermochemical Conversion of Chicken Bone Waste into Energy or Valuable Products

In alignment with the concept of a circular economy, animal-derived waste has been the focus of research regarding treatment with different thermochemical processes, like pyrolysis, gasification, and hydrothermal processes, that reintroduce valuable products into the economy. The thermochemical conversion of animal-derived waste primarily occurs through two pathways: pyrolysis and gasification. These processes utilize thermal and chemical energy at high temperatures and involve various agents to produce valuable chemicals and by-products.

Figure 5 presents the focus of this mini-review, which is mainly the conversion of chicken bones through pyrolysis and gasification treatments into biochar, bio-oil, and gas

but also valuable products (e.g., fertilizers, adsorbents, catalysts, or energy feedstocks). Moreover, the pyrolysis of chicken bone is an effective treatment for creating charcoal, which is rich in phosphorus and calcium and has a low carbon content. This composition qualifies the produced charcoal as an excellent organic fertilizer: bio-phosphate [77]. Typically, bio-phosphate is created with a mineral phosphate (apatite), classified as a critical raw material from the European Commission's point of view [78]. By generating bio-phosphate from the pyrolysis of animal bones, reliance on the natural form is reduced [19], thus decreasing the phosphorus footprint.

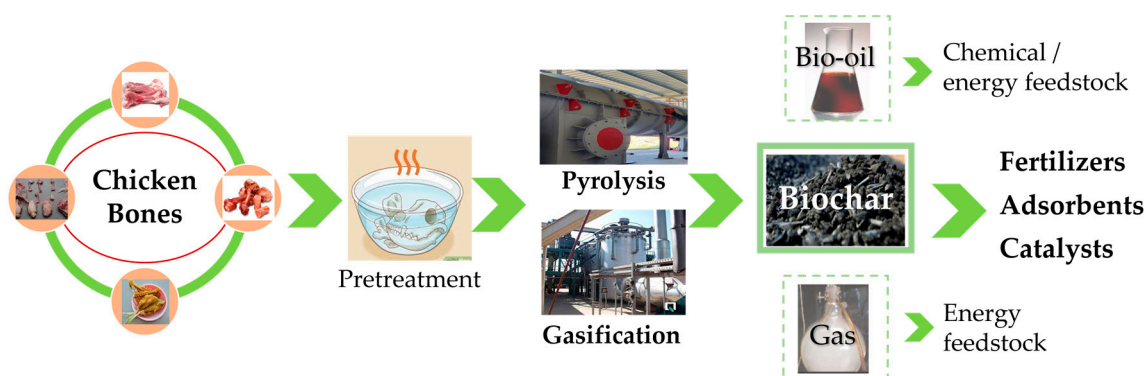


Figure 5. Schematic representation of the thermochemical conversion of chicken bone waste through pyrolysis and gasification processes into biochar (primarily), bio-oil, and gaseous components.

Regarding meat production from livestock, poultry meat accounts for more than 36% [20], translating to 15.15 kg/year per capita [3]. This offers a great opportunity for waste valorizations, especially with respect to the chicken bone waste generated. Because of the increase in the consumption of poultry products, chicken production is estimated to reach 181 million tons by the year 2050 [79], an increase of 120.7% compared to the year 2005. This creates the background for improving waste management in a circular economy framework. Based on its physicochemical composition, chicken bone waste is suitable for exploration for its conversion via unconventional thermochemical processes. Thus, the valorization of chicken bones through pyrolysis and gasification will become more and more relevant.

Further on, we present the current literature on chicken bone waste pyrolysis and gasification, also including other animal-derived waste such as MBM, pig bones, cattle bones, and sheep bones.

4.1. Pyrolysis of Chicken Bone Waste

Given that food wastage and its accumulation have become major problems in recent years, pyrolysis technology has received extensive attention, and corresponding studies have been conducted [80–83]. We found that some studies have also focused on the pyrolysis used to valorize chicken bone. The main objectives of these investigations are concentrated on the biochar structure and bio-oil composition during the pyrolysis of animal-derived waste. The results, operating parameters, yield distribution, and reactor types are presented in Table 3. It can be observed that the most commonly used reactor type is a muffle furnace, operated at temperatures between 300–1000 °C. The studies on the pyrolysis of animal-derived waste, including chicken bone waste, have as an aim the production of solid by-products in the form of biochar. This biochar presents good properties as fertilizer [84–86] and an adsorbent [85,87] and in other applications (such as catalysts and enhanced carbon materials). Because the focus of these studies was on converting chicken bone waste into a solid product, the information regarding the liquid and gaseous yields is not very well described.

Table 3. Pyrolysis process parameters of chicken bone waste and other types of animal-derived waste (such as pig, cattle, sheep bones, and MBM).

Feedstock	Temperature	Reactor Type	Yield Distribution (%)		Products	References
			Solid	Liquid		
Chicken bones	800 °C	Quartz tube furnace	-	-	N-doped porous carbon	[88]
Chicken bones	300 °C	Steel container placed in an electric oven	84.8	-	P Fertilizers	[84]
	500 °C		55.0	-		
	700 °C		55.0	-		
	900 °C		48.0	-		
Sheep bones	300 °C		71.3	-		
	500 °C		58.7	-		
	700 °C		54.0	-		
	900 °C		52.0	-		
Pig bones	300 °C		78.6	-		
	500 °C		75.0	-		
	700 °C		72.0	-		
	900 °C		58.0	-		
Chicken skin, fat, and bones	400 °C	Cylindrical stainless steel pyrolyzer enveloped by an electrical furnace	-	45.33	A new carbon-based catalyst (CBC)	[89]
	500 °C		-	61.60		
	600 °C		-	-		
Chicken bones	800 °C	Bench reactor, operating in a batch system.	64.62	-	Activated carbon and biochar, which were used to remove basic fuchsin from aqueous solutions.	[87]
Chicken bones	500 °C	-	-	-	Mesoporous sulfonated carbon materials	[84]
	700 °C					
	900 °C					
Chicken bones	500 °C	Nabertherm; LE 1/11, Germany	-	-	Magnetite-modified chicken bone biochar (MCB)	[90]
Chicken bones	200 °C	Muffle furnace	-	-	Biofertilizer Nano-bio-adsorbent	[85]
	400 °C					
	600 °C					
	800 °C					
	1000 °C					
Chicken bones	30 °C to 600 °C	Muffle furnace (Nabertherm, model LE2/11/R7, Germany)	-	-	Chicken bones biochar for fluoride elimination	[91]
Chicken bones	600 °C	-	-	-	Asymmetric resorbable membrane based on a hybrid of chitosan and natural HAp for guided bone regeneration	[92]
	700 °C					
	800 °C					
	900 °C					
Chicken bones	1000 °C	Muffle furnace	-	-	Adsorbent material with high efficiency in removing Cu ²⁺ from wastewater.	[93]
	500 °C					

Table 3. Cont.

Feedstock	Temperature	Reactor Type	Yield Distribution (%)		Products	References
			Solid	Liquid		
Chicken bones	300 °C	Muffle furnace (Model KT44-13B, Kastech, Korea)			Adsorbents used for a real application in groundwater	[94]
	400 °C					
Cattle bones	300 °C					
	400 °C					
Cattle bones	350 °C	Tube furnace (HTF-Q70, Hantech, Korea)	-	-		
	400 °C					
	500 °C					
	600 °C					
	700 °C					
MBM	300 °C	Electrically heated tubular batch reactor	-	-	Liquid hydrocarbon-based fuel	[95]
	350 °C					
	400 °C					
	450 °C					
	500 °C					
	550 °C					
MBM	600 °C	Muffle furnace (FO810, Yamato Scientific, Japan)	48.40	-	Organic fertilizer	[86]
	500 °C					
	800 °C					
	1000 °C					

4.1.1. Pyrolysis Process and Conditions

Pyrolysis is the process in which an organic material is thermally decomposed at high temperatures (300–800 °C) in a non-oxidant atmosphere. When pyrolysis is performed on organic masses (i.e., biomass or bones), the carbon's form or structure changes, shifting from organic to inorganic states. Initially, degradation of the large organic molecules present in the material occurs. The heat or high temperature leads to this degradation, creating smaller molecules or fragments from the initial larger species. Additionally, the condensation of these molecules into aromatic benzene rings, leading to the formation of a graphitic structure [96], is another effect.

Products such as biochar (solid fraction), bio-oil (small quantities of condensable liquid), and non-condensable gases are formed during the pyrolysis of meat and bone meal. The resulting liquid species are generally bio-oils, whose composition depends on the material used as the feedstock. The bio-oil derived from pyrolyzing chicken bones contains a complex array of organic compounds (such as carboxylic acids, aldehydes, ketones, and esters) and hydrocarbons (alkanes, alkenes, cyclic compounds, etc.) [89]. Regarding the gas fraction, the most common chemical components are CO₂, CO, H₂, and C_xH_y, although NO_x can also be present depending on the N content of the initial material [97]. Temperature, heating rate, nitrogen flow rate, particle size, reactor type, relative gas–solid flow direction, and residence time are the main factors controlling the pyrolysis process and greatly determine the nature and distribution of the generated products. The pyrolysis conditions can be changed according to the targeted product of the process. Lower heating rates are favored to produce mainly biochar material, while processes with fast heating rates are generally preferred if gases or bio-oils are the objectives of the thermochemical process [98]. The pyrolysis of bones starts to release gases at T > 400–500 °C, although these values may vary depending on the characteristics of the bones and their organic matter content [51].

The literature data reveal that thermochemical processes involving animal-derived waste pyrolysis have been studied in different reactors, including calcination ovens, thermobalance units, and fixed-bed reactors [87,92,99–101]. The most common process used for chicken bone pyrolysis is the calcination process. The pyrolysis of chicken bone waste at different temperatures (500, 700, and 900 °C) led to the production of HAp, which [102] could provide many benefits in bone-engineering applications [24].

The studies addressed in the present mini-review have reported a wide range of values for the pyrolysis process parameters, namely, temperature, heating rate, residence time, atmosphere, and inert gas, applied to chicken bones during thermochemical degradation. Thus, it was found that the process temperature has limits between 400 °C [89] and 1000 °C [92]; the lowest heating rate was 3 °C/min [91], while the highest heating rate reached 20 °C/min [89]. In general, nitrogen (N₂) is introduced to maintain a non-oxidative atmosphere, and its residence time is between 30 min [89] and 20 h [92]. It is also reported that the pretreatment (drying/pre-carbonization) of bone is usually conducted before proceeding with the pyrolysis process and after the washing of the bone [85,90]. Also, in most of the studies, the bones were pre-carbonized. The pretreated bones were generally dried in an oven at 80 °C for 24 h.

4.1.2. Product Yield

The effect of pyrolysis conditions on product yield has been investigated and reported in the literature [103–105]. The study by Jia et al. [106] concerning chicken bone pyrolysis presented the following product distribution: bio-oil—6.67%, gases—41.03%, and biochar—36.09%; the reaction conditions were as follows: catalyst—1.5 g, cellulose—0.5 g, temperature—650 °C, and NH₃ flow rate—80 mL/min. The experimental results presented in [89] revealed a high yield of the liquid fraction generated from chicken bone pyrolysis. This value was achieved at 500 °C for 120 min at a 10 °C/min heating rate. Mărculescu et al. [95] studied the effect of temperature on pyrolysis products for pig bone and meal. The carbon concentration in char decreased from 42% at a temperature of 300 °C to 18% at 700 °C. H₂ followed the same decreasing trend, decreasing from a concentration of 6.5% to 1.2% for the same temperatures, while these two components maintained a constant concentration level in the liquid fraction, independent of temperature [95]. The authors also concluded that a higher process temperature will improve the energy content of the liquid fraction at the expense of the solid fraction [95] and that the maxim devolatilization of the product occurred at 500 °C (77.5%) after 25 min [107].

4.1.3. Catalyst Production from Chicken Bones

Catalyst addition is an excellent method for improving the yield and selectivity of pyrolysis. However, the catalytic pyrolysis of food waste has not been studied. First, it must be emphasized here that the pyrolysis of chicken bones represents a way of producing catalysts. Nie et al. (2022) [84] demonstrated a strategy for preparing mesoporous sulfonated carbon materials from chicken bones to convert carbohydrates to 5-ethoxymethylfurfural (EMF), a great fuel additive with multiple advantages. Also, in their study, Farooq et al. [108] presented the processes through which catalysts were prepared from raw chicken bones. These bones could be successfully used as an efficient heterogeneous catalyst for biodiesel production via the transesterification of low-FFA (Free Fatty Acid) waste cooking oil. A highly stable catalyst in the field of CFP (catalytic fast pyrolysis) was reported for the first time by Jia et al. [106]. This catalyst proved to be economically feasible for the large-scale production of value-added chemicals.

4.2. Gasification of Chicken Bone Waste

The literature on chicken bone waste gasification is scarce, with the studies found focusing mostly on feather [109–112] or manure waste. These feedstocks do not meet the objectives of the current survey; thus, they were not included in this study. It is worth mentioning that in most studies, the source of the animal waste is not defined. Therefore,

in this subchapter, we will focus on the gasification of other animal-derived waste, such as MBM, pig bones, and meat, relevant to this survey.

Gasification can convert organic matter at 350–1000 °C in different gasifying mediums (oxygen, steam, air, CO₂, etc.) into combustible synthetic gas in an oxygen-deficient environment [113]. Syngas mainly consists of H₂, CO, CO₂, and CH₄ and can be used as a fuel or substrate in boiler combustion, fuel cells, and the synthesis of chemical products. The yield is mainly influenced by operating temperature, residence time, pressure, the gasifying agent used, the type of reactor, system configuration, and the absence/presence of a catalyst. For instance, compared with other reactors, using a downdraft gasifier diminishes tar production [114].

Compared with using air as a gasifying agent, steam and hydrothermal gasification are efficient when applied to moist animal-derived waste. Moisture-rich animal-derived waste results in a high H₂ yields [115] and CO₂ selectivity [116].

Generally, in the gasification process, using a catalyst reduces tar formation, increases the formation of gaseous products [117], and improves overall process efficiency. The catalysts used in the steam gasification of organic waste for increasing H₂ production were the natural catalysts dolomite (CaMg(CO₃)₂) and olivine ((Mg, Fe)₂ SiO₄) [118,119]; alkali and alkaline catalysts and alkaline earth metal salts (sodium additives: NaCl, NaOH, Na₂CO₃, and Na₂SiO₃); potassium additives (K₂CO₃, KOH, K₂CO₃, CH₃COOK, and KCl); calcium additives (CaCl₂, CaCl₂, Ca(OH)₂, (Ca(NO₃)₂), and (CaHPO₄)), magnesium salts, namely, MgCl₂ [120,121]; transition metals (Ni, Pt, Ru, Rh etc.); and carbon-based materials (activated carbon and char) [122,123]. Su et al. [124] concluded that the presence of catalysts used in subcritical water gasification of waste increased the H₂ yield. They ranked the catalytic efficiency in the following order: KOH (1.88 mol/kg) > NaOH (1.7 mol/kg) > Ni/g-Al₂O₃ (1.39 mol/kg) > Ni/ZrO₂ (1.23 mol/kg) > FeCl₃ (1.22 mol/kg) [124].

Table 4 presents a synthesis of various feedstock types and their processing conditions, along with reactor types and agent usages, highlighting the yield distribution of the resulting products. The most researched feedstock is MBM, treated at temperatures between 650 and 850 °C, while the gasification of chicken bone waste is not as prevalent in the literature. These investigations have as an objective the maximization of gas yield and H₂ production by exploring different feedstock mixtures or different reactor configurations.

Table 4. Gasification process applied to meat and bone meal, pig bones, and coal–MBM mixtures.

Feedstock	Temperature	Reactor Type	Agent	Yield Distribution (%)			Results	References
				Solid	Liquid	Gas		
MBM	800 °C	Thermogravimetric analyzer	60% H ₂ O 40% N ₂	-	-	-	MBM char has high gasification selectivity	[57]
MBM	650–850 °C	Fixed-bed reactor	N ₂ and O ₂	25–19	50–40	25–30	Two-stage system increases H ₂ and gas yield	[54]
		Fixed-bed reactor couple with tar-cracking reactor two-stage fixed-bed reaction		18–19	25–19	42–55		
MBM	650–850 °C	Two-stage steam gasification	steam/MBM (wt/ wt) 0.4–0.8	14.1–21.7	52.2–57.9	8.7–18.1	With the increase in steam/MBM ratio, the amounts of H ₂ and gas increase	[125]
Pork bones and meat residues	650–800 °C	Tubular batch	Air	-	-	-	-	[126]
Coal and MBM (99:1 weight)	800 °C/ Silica bed	Fluidized bed	Air	-	-	-	-	[127]
Coal and MBM	800–900 °C	Fluidized bed	Air	70	-	-	The addition of 1%wt of MBM to coal has no effect on CO and H ₂ production	[128]

In conclusion, overall, the gas composition changes with the increase in temperature. Soni et al. [54] concluded that applying an increase in temperature from 650 °C to 850 °C

to MBM air gasification increased the H₂ and CO proportions from 5.5 to 7.3 vol.% and 10 to 51.6 vol.%, respectively, while CO₂ decreased from 55 to 20.5 vol.%. The same research group [125] conducted MBM steam gasification between 650 °C and 850 °C, revealing a similar tendency: the H₂ and CO yields increased from 42 to 52.2 and 10.2 to 26.8 vol.%, while the CO₂ yield decreased from 25.9 to 12.8 vol.%. The latter can be explained by the Boudard reaction ($\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$), which is partially responsible for the decrease in CO₂ corresponding to the increase in CO.

5. Conclusions

Recovering resources from animal-derived waste has proven to be a valuable approach to promoting environmental and resource sustainability. Through thermochemical processes such as calcination, pyrolysis, gasification, and hydrothermal treatments, animal bones can be converted into various value-added materials. These materials exhibit favorable physicochemical properties, such as a high surface area, mesoporous microstructures, and functional groups, making them suitable for applications as adsorbents and catalysts and for soil remediation and biomedical uses. We found that the most common compounds extracted from animal bones are HAp and other proteins (keratin and collagen), which are suitable for biomedical applications because of their biocompatibility and adsorption properties.

This mini-review of the literature demonstrates that the thermal treatment of animal-derived—particularly chicken—waste through pyrolysis and gasification has been studied in different reactors, including thermobalance units, fluidized bed reactors, fixed-bed reactors, tubular batches, and those - fitted for two-stage steam gasification. Evaluating the influence of other variables on important process parameters is essential to validate both processes as potential alternatives to manage animal-derived waste. In general, biochar and bio-oil are promising and sustainable materials, and their applications align with the principles of the circular economy. The current study reveals that the gasification of animal-derived waste, specifically chicken bones, has been investigated at a lower rate compared to other thermochemical processes such as hydrothermal treatment, pyrolysis, and combustion. The lack of studies on the thermochemical conversion of animal bone waste through pyrolysis and gasification can be explained by the availability of other valuable green chemical compounds that can be extracted from this waste source, such as protein, HAp, calcium carbonate, chitin, collagen, and polysaccharides. These compounds can find reasonable use in other sectors.

Future studies should further explore the pyrolysis and gasification of chicken bone waste to scale up the efficient application of a chosen treatment. These treatments can be applied as stand-alone treatments or integrated into a chain, boosting the transition towards a circular economy as targeted by the Waste Framework Directive and other sustainability goals.

Author Contributions: Conceptualization, M.G.M., V.-C.G., G.I., A.V., R.P., C.M. and A.M.; Methodology, M.G.M., V.-C.G., G.I., C.M. and A.M.; Data curation M.G.M., V.-C.G. and G.I.; Writing—original draft preparation, M.G.M., V.-C.G. and G.I. Writing—review and editing, M.G.M., V.-C.G., G.I., A.V., R.P., C.M. and A.M.; Visualization, M.G.M., A.V., R.P. and C.M.; Supervision, C.M. and A.M.; Project administration, C.M. and A.M.; Funding acquisition, C.M. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Romania’s National Recovery and Resilience Plan, Pillar III, “Smart, sustainable and inclusive growth, including economic cohesion, jobs, productivity, competitiveness, research, development, and innovation, and a well-functioning internal market with strong small and medium-sized enterprises (SMEs)”, Component C9, providing support for the private sector, research, development, and innovation, I8 “Development of a program to attract highly specialized human resources from abroad in research, development and innovation activities”. The project name is “Green chemistry and thermochemical processing, a convergent approach towards biobased chemicals and hydrogen synthesis—ConverGreen”, ID: CF 86/15.11.2022, cod 86.

Data Availability Statement: Data are contained within the article.

Acknowledgments: This work was funded by Romania’s National Recovery and Resilience Plan, Pillar III, “Smart, sustainable and inclusive growth, including economic cohesion, jobs, productivity, competitiveness, research, development, and innovation, and a well-functioning internal market with strong small and medium-sized enterprises (SMEs)”, Component C9, providing support for the private sector, research, development, and innovation, I8 “Development of a program to attract highly specialized human resources from abroad in research, development and innovation activities”. The project name is “Green chemistry and thermochemical processing, a convergent approach towards biobased chemicals and hydrogen synthesis—ConverGreen”, ID: CF 86/15.11.2022, cod 86.

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

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