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Review

Technical Feasibility of Producing and Utilizing Livestock Manure-Derived Biochar for Soil Carbon Sequestration in South Korea: A Review

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Abstract

In Korea, policy efforts are being made to achieve carbon neutrality in the agricultural sector by promoting the production and utilization of livestock manure-derived biochar. Recently, new quality standards for livestock manure biochar have been introduced. However, some of the produced biochar does not meet the criteria required for soil carbon sequestration. In this study, a literature review evaluated the technical feasibility of livestock manure biochar to support its industrial utilization and activation. This study performed a literature review to comparatively assess the physicochemical properties of woody, herbaceous, and livestock manure biomass, and to evaluate the quality standards of biochar derived from these feedstocks through pyrolysis and hydrothermal carbonization (HTC). According to an analysis of previous studies, the carbon content of woody biochar produced by pyrolysis ranged from 46.3% to 93.5% (n = 29), with average H/C and O/C molar ratios of 0.49 and 0.09, respectively. Herbaceous biochar exhibited a carbon content ranging from 26.1% to 83.8% (n = 34), with mean H/C and O/C molar ratios of 0.48 and 0.28, respectively. Thus, most woody and herbaceous biochars met the biochar quality criteria (H/C < 0.7, O/C < 0.4). In contrast, manure-derived biochar demonstrated a comparatively lower carbon content, ranging from 29.0% to 44.6% (n = 21). The average H/C molar ratio for manure-derived biochar was higher at 0.60, and 73% of samples exceeded the established quality threshold for H/C (<0.7). Hydrothermal carbonization (HTC), which is suitable for high-moisture feedstocks such as manure, yields hydrochar with an average H/C ratio of 1.01, indicating lower aromaticity and reduced carbon stability, thereby limiting its potential for long-term carbon sequestration. These findings underscore the necessity for region-specific standards and further investigation into the properties of manure-derived biochar to promote sustainable soil carbon sequestration practices.

Keywords: biochar; pyrolysis; hydrothermal carbonization; carbon sequestration; livestock manure

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1. Introduction

Biochar, a carbon-rich material, is produced through the thermochemical conversion of biomass under oxygen-deficient conditions, resulting in a substance with a high content of non-biodegradable carbon. The stability of the aromatic carbon structures formed

during thermochemical conversion renders biochar resistant to microbial degradation when applied to soils. This characteristic enables biochar to sequester atmospheric carbon dioxide (CO_2) in soils over extended periods, thereby contributing to greenhouse gas mitigation [1–4]. Notably, biochar applied to soil has been reported to sequester approximately 2.5 tons of CO_2-eq. greenhouse gases per ton [5]. According to the Intergovernmental Panel on Climate Change (IPCC), the global application of biochar has the potential to sequester up to 6.6 Gt CO_2-eq. per year. In addition, biochar can improve the soil quality by enhancing its cation exchange capacity, water retention, and microbial activity, thus contributing to increasing the soil fertility of agricultural lands [3,6].

The effects of biochar on the sequestration of carbon in soil and improvement of the soil quality vary depending on the feedstock materials used for biochar production and the conditions under which these materials are processed via thermochemical conversion [7]. Biochar is produced from a wide range of biomass feedstocks that can be divided into the following general categories: lignin-rich woody biomass, cellulose-rich herbaceous biomass, and livestock manure with mixed components [8–10]. The composition of the biomass in terms of cellulose, hemicellulose, lignin, as well as moisture, salt, and inorganic matter, significantly influences the carbonization stability and environmental safety of the resulting biochar [11–13]. In particular, the organic carbon content of the biomass is a key factor determining the carbonization stability of biochar and, depending on the pyrolysis temperature, the carbon content of biochar has been reported to range from 38% to 93% [14,15]. For example, biochar derived from cellulose-rich biomass such as rice straw typically contains 40–50% carbon, whereas biochar produced from woody biomass contains 70–90% carbon [7]. Biochar production technologies can be classified as pyrolysis, torrefaction, or hydrothermal carbonization (HTC) depending on the reaction conditions such as the temperature, moisture, pressure, and residence time [8,16,17]. The selection of a particular thermochemical conversion technology for biochar production is largely determined by the physicochemical properties of the feedstock and the economic considerations of the production process. Typically, woody and herbaceous biomass types with low moisture content are processed using pyrolysis or torrefaction, whereas high-moisture biomass such as livestock manure is converted via hydrothermal carbonization. The thermochemical conversion technology that is ultimately adopted dictates the specific reaction conditions for each type of biomass, and the differences in the process parameters affect the carbonization stability of biochar as well as its content of volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and heavy metals, all of which influence its environmental safety [18]. In general, high-temperature pyrolysis increases the aromaticity and fixed carbon content of biochar, thereby enhancing its carbonization stability; however, it can also reduce the cation exchange capacity, which is important for soil fertility [19–21]. HTC is advantageous for the thermochemical conversion of high-moisture biomass from an economic perspective; however, the relatively low carbonization stability of biochar produced via this process has raised concerns regarding its effectiveness for long-term soil carbon sequestration [22]. Therefore, to ensure the effectiveness of biochar for carbon sequestration and soil improvement while minimizing potential environmental risks from hazardous substances, international certification standards such as the International Biochar Initiative (IBI) and the European Biochar Certificate have been established. In Korea, official biochar quality standards were also enacted in 2024 through the "Fertilizer Process Standards" notification.

Korean quality standards for biochar have partially adopted indicators such as the H/C and O/C molar ratios to assess the carbonization stability, where H, O, and C denote the molar proportions of hydrogen, oxygen, and carbon in the biomass, respectively. However, the quantitative criteria were largely established by referencing international certification standards, and insufficient consideration has been given to the applicability

of these standards to the characteristics of domestic biomass feedstocks and conversion technologies. In addition, thresholds for hazardous substances such as heavy metals, PAHs, and dioxins are either less stringent than those of international standards (EBC, IBI) or only selectively applied to a limited number of parameters (e.g., NaCl). For instance, the Korean limits for Cd (5 mg/kg), Cr (200 mg/kg), and Zn (900 mg/kg) are considerably higher than the corresponding EBC standard limits (Cd 1.5, Cr 90, and Zn 400 mg/kg) [7,23]. This has given rise to concerns about the potential risks of salt accumulation and heavy metal buildup in soils following the application of biochar [24,25]. Notably, biochar derived from livestock manure, which is newly introduced in Korea, generally has a lower carbon content and higher levels of moisture and ash compared to lignin- or cellulose-based biochars, due to the inherently low carbon and high ash contents of the raw material. This makes it difficult to meet the established quality standards for biochar [3,7,26]. Nevertheless, research on livestock manure biochar and the industrial production thereof in Korea remain extremely limited, and the unavailability of research data to support improvements in quality standards for the activation of the livestock manure biochar industry is problematic. The objective of this review is to evaluate the technical feasibility of applying livestock manure-derived biochar, recently introduced in South Korea, for soil carbon sequestration. To this end, published data on biochar production from diverse biomass feedstocks under varying pyrolysis conditions were synthesized to examine how feedstock characteristics and thermochemical conversion pathways affect biochar physicochemical properties and alignment with established quality standards. In addition, this review explores technical and institutional strategies to improve the applicability of manure-based biochar in meeting the criteria required for long-term carbon sequestration.

2. Materials and Methods

In this study, the effects of thermochemical conversion processes (pyrolysis, torrefaction, and HTC) and biomass types (woody biomass, herbaceous biomass, and livestock manure) on the physicochemical properties and carbon stability of produced biochar were investigated through a comprehensive review of existing literature. And the quality characteristics of biochar produced by each thermochemical conversion technology and biomass type were examined in comparison with biochar quality standards established by the Korean Rural Development Administration (Korean Biochar Fertilizer Quality Standard; K-BFQS), the International Biochar Initiative (IBI) , and the European Biochar Certificate.

Thermochemical conversion processes were categorized into pyrolysis, torrefaction, and HTC, and the thermochemical reaction characteristics of each process were reviewed and summarized. Biomass feedstocks used for biochar production were classified as lignin-rich woody biomass, cellulose-rich herbaceous biomass, and livestock manure with mixed compositions. The elemental composition of raw materials was investigated and summarized based on reviewed literature. Due to limited studies on livestock manure biochar produced via torrefaction, the review excluded torrefaction and focused on the physicochemical properties and carbon stability of biochar produced by pyrolysis and HTC thermochemical conversion technologies.

As summarized in Table 1, this review analyzed 12 woody biomass species, 23 herbaceous biomass species, and 10 livestock manure samples from published studies. The physicochemical properties of biomass were assessed through elemental composition (C, H, O, N, S), volatile matter, ash, and fixed carbon content. The produced biochar was evaluated for elemental composition (C, H, O, N, S), ash content, electrical conductivity, cation exchange capacity (CEC), and specific surface area (SSA). Carbon stability, representing biochar's soil carbon sequestration potential, was analyzed by examining the H/C and O/C molar ratios. To compare the physicochemical and carbon stability characteris-

tics of biomass and corresponding biochars by feedstock, descriptive statistics including mean, median, standard deviation, maximum, and minimum values were calculated and presented for each parameter.

Table 1. Types of biomass investigated in this study.

Classification	Biomass
Woody (12 types)	Bamboo [27], Cocoa [28], Fallen leaves [17,29,30], Grape [31], Oak [15], Olive [32], Pine [14,33,34], Poplar [27,35], Pear tree [36], Spruce [31,35], Sawdust [37–40], Tea tree [41]
Herbaceous (23 types)	Apple [17,42], Banana [28], Bamboo shoot shell [17], Canola [39], Chinese fan palm [43], Chinese cabbage [44], Coffee [29,45], Corn [17,46–48], Cotton [17,49], Grape [17,50], Grass [37], Miscanthus [38,51–54], Oil-rape [49], Orange [55], Peanut [56], Rice [17,28,33,49,57–59], Straw [37], Sesame [60], Soybean [56], Sunflower [61], Water hyacinth [15], Watermelon [62], Wheat [35,39,49]
Livestock manure (10 types)	Beef cattle [63], Broiler [63], Dairy cattle [63], Layer chicken [63], Manure pellet [39], Pig [64], Poultry [33,61], Poultry litter [63], Swine [33,63], Yak dung [65]

3. Results and Discussion

3.1. Biochar Production Technologies

The thermochemical decomposition technologies applied to biomass result in biochars with distinct physicochemical properties due to differences in the reaction conditions and mechanisms of these technologies. For the agricultural application of biochar, comprehensive consideration of product carbonization stability, by-product utilization, and post-treatment requirements is essential. Thermochemical decomposition technologies for biochar production can be broadly classified into pyrolysis, hydrothermal carbonization (HTC), and torrefaction, based on the reaction environment and temperature (Table 2). During pyrolysis, which occurs at temperatures above approximately 400 °C, the primary components of biomass—cellulose, hemicellulose, and lignin—undergo sequential dehydration, decarboxylation, and dehydrogenation reactions. This leads to the formation of polycondensed aromatic rings, resulting in low H/C and O/C molar ratios and high resistance to biodegradation [66]. Lehmann and Joseph (2015) described the pyrolysis process under oxygen-deficient conditions as a sequence in which the main organic components of biomass are thermally decomposed, volatile compounds are released, and the remaining carbon is condensed into aromatic ring structures, thereby transforming into biologically stable forms of carbon [3]. The supply of oxygen during the carbonization of biomass is strictly limited, which is a critical condition to prevent combustion and ensure that carbon remains in a stable solid form. Pyrolysis most clearly demonstrates this carbonization mechanism; for example, under oxygen-deficient conditions at 450–600 °C, the pyrolysis of woody biomass such as pine or oak sawdust lowers the volatile matter content to approximately 20–25% and increases the fixed carbon content to 65–80% [15]. These changes are attributed to the removal of volatile organic compounds and the progressive condensation of aromatic rings. At temperatures above 600 °C, highly polycondensed aromatic rings are formed, resulting in stable biochar with carbon contents characterized by H/C ratios below 0.4 and O/C ratios below 0.2 [3,67]. Generally, as the carbonization temperature increases, the specific surface area of biochar becomes larger and its pH becomes more alkaline, thereby enhancing its potential as a soil amendment and adsorbent [7,66]. Although pyrolysis requires relatively high temperatures (400–700 °C) and thus greater energy input, it is considered economically advantageous due to the recovery of high-value by-products such as bio-oil and syngas, in addition to the production of biochar with a high fixed carbon content [3]. Torrefaction is a mild thermochemical pretreatment conducted at 200–300 °C, and is primarily aimed at lowering the moisture content and increasing the

energy density of the feedstock. The resulting solids typically have a lower fixed carbon content and carbon stability, making this technology more suitable for the production of solid fuels [68]. Furthermore, because torrefaction is conducted in a lower temperature range (200–300 °C) than pyrolysis, torrefaction is less energy intensive. However, due to the low carbonization stability and limited applicability of the resulting products, the use of torrefaction is restricted in fixed carbon-based applications [68]. Hydrothermal carbonization (HTC) is performed in a sealed reactor, in which biomass is reacted in the liquid phase at temperatures ranging from 180 to 250 °C. The carbonization process is driven under the autogenous steam pressure generated during the reaction. The products of HTC generally have high H/C molar ratios (>0.8), low degrees of aromatic ring condensation, and acidic pH values [22]. Notably, from a reaction mechanism perspective, pyrolysis involves high temperature dry thermal decomposition (including decomposition, dehydration, and devolatilization) that primarily drives the breakdown of organics and formation of pyrolytic products. In contrast, HTC operates under relatively low-temperature, high-pressure aqueous conditions, where hydrolysis, dehydration, and condensation reactions mediated by water constitute the main pathways. This fundamental difference in reaction mechanisms results in distinct physicochemical properties between pyrolysis biochar and HTC biochar [3,22,69]. Reflecting these characteristics, the product of the HTC process is often referred to as hydrochar, and solid–liquid separation is required to recover the hydrochar after the reaction. Notably, water-soluble salts are removed with the liquid phase during this process, resulting in hydrochar of which the electrical conductivity (EC) is lower compared to that of biochar produced by conventional pyrolysis (Table 3) [22,70].

Table 2. Summary of biomass thermochemical conversion processes and their characteristics [12,67,68].

Process	Description	Advantages	Disadvantages
Pyrolysis	The thermal decomposition of biomass at 400~700 °C, in the absence of oxygen, producing solid biochar, liquid bio-oil, and gaseous syngas.	- High yields of bio-oil and syngas, typically in the range of 75–80% - Effective waste reduction and potential for resource recycling - Capability to produce a diverse range of valuable product	- High energy consumption and elevated operating costs - Requirement for precise control of process parameters - Instability of bio-oil and challenges associated with its handling and storage
Hydrothermal carbonization	A thermochemical process that converts wet biomass into biochar (called hydrochar) in hot compressed water (180~250 °C) with the autogenic saturation vapor pressure of water.	- Capable of processing biomass with high moisture content - Preservation of polymeric structures enables the formation of solid fuels - Maintains high product yields after short processing durations	- High-pressure equipment requirements and operational complexity - Necessity for optimization of process parameters

Table 2. *Cont.*

Process	Description	Advantages	Disadvantages
Torrefaction	A mild pyrolysis process within the temperature range of 200~300 °C in the absence of oxygen, which serves as the pretreatment of biomass to increase the heating value and hydrophobicity.	- Increased energy density ranging from 16.8 to 22.0 MJ/kg - Reduced hygroscopicity of biomass after treatment, facilitating improved storage and handling - Low energy consumption during the torrefaction process.	- Possible reduction in yield due to mass loss after processing - Extended reaction times and optimization of temperature are required

Table 3. Comparison of thermochemical char production methods according to their properties and use.

Parameter	Pyrolysis	HTC [1]	Torrefaction
Biomass type	Dry	Wet	Dry
Byproduct	Biochar, Bio-oil, Syngas	Hydrochar, Bio-Oil, Syngas	Mildly carbonized biomass, a little gas
Temperature (°C)	400–800	160–300	200–300
Residence time	Minutes to hours	Minutes to hours	Minutes to hours
Solid yield (wt, %)	25–50	50–80	70
Carbon content	High, aromatic 76–85	60–75	55–70
Surface area (BET, m^2/g)	High (~200–400)	Low (1–20)	5–50
Functional groups (FTIR)	C=C, COOH,	COOH, OH, C=O, C-O, limited aromatics	Limited(aromatic C-H), C=C
pH	Alkaline	Acidic to neutral	Neutral to slightly acidic
Ash content (compared to the raw biomass feedstock)	High	Low (the presence of compressed liquid)	High (depending on feedstock)
Heavy metal retention	Possible accumulation	Potentially high	Feedstock dependent
Leaching risk (toxicity)	Low if well-produced	Higher due to PAHs	Low
Water holding capacity	High	Moderate	Low
GHG mitigation potential	High (C sequestration, N_2O reduction)	High	Low
applications	Soil amendment, carbon sink adsorbent, soil additive, filler	Soil amendment, solid biofuel, functional material precursor, pollution control & water treatment	Renewable solid fuel, Co-firing with coal, bioenergy supply chain & logistics, feedstock for biochar

[1] Hydrothermal carbonization. Ref.: [16,20,22,42].

3.2. Thermochemical Decomposition Characteristics of Biomass

Biomass primarily consists of cellulose, hemicellulose, and lignin, and the relative abundance of these components influences the thermochemical decomposition behavior of different feedstocks—namely woody biomass, herbaceous biomass, and livestock manure [22,71,72]. Woody biomass, which is characterized by slow growth, possesses dense outer tissues, whereas herbaceous biomass, typically perennial, has more loosely bound fibers and a lower lignin content [16,73]. Moreover, the higher cellulose and lignin contents of woody biomass promote the formation of fixed carbon and aromatic structures during pyrolysis, and also result in a higher amount of volatile matter compared to herbaceous biomass [16,73]. Livestock manure reportedly contains higher concentrations of organic and inorganic nutrients, resulting in distinct thermochemical conversion behavior compared to woody and herbaceous biomass [74,75]. Williams et al. (2017) reported that woody biomass with cellulose, hemicellulose, and lignin contents of 51.2%, 21.0%, and 26.1%, respectively, produced 84.0% volatile matter and 1.3% ash, whereas herbaceous biomass that contained 32.1%, 18.6%, and 16.3% of these respective components yielded 79.1% volatile matter and 5.5% ash [66,76,77].

Numerous studies have reported that the cellulose and hemicellulose contents significantly influence the carbon and ash content of pyrolyzed biomass [18,78,79], and that the yield of pyrolysis products is associated with the inorganic components present in the feedstock. It has also been observed that higher ash content tends to correspond with lower volatile matter (VM) content [66]. According to Sun et al. (2014), the carbon content of hickory, bagasse, and bamboo biomass was 45–46%, and their pH values were 5.8, 6.0, and 6.6, respectively, indicating slightly acidic properties [80]. Yang et al. (2007), using infrared (IR) spectroscopy analysis, identified the characteristic absorption bands corresponding to cellulose at 3400–3200 cm^{-1} (–OH) and 1215 cm^{-1} (C–O), hemicellulose at 1510–1560 cm^{-1} (C–O), and lignin within the range of 1830–730 cm^{-1} (methoxyl –O–CH_3, C–O–C, C=C) [81]. Their study also found that the weight loss rates (%) for hemicellulose (0.95), cellulose (2.84), and lignin (<0.14) corresponded to decomposition ranges of 220–315 °C, 315–400 °C, and from room temperature to 900 °C, respectively, with cellulose beginning to decompose at the lowest temperature. Although correlations between the feedstock type and the yield of pyrolysis by-products have been investigated, laboratory-scale thermogravimetric analysis (TGA) did not reveal significant effects. However, the ash content of black pine (a softwood) was reported to be 0.32%, whereas willow and poplar (both hardwoods) had higher ash contents of 2.04% and 1.49%, respectively [72]. The volatile matter content of hardwoods (willow, 81.44%; poplar, 82.53%) and softwood (82.38%) was similar, with all three types containing approximately 6% hydrogen. Notably, the carbon content of softwood (black pine, ~52%) was reported to be higher than that of hardwoods (poplar and willow, ~49%) [72].

Table 4 summarizes the physicochemical properties of biomass derived from woody, herbaceous, and livestock manure, whereas Table 5 presents the reaction characteristics of biomass components during pyrolysis, such as the carbon content, pH, cation exchange capacity, specific surface area, and volatile matter content. Biomass typically consists of volatile matter (>50%), ash (<50%), and fixed carbon (<30%) [82]. Woody biomass is characterized by low moisture and ash contents, a higher heating value (HHV), high bulk density, and low porosity, whereas cellulose-based herbaceous biomass and livestock manure exhibit higher moisture and ash contents, lower heating values, lower density, and higher porosity [83,84]. The results presented in Table 4 show that the volatile matter content was 84.9% for woody biomass (n = 3), 79.5% for herbaceous biomass (n = 11), and 57.7% for livestock manure (n = 8). Moghtaderi (2004) reported that, during the pyrolysis of coal-woody biomass mixtures, pine sawdust generated a volatile yield of approximately

98%, which may be attributed to the influence of pyrolysis conditions on polymerization reactions, leading to the rapid conversion of volatile content into woody biomass [85]. The ash content of livestock manure was the highest at 27.3%, while woody and herbaceous biomass had lower values of 3.2% and 6.6%, respectively. High ash content can cause issues such as slagging and fouling during combustion, and necessitates additional process management when used as a fuel [63,86]. The fixed carbon content of woody biomass (18.9%) was the highest, followed by that of livestock manure (14.0%) and herbaceous biomass (11.8%). Fixed carbon, which represents the non-volatile carbon fraction excluding volatile matter and ash, contributes to the thermal and biological stability of biochar, as well as its long-term carbon sequestration and soil amendment potential [87]. Owing to these characteristics, the fixed carbon content is regarded as a critical evaluation criterion in biochar quality certification systems (e.g., EBC, IBI), and serves as an important determinant in the establishment of quality standards [7,26]. The ash content of biomass was found to range from 0.7–10.6% for woody biomass (n = 7), 1.6–16.1% for herbaceous biomass (n = 21), and 8.2–47.1% for livestock manure (n = 9). Enders et al. (2012) also reported that the ash content can vary significantly depending on the feedstock after analyzing hazelnut shells, oak, and pine (woody), corn (herbaceous), and bull, dairy cow, and poultry manure (livestock) [87].

Table 4. Physicochemical properties of biomass derived from woody, herbaceous, and livestock manure sources.

Biomass	Statistics Parameter	Elemental Composition					Proximate Analysis		
		C	H	O	N	S	VM [1]	Ash	FC [2]
		(%, *w*/*w*)					(%, *w*/*w*)		
Woody	n [3]	8	5	3	7	0	3	7	4
	Mean	48.8	6.2	42.2	0.9	-	84.9	3.2	18.9
	S.d. [4]	2.9	0.8	6.2	0.6	-	11.1	3.5	23.3
	Min. [5]	44.1	5.4	37.4	0.1	-	72.5	0.7	0.1
	Max. [6]	53.7	7.4	49.2	1.8	-	94.1	10.6	49.5
	Median	48.7	6.1	40	0.8	-	88.0	1.8	13.1
Herbaceous	n	24	18	16	21	10	11	21	11
	Mean	43.8	5.8	42.5	3.2	1.1	79.5	6.6	11.8
	S.d.	4.4	1.1	4.1	8.2	3.1	7.1	4.2	7.2
	Min.	34.2	3.4	36.1	0.1	0	62.0	1.6	0.0
	Max.	49.7	8.1	51.1	38.7	9.9	86.7	16.1	17.7
	Median	44.2	6.1	41.7	1.2	0.1	81.7	6.4	14.9
Livestock manure	n	9	9	9	9	2	8	9	8
	Mean	35.4	4.7	26.9	3.4	10.7	57.7	27.3	14.0
	S.d.	5.8	1.1	10.9	2.5	14.8	12.0	11.3	5.0
	Min.	21	1.8	0.5	1.5	0.2	37.8	8.2	8.7
	Max.	40.9	5.7	41	9.6	21.2	68.3	47.1	23.5
	Median	36.8	4.9	28.6	2.7	10.7	62.8	26.7	12.4

[1] Volatile matter, [2] Fixed carbon, [3] Number of samples, [4] Standard deviation, [5] The lowest among the samples, [6] The highest among the samples.

Table 5. Summary of conversion characteristics of biomass through thermochemical reactions.

Parameter	Conversion Characteristics of Biomass	Reference
Carbon	Woody biomass yields → high C [1], Poultry litter biochar → may reduce C at high T [2]	[66,87,88]
Ash	High ash content (e.g., in manure) → increases risk of PAHs [3] and trace metal retention	
pH	High-lignin biomass → alkaline pH (up to 10.5)	[3,89,90]
CEC [4]	High ash and oxygenated groups → enhance CEC	
Surface functional groups	Functional groups (O-containing) degrade at high T → lower adsorption capacity	
VM [5]	VM decreases with increasing T → greater stability and sorption capacity	[62,88,91]
Specific surface area	Surface area increases with T up to 600 °C → then may decrease due to structural collapse	
Pore volume	High T releases volatiles → leading to pore formation	

[1] Carbon, [2] Temperature, [3] Polycyclic Aromatic Hydrocarbons, [4] Cation Exchange Capacity, [5] Volatile Matter.

3.3. Standards for Biochar Quality

Although biochar has significant potential as a carbon-based resource for greenhouse gas mitigation and soil improvement, proper quality control regarding the feedstock type, thermochemical reaction conditions, and contaminant content is required for its effective agricultural application [3]. Internationally, the International Biochar Initiative (IBI) established its quality standards in 2012 and revised them to version 2.1 in 2015. The IBI operates a unified, product-oriented standard system [51]; however, the IBI Biochar Standard was retired in April 2024 and will not be updated further [26]. The IBI is a nonprofit organization aimed at promoting biochar production and utilization to address climate change, improve soil health, and advance sustainable agriculture and energy systems; it operates the IBI biochar certification program. The IBI certification system provided quality assurance throughout the entire production chain—from feedstock to final product—and was recognized as an international standard for biochar quality, together with the European Biochar Certificate. The European Biochar Certificate, since its introduction in 2012, developed into a multilayered and integrated management system by 2024 (version 10.4), encompassing feedstock, production processes, product quality, and facility requirements. A distinctive feature of the EBC is its categorization of biochar into seven classes based on intended use including EBC-Feed (for feed), EBC-Agro (for agriculture), and EBC-Urban (for urban landscaping) with quality criteria tailored to the specific applications. These quality certification systems not only verify the carbon sequestration potential of biochar, but also provide objective data on its carbon reduction and storage effects, thereby supporting its integration into the carbon credit market [7]. Korea established its biochar quality standards in 2024 by reviewing the international certification criteria of the IBI and EBC, and enacting the "Fertilizer Process Standards." This notification categorizes feedstocks used for biochar production and sets specific quality standards for biochar derived from both agroforestry residues and livestock manure [23]. In the case of the former, the approved feedstocks include crop residues (such as rice straw and husks), fruit tree prunings, and wood materials (including sawdust, wood chips, and wood pellets). For the latter type of biochar, only livestock manure and the same feedstocks permitted for biochar from agroforestry residues are allowed. Thus, a distinctive feature of Korea's biochar quality standards is the explicit inclusion of biochar derived from livestock manure, which provides an institutional basis for recognizing the soil carbon sequestration potential of manure-based biochar (Table 6).

Table 6. Comparative summary of biochar certification standards: K-BFQS, IBI, and EBC.

Category	K-BFQS [1]	IBI [2]	EBC [3]
Definition	Biochar from agricultural and livestock residues, pyrolyzed at ≥350 °C	Biochar for soil use with no legal fertilizer status	Certified biochar for conventional or organic agriculture
Carbon content (dry basis)	Agri-forestry residues: ≥40% Livestock manure: ≥30%	Class1: ≥60% Class2: ≥30% and <60% Class3: ≥10% and <30%	Declaration
H/C molar ratio		<0.7	
O/C molar ratio	<0.4	-	<0.4 Declaration Recommended
Moisture content	≤30%	Declaration	30% Recommended
HCl-insoluble residue	≤25%	-	-
Labeling Requirements	Must display pH, and recommended usage on the package	Test results encouraged	Mandatory QR code, batch ID, and certification info
pH		Declaration	
Volatile matter	-	Optional, declaration, % of total mass, dry basis	Required in basic analysis, thermogravimetric analysis (TGA)
Nutrients	-	Optional (N, P, K, Ca, Mg, S)	Declaration (N, P, K, Mg, Ca, Fe)
Electrical conductivity	-	Declaration (EC, dS/m)	Declaration Solid biochar EC differs from leachate EC, which reflects salt content
Ash content	-	Declaration, % of total mass, dry basis	Declaration
Bulk density	-	-	Declaration
Particle size distribution	-	Declaration	Recommended
Liming (if pH is above 7)	-	Declaration, %, $CaCO_3$	-
Water holding capacity (WHC)	-	Optional	Declaration
Cation exchange capacity (CEC)	-	Optional	-
Batch traceability/ QR Code	-	-	Mandatory for certified products
Total surface area m^2/g	-	Optional, Declaration,	-
Feedstock traceability	-	Voluntary	Mandatory with full documentation
Fire/explosion Safety	-	-	30%, recommended

[1] Korean Biochar Fertilizer Quality Standards; Rural Development Administration (RDA), [2] International Biochar Initiative; version 2.1 2015, [3] European Biochar Certificate; EBC-Agro version 10.4, 2024.

In general, the criteria for biochar quality standards are designed to assess both the carbonization stability and environmental safety of biochar. The carbonization stability, a key indicator of the long-term carbon storage potential and resistance to biological degradation, is typically reflected by the H/C and O/C molar ratios, which represent the carbon density and structural stability [87,89,92,93]. The environmental safety is evaluated to ensure the safe application of biochar to soils and to minimize environmental risks, using indicators such as the electrical conductivity (EC), NaCl content, heavy metals, and organic pollutants [7,26] (Table 7). Notably, the EBC standard incorporates leachate-based EC measurements and applies WHO-TEQ (World Health Organization-Toxicity Equivalents) to account for salt accumulation and ecotoxicity in agricultural soils. Additionally, the EBC specifies quantitative limits for heavy metals (Cd 1.5 mg/kg, Pb 120 mg/kg) and organic pollutants (PAHs 6 mg/kg, PCDD/Fs 20 ng/kg WHO-TEQ), thus emphasizing the scientific management of ecotoxicity [7]. In contrast, the IBI provides information and recommendations for most hazardous assessment items to enable users to determine the suitability of biochar for agricultural use. Thus, the EBC and IBI quality certifications differ in terms of their quality criteria, assessment methods, certification operations, and levels of accountability, particularly with respect to the evaluation of carbon stability, hazardous substances, and salinity.

Table 7. Comparison of contaminants and safety standards for biochar quality: K-BFQS [23], IBI [26], EBC [7], USEPA-Biosolids [94], and K-Compost [23].

Contaminants		**K-BFQS** [1]	**IBI** [2]	**EBC** [3]	**USEPA-Biosolids** [4]	**K-Compost** [5]
Salt Content (NaCl or EC [6])		≤2.0% NaCl	EC Declaration	Salt content: EC (μS/cm) × 52.8: indicate contamination of the feedstock.	-	-
Heavy Metals (mg/kg^{-1}, dry matter, MCL [7])	Cd	5	1.4–39	1.5	39	5
	Pb	130	121–300	120	300	130
	Hg	2	1–17	1	17	2
	Cr	200	93–1200	90	3000	200
	Cu	360	143–6000	100	1500	360
	Zn	900	416–7400	400	2800	900
	Ni	45	47–420	50	420	45
	As	45	13–100	13	41	45
Organic Pollutants (dry basis, MCL)	PAHs [8] (mg/kg)	6	6–300	6 ± 2.4	-	-
	PCDD/Fs [9] (ng/kg, WHO-TEQ [10])	20	17	20	-	-
	PCBs [11] (mg/kg)	0.2	0.2–1	0.2	4.6	-

[1] Korean Biochar Fertilizer Quality Standards, [2] International Biochar Initiative; version 2.1, 2015 [3] European Biochar Certificate; version 10.4 2024, [4] United States Environmental Protection Agency (as reference concentration of a pollutant in biosolids), [5] Korean compost [6] Electrical conductivity [7] Maximum concentration limit [8] Polycyclic Aromatic Hydrocarbons, [9] Polychlorinated dibenzo-*p*-dioxins and dibenzofurans, [10] World Health Organization-Toxic equivalents [11] PCBs: Polychlorinated Biphenyls.

3.4. Physicochemical Charateristics of Biochar

This study compared and analyzed the physicochemical properties of biochar produced from woody, herbaceous, and livestock manure biomass feedstocks using pyrolysis

and hydrothermal carbonization (HTC) as thermochemical conversion processes. Biochar produced by pyrolyzing woody biomass had the highest carbon content (66.8%, *n* = 29) and the lowest ash content (8.5%, *n* = 23), indicating superior carbon stability. Herbaceous biomass exhibited similar carbon content (65.6%, *n* = 34), but higher ash content (15.2%, *n* = 29). Livestock manure biomass had the lowest carbon content (37.7%, *n* = 21) and the highest ash content (51.3%, *n* = 21), which reflects the inherent compositional differences of the feedstock and suggests a greater risk of heavy metal and inorganic accumulation, as well as the increased formation of hazardous substances such as PAHs in high-ash feedstocks. In addition, environmental and soil amendment indicators such as the pH and cation exchange capacity (CEC) also varied depending on the feedstock characteristics and thermal treatment conditions (Table 8). HTC-produced biochar has an overall carbon content lower than that obtained with pyrolysis (woody biomass (*n* = 20): 60.9%, herbaceous biomass (*n* = 63): 57.2%, livestock manure (*n* = 25): 41.0%), whereas the ash content remained high in herbaceous biomass (*n* = 35, 18.2%) and livestock manure (*n* = 25, 38.3%) (Table 9). This can be attributed to the fact that HTC is conducted in a wet environment at relatively low temperatures, which results in less leaching of inorganic components and a lower degree of thermal carbon concentration compared to pyrolysis.

Table 8. Physicochemical properties of biochars derived from woody, herbaceous, and livestock manure biomass through pyrolysis.

Biomass	Statistic Parameters	Elemental Composition						pH	EC [1]	CEC [2]	SSA [3]
		C	H	O	N	S	Ash				
		(%)						(-)	(dS/m)	(cmol/kg)	(m^2 /g)
Woody	n [4]	29	13	5	13	1	23	28	18	9	4
	Mean	66.8	3.1	17.3	0.7	0.1	8.5	8.6	5.0	55.0	53.0
	S.d. [5]	14.3	1.5	8.3	0.4	-	4.9	1.5	8.7	11.0	102.7
	Min. [6]	46.3	1.3	7.0	0.1	0.1	1.9	5.3	0.2	36.5	1.0
	Max. [7]	93.5	6.5	28.6	1.2	0.1	16.6	10.9	28.3	69.3	207.0
	Median	68.9	2.8	19.3	0.8	0.1	8.2	8.9	1.3	57.4	1.9
Herbaceous	n	34	42	39	42	16	29	13	5	6	26
	Mean	65.6	4.6	21.4	1.5	0.2	15.2	9.2	22.6	16.9	146.0
	S.d.	13.5	10.2	11.2	0.9	0.2	11.7	1.2	44.7	10.3	215.5
	Min.	26.1	0.1	3.3	0.4	0.0	0.3	7.3	0.2	10.5	1.0
	Max.	83.8	68.3	54.7	3.6	0.8	37.5	11.3	102.5	37.7	859.0
	Median	69.4	2.9	18.7	1.2	0.1	12.7	9.1	4.4	13.8	18.0
Livestock manure	n	21	21	21	21	17	21	2	2	2	0
	Mean	37.7	1.5	6.3	2.4	1.6	51.3	8.3	12.1	12.5	-
	S.d.	4.5	0.6	3.6	0.7	3.0	6.8	0.6	5.8	1.3	-
	Min.	29.0	0.6	0.3	1.4	0.4	40.9	7.8	8.0	11.6	-
	Max.	44.6	3.0	11.4	4.6	12.6	68.2	8.7	16.2	13.4	-
	Median	37.5	1.4	6.5	2.3	0.6	50.0	8.3	12.1	12.5	-

[1] Electrical conductivity, [2] Cation exchange capacity, [3] Specific surface area, [4] Number of samples, [5] Standard deviation, [6] The lowest among the samples, [7] The highest among the samples.

Table 9. Physicochemical properties of biochars derived from woody, herbaceous, and livestock manure biomass through HTC [1].

Biomass	Statistical Parameters	Elemental Composition						pH	EC [2]	CEC [3]	SSA [4]
		C	H	O	N	S	Ash				
		(%)						(-)	(dS/m)	(cmol/kg)	(m^2 /g)
Woody	n [5]	20	11	10	11	1	9	12	3	3	7
	Mean	60.9	4.3	28.1	1.0	0.3	17.3	4.5	0.1	21.3	7.1
	S.d. [6]	7.8	0.9	4.9	0.9	-	21.0	1.0	0.1	5.3	10.8
	Min. [7]	48.8	2.9	20.1	0.1	0.3	0.2	3.3	0.1	15.1	0.7
	Max. [8]	75.4	5.6	37.2	2.3	0.3	54.0	7.0	0.2	24.4	30.6
	Median	60.4	4.4	28.1	1.1	0.3	7.6	4.3	0.1	24.4	2.7
Herbaceous	n	63	31	31	30	7	35	30	16	1	20
	Mean	57.2	5.4	26.3	1.7	0.1	18.2	5.7	0.7	9.7	5.6
	S.d.	13.1	1.4	7.7	0.9	0.1	27.5	1.0	0.8	-	3.2
	Min.	0.8	0.8	4.5	0.1	0.1	0.3	4.2	0.1	9.7	1.8
	Max.	73.5	9.3	39.9	3.3	0.3	145.0	7.5	2.5	9.7	17.0
	Median	58.2	5.4	26.8	1.9	0.1	7.9	5.5	0.5	9.7	4.7
Livestock manure	n	25	25	25	25	18	25	8	6	3	5
	Mean	41.0	4.1	15.4	2.5	0.5	38.3	6.9	8.1	14.0	20.9
	S.d.	12.5	1.2	5.9	1.1	0.1	18.6	0.9	8.9	0.6	17.3
	Min.	17.0	1.4	3.9	1.3	0.3	4.3	5.5	0.2	13.4	1.7
	Max.	66.6	6.3	26.9	5.7	0.7	77.3	8.4	19.9	14.7	47.6
	Median	40.1	4.3	15.0	2.1	0.6	35.2	6.8	5.8	14.0	17.4

[1] Hydrothermal carbonization [2] Electrical conductivity, [3] Cation exchange capacity, [4] Specific surface area, [5] Number of samples, [6] Standard deviation, [7] The lowest among the samples, [8] The highest among the samples.

As shown in Figure 1, the H/C and O/C molar ratios serve as indicators of the degree of carbonization in biochar and are essential factors for determining carbon stability. These parameters are also critical for assessing the value of biochar as a carbon sink [7]. Woody biochar, particularly that produced by pyrolysis, exhibits low H/C and O/C ratios (i.e., higher aromaticity and degree of carbonization), which translates to greater long-term stability. In contrast, biochar derived from livestock manure and HTC biochar tend to have higher H/C and O/C ratios, indicating relatively lower stability. Keiluweit et al. (2010) demonstrated that, for an H/C ratio below 0.7, aromatic condensation structures predominantly exist, resulting in higher resistance to biodegradation and enhanced long-term carbon stability [66]. Notably, the relatively high H/C ratios (0.8–1.0) obtained for HTC-treated biochar exceed the aromaticity threshold suggested by Keiluweit et al. (2010), indicating structural incompleteness and lower carbon stability [66]. These findings highlight the necessity of carefully selecting feedstocks and production processes for biochar to ensure quality certification and to maximize its effectiveness as a soil amendment and for carbon sequestration.

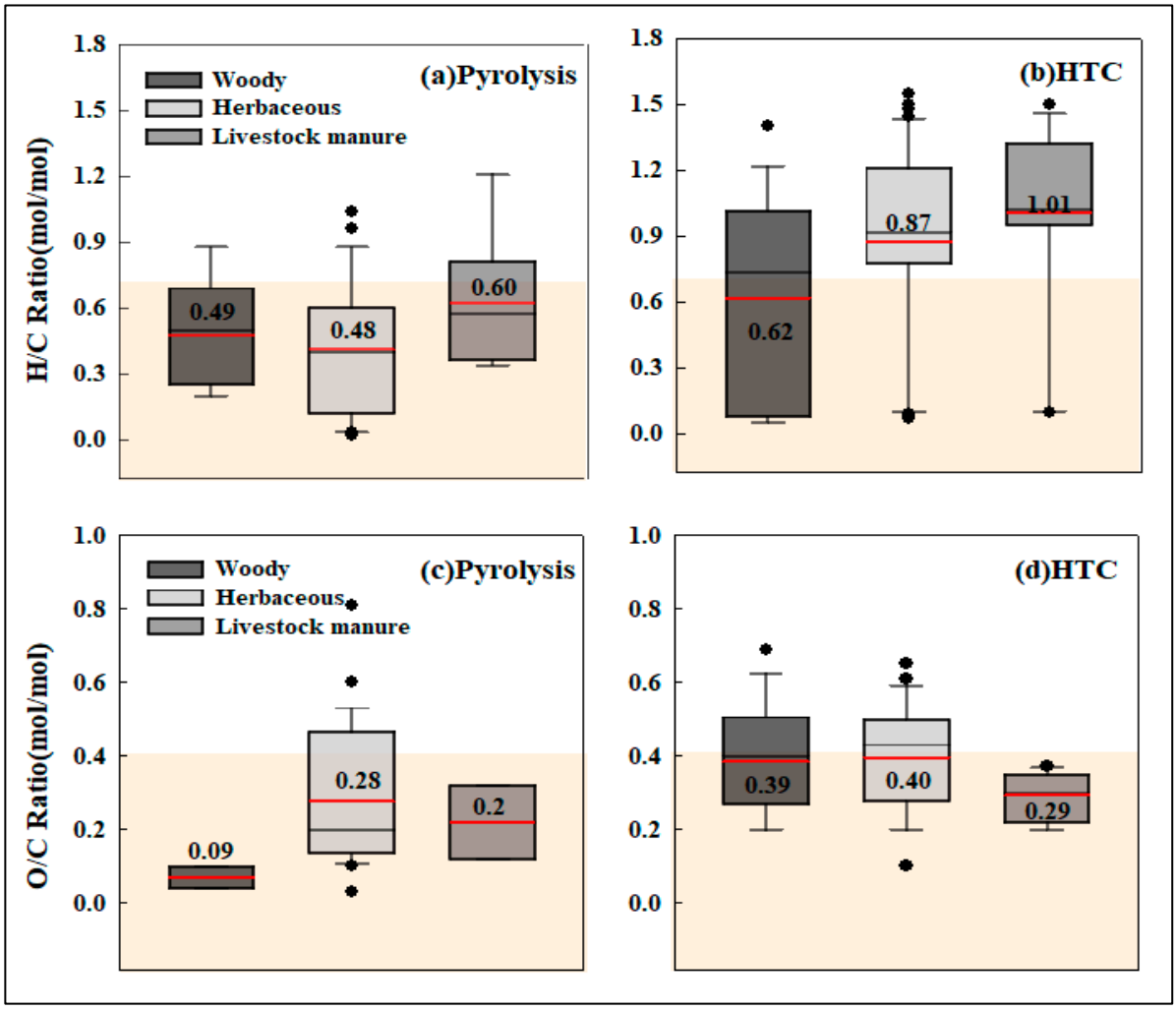


Figure 1. H/C and O/C ratio of biochars derived from feedstock types and the type of thermal conversion technology. In the boxplot, the red line represents the mean value, and the black line indicates the median value.

4. Conclusions

This study addresses the critical need to enhance the quality standards and production technologies for livestock manure-derived biochar to facilitate its broader application in agricultural and carbon sequestration practices. While international standards such as IBI and EBC are primarily based on woody biomass, their applicability to manure biochar remains limited due to distinctive feedstock characteristics, notably high ash content and lower organic carbon levels. Current national standards in South Korea, adopting these international criteria, often result in manure biochar failing to meet desired quality thresholds for soil carbon sequestration, posing challenges to its widespread utilization. Technologically, pyrolysis at high temperatures yields biochar with favorable physicochemical properties—high carbon content, low H/C and O/C molar ratios, and enhanced aromaticity—consistent with international standards and suitable for carbon sequestration. Conversely, hydrothermal carbonization (HTC), though effective for high-moisture feedstocks such as livestock manure, produces hydrochar with higher H/C ratios and lower aromaticity, limiting its stability and sequestration potential. To overcome these limitations, tailored technological solutions are needed. Optimizing pyrolysis conditions particularly reaction temperature and duration can improve manure biochar's carbon stability. Pre- and post-treatment processes should be employed to remove hazardous components, ensuring

environmental safety. Moreover, developing flexible quality standards specifically for non-woody biomass and accumulating domestic demonstration data are essential for establishing scientifically supported thresholds. Long-term field experiments and ecological assessments are critical to elucidate the soil amendment and carbon sequestration efficacy of manure-derived biochar. In conclusion, advancements in feedstock characterization, process optimization, and regulatory frameworks are vital to realizing manure biochar's potential as a sustainable tool for achieving carbon neutrality in agriculture. Addressing current technological and institutional challenges will facilitate the development of a circular, climate-smart biomass management system and promote the extensive utilization of manure-derived biochar in sustainable agriculture.

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