

Evaluation of Indicators and Effects of Crop-Livestock Recycling Farming According to Certification Types of Hanwoo (Korean Cattle) Beef Farms

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Abstract: This study evaluated crop-livestock recycling and carbon reduction across four Hanwoo (Korean cattle) farm types: organic, PGS-certified, grazing-based ecological livestock farms, and conventional, based on surveys of 58 farms. Grazing-based ecological farm had the lowest baseline carbon emissions (4,994.3 kg CO₂-eq), largest farmland (35.7 ha), and highest forage self-sufficiency (31.6%). Organic farms had the highest emissions (6,764.8 kg CO₂-eq) but achieved the greatest reduction (15.3%) via organic feed and compost recycling. PGS-certified farms also demonstrated significant environmental benefits (6,284.8 kg CO₂-eq; 13.6% reduction). No statistically significant differences were observed in nutrient use efficiency among certification types. Expanding farmland, improving compost recycling, and increasing on-farm feed effectively reduced nutrient surplus and carbon footprint. These results suggest that organic and PGS-certified systems can serve as economically and environmentally sustainable models if they integrate on-farm forage production from the grazing-based ecological livestock farms model.

Keywords: Carbon footprint, Certification types, Circulation indicators, Hanwoo farms, Livestock density index

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Introduction

Hanwoo (Korean cattle) farming in Korea has undergone notable structural changes in recent years. Since 2014, the number of small-scale farms with fewer than 20 head has declined, whereas large-scale operations with more than 100 head have increased, alongside a continuous growth in the total cattle population, based on national livestock statistics published by Statistics Korea in 2024. Large-scale conventional livestock systems produce livestock manure that exceeds the capacity of agricultural land, deteriorating regional nutrient balances [1]. Furthermore, methane gas is emitted during feed feeding and animal respiration [2]. Furthermore, carbon emissions increase sharply as livestock density increases. In fact, analysis results show that for every 1,000 head increase in the number of Korean and beef cattle, approximately 5,339 tons (CO₂-eq) of additional greenhouse gas emissions are emitted, confirming that density management in the livestock sector is a key challenge for achieving carbon neutrality [3]. Carbon emissions from livestock pro-

duction vary greatly depending on feeding practices and breeding environment conditions.

Crop–livestock recycling agriculture is a circular farming system in which livestock by-products are used for crop production and crop by-products are returned to livestock feeding. In a narrow sense, it refers to nutrient circulation within the farm, while in a broader sense, it includes circulation at the regional level [4]. The utilization of externally sourced livestock manure resources, including compost and liquid manure, by crop farms without livestock as substitutes for chemical fertilizers plays a critical role in mitigating regional nutrient imbalances and improving soil fertility through increased soil organic matter content, as demonstrated in the research report *Analysis of the Integrated Crop–Livestock Farming System and Improvement Ways* published by the Korea Rural Economic Institute. Furthermore, on-farm forage production using livestock manure reduces external nutrient inflows derived from imported feeds (nitrogen and phosphorus), thereby fundamentally decreasing ecological environmental loads such as nutrient accumulation in soils, eutrophication of water bodies, and greenhouse gas emissions [5]. In regions with relatively large farmland areas and low nutrient surpluses, sustainable agricultural systems can be established through the application of compost and liquid manure derived from livestock manure, as reported in the study *A Study on Sustainable Livestock Manure Management* published by the Korea Environment Institute.

Crop–livestock recycling agriculture reduces carbon emissions by decreasing feed transportation through on-farm feed production and by recycling compost and agricultural by-products [3]. In addition, organic farming practices reduce the use of chemical fertilizers and synthetic pesticides, resulting in lower nitrous oxide emissions [3]. Such circular systems represent sustainable agricultural models with multifaceted environmental benefits, including reduced feed and fertilizer costs, mitigation of surplus nutrients, alleviation of environmental pollution, and reduction of carbon emissions.

Sustainable Hanwoo production based on crop–livestock recycling can also contribute to price stability by reducing production costs. However, imported beef accounts for approximately 58.1% of the domestic market and continues to increase due to its relatively lower price compared with domestic beef [6]. At the same time, consumer preference for high-quality beef has been increasing [7]. In response to these trends, Hanwoo farms with various certification types, including organic livestock certification, participatory guarantee systems (PGS), and grazing ecological livestock farms, have increased, as reported in the research report *Analysis of the Integrated Crop–Livestock Farming System and Improvement Ways* published by the Korea Rural Economic Institute.

Nevertheless, studies that comprehensively and quantitatively compare the effects of different certification systems on crop–livestock recycling indicators and carbon reduction are still very limited, both domestically and internationally. Therefore, this study aimed to compare and analyze crop–livestock recycling indicators, nutrient balances, and carbon footprints among Hanwoo farms with different certification types, including conventional farms. Based on these analyses, this study seeks to propose economically and environmentally sustainable Hanwoo production models suitable for Korea.

Results and Discussion

Crop–Livestock Circulation Indicators by Hanwoo Certification Type

The results of the analysis of crop–livestock circulation indicators by certification type of Hanwoo farms are presented in Table 1. The number of cattle was highest in conventional farms, with an average of 112.9 head, which was significantly higher than that of other certification types ($p < 0.05$). Cropland area per farm and cropland area per head were highest in grazing-based ecological livestock farms, at 34.5 ha and 4,237 m², respectively, showing significantly higher values compared to other farm types ($p < 0.05$). Forage crop area per farm and forage crop area per head were also significantly largest in grazing-based ecological livestock farms, at 33.1 ha and 4,066.4 m², respectively. In terms of forage crop area per head, organic livestock farms secured a relatively larger area of 628.5 m²/LSU (Livestock Unit) compared to participatory certification and conventional farms (187.9–203.5 m²/LSU); however, this difference was not statistically significant. Livestock density based on cropland and forage crop area was lowest in grazing-based ecological livestock farms, at 2.4 head/ha and 2.5 head/ha, respectively, which was significantly

Table 1. Crop-livestock circulation agriculture indicators according to the certification types of Hanwoo farm

Farming types	Number of Livestock (LSU ¹⁾ /Farm)	Crop cultivation area		Forage crop cultivation area		Livestock unit density		Forage self-sufficiency rate ²⁾ (%)
		ha/Farm	m ² /LSU	ha/Farm	m ² /LSU	LSU/ha of total crop	LSU/ha of forage crop	
Organic	89.2±7.4 ^{3)ab4)}	8.6±2.2 ^b	965.4±250.2 ^b	5.6±1.7 ^b	628.5±161.9 ^b	10.4±4.1 ^a	15.9±3.6 ^a	76.2±19.6 ^b
PGS ⁵⁾	54.5±7.9 ^b	3.6±0.7 ^b	665.3±272.1 ^b	1.0±0.4 ^b	187.9±121.7 ^b	15.0±7.2 ^a	53.2±7.4 ^a	22.8±14.8 ^b
Grazing eco-farm	81.4±5.5 ^{ab}	34.5±8.0 ^a	4,237.0±1,205.2 ^a	33.1±8.2 ^a	4,066.4±1,207.6 ^a	2.4±0.9 ^b	2.5±0.8 ^b	492.9±146.4 ^a
Conventional	112.9±10.6 ^a	6.8±1.0 ^b	597.8±194.2 ^b	2.3±0.6 ^b	203.5±54.5 ^b	16.7±7.9 ^a	49.2±6.5 ^a	24.7±6.6 ^b

¹⁾ LSU: Livestock Standard Unit.

²⁾ Forage self-sufficiency rate (%) = [Forage area per head (m²/LSU) / Standard forage area (825 m²/LSU)] × 100.

³⁾ All values are means±standard error.

⁴⁾ Means followed by the same letter within a column are not significantly different according to Scheffé's multiple range test at $p < 0.05$.

⁵⁾ PGS: Participatory Guarantee Systems.

lower than that of other farm types ($p < 0.05$). In particular, the forage crop self-sufficiency rate was highest in grazing-based ecological livestock farms at 492.9%, showing a statistically significant difference compared to other types (22.8–76.2%) ($p < 0.05$).

The number of cattle per farm was highest in conventional farms (112.9 head), whereas participatory certification farms had the lowest number, with 54.5 head. This is because the Catholic Farmers' Movement, which operates participatory certification, applies a standard that limits the number of cattle per farm to 20 head. Such institutional measures may serve as a foundation for enhancing the stability of nutrient cycling within farms. Grazing-based ecological livestock farms possessed larger cropland and forage crop areas than other farm types. Yang et al. [8] reported that grazing and exercise in breeding cows improve calf production efficiency, suggesting that grazing-based ecological livestock farms may achieve substantial reductions in production costs, such as calf purchase expenses.

The average forage crop area per head across all farms was 1,271.6 m²/LSU. Lee et al. [9] reported a similar value, suggesting an appropriate forage crop area of 1,012 m²/LSU when compost return to soil is calculated based on phosphorus content. Excluding grazing-based ecological livestock farms, the average forage crop area per head was 340 m², which was comparable to the national average of 366.1 m² reported in the livestock statistics published by Statistics Korea in 2024. In contrast, organic livestock farms had a forage crop area of 628.5 m²/LSU, exceeding the national average, indicating efforts to achieve organic forage self-sufficiency and to maintain a livestock management system suitable for crop–livestock circulation.

The high forage crop self-sufficiency observed in grazing-based ecological livestock farms is interpreted not merely as a difference in livestock management practices, but rather as a result of structurally different strategies for securing cropland relative to herd size. This suggests that nutrient cycling can be achieved without external feed inputs when livestock density is reduced and land-based feeding systems are maintained. Conversely, despite meeting certification requirements, organic and participatory certification farms exhibited limited levels of cropland requirements, indicating that institutional certification does not necessarily lead directly to substantial improvements in crop–livestock circulation.

Amount of Self-Produced and Purchased Feed Supplied by Certification Type

The results of the analysis of feed supply per head by certification type are presented in Table 2. For self-produced forage, grazing-based ecological livestock farms supplied 1,255.9 kg per head, which was approximately 4.8 times higher than that of participatory certification farms (264.1 kg). In contrast, the amount of self-produced by-product feed supplied in grazing-based ecological livestock farms was only 51 kg per head, accounting for a very small proportion.

Among domestically purchased feeds, organic livestock farms recorded the highest level of roughage supply, at 2,685 kg per head. Domestically purchased by-product feed was highest in participatory certification farms at 1,867.4 kg per head, which was markedly higher than that of organic livestock farms (150.4 kg). The total amount of domestically purchased feed was similar between organic livestock farms (2,835.4 kg) and participatory certification farms (2,530.7 kg), whereas grazing-based ecological

Table 2. Crop-livestock circulation agriculture indicators according to the certification types of Hanwoo farm

Farming types	Self-production feed (kg/LSU ¹⁾)			Domestic purchased feed (kg/LSU)			Imported feed (kg/LSU)			Total (kg/LSU)
	Forage	By-product feed	Subtotal	Forage	By-product feed	Subtotal	Concentrates	Forage	Subtotal	
Organic	826.5± 188.4 ^{2)(ab3)}	363.9± 103.9 ^a	1,190.4± 243.1 ^a	2,685.0± 316.4a	150.4± 66.4 ^b	2,835.4± 321.7 ^a	2,482.4± 273.2 ^a	0.0± 0.0 ^b	2,482.4± 273.2 ^a	6,508.1± 255.5 ^a
PGS ⁴⁾	264.1± 109.0 ^b	936.9± 259.5 ^a	1,201.0± 330.9 ^a	663.2± 221.6 ^b	1,867.4± 288.1a	2,530.7± 298.7 ^a	1,055.0± 260.9 ^b	44.5± 15.2 ^b	1,099.5± 268.0 ^b	4,831.1± 279.1 ^b
Grazing eco-farm	1,255.9± 190.5 ^a	51.0± 0.0 ^b	1,255.9± 190.5 ^a	182.3± 88.5 ^b	214.6± 87.6ab	396.9± 151.3 ^b	1,610.1± 415.1 ^{ab}	717.2± 256.9 ^a	2,327.3± 369.5 ^{ab}	3,980.1± 161.0 ^b
Conventional	565.3± 102.1 ^{ab}	532.7± 119.6 ^a	1,098.0± 165.8 ^a	357.4± 97.4 ^b	1,459.0± 226.2ab	1,816.4± 235.0 ^{ab}	1,735.0± 173.9 ^{ab}	176.2± 49.0 ^b	1,911.2± 174.7 ^{ab}	4,825.6± 211.0 ^b

¹⁾ LSU: Livestock Standard Unit.

²⁾ All values are means±standard error.

³⁾ Means followed by the same letter within a column are not significantly different according to Scheffé's multiple range test at $p < 0.05$.

⁴⁾ PGS: Participatory Guarantee Systems.

livestock farms showed a significantly lower level at 396.9 kg per head.

For imported feed, the supply of concentration feed was highest in organic livestock farms, at 2,482.4 kg per head, exceeding that of participatory certification farms (1,055 kg) by more than twofold. The amount of imported roughage supplied was highest in grazing-based ecological livestock farms at 717.2 kg, accounting for a large proportion of imported feed.

The amount of self-produced forage supplied was the highest in grazing-based livestock farms, as the forage crop area and forage crop cultivation satisfaction rate were higher than in other types of farms (Table 1). These farms supplied relatively small amounts of self-produced by-product feed but larger amounts of imported roughage, likely because imported roughage is used to supplement insufficient nutrients during periods when grazing is difficult [10]. The amount of domestically purchased feed supplied was high in organic livestock farms and participating certified farms. This is because organic livestock farms supplied a large amount of forage, and participating certified farms, which have non-GMO feed and domestic feed as basic certification conditions, supplied a large amount of rice straw feed, a by-product that is easily supplied domestically. Participatory certified farms use agricultural byproducts in addition to rice straw. Mixed agricultural byproduct feed is effective in disease control, increased meat yield, and improved meat quality [11], making it a sufficient substitute for imported concentrate feed. Grazing-based ecological livestock farms supplied smaller amounts of domestically purchased feed because they relied more heavily on self-produced and imported roughage. The total amount of feed supplied from self-produced, domestically purchased, and imported sources was highest in organic livestock farms at 6,508.1 kg per head, consistent with the findings of Lim et al. [12], who reported higher feed supply levels in organic livestock farms.

In organic livestock farms, the supply of domestically purchased roughage and imported concentrate exceeded that of self-produced feed, indicating that organic livestock certification is characterized by a feeding system that depends more on organically certified domestic and imported concentrate feed than on self-produced feed. Therefore, to ensure sustainable Hanwoo cattle farming, priority should be given to creating an eco-friendly livestock cycle environment through self-production of forage, rather than focusing on maintaining organic livestock certification through externally purchased feed [13].

Proportion of Self-Produced and Purchased Feed Supplied by Certification Type

The proportion of self-produced feed supplied by certification type is shown in Fig. 1. The proportion of self-produced roughage was highest in grazing-based ecological livestock farms at 31.6%, which was significantly higher than that of other certification types ($p < 0.05$). In contrast, organic livestock farms showed a value of 12.7%, conventional farms 11.7%, and participatory certification farms the lowest at 5.5%.

The proportion of self-produced by-product feed ranged from 0 to 19.4%, with no statistically significant differences among

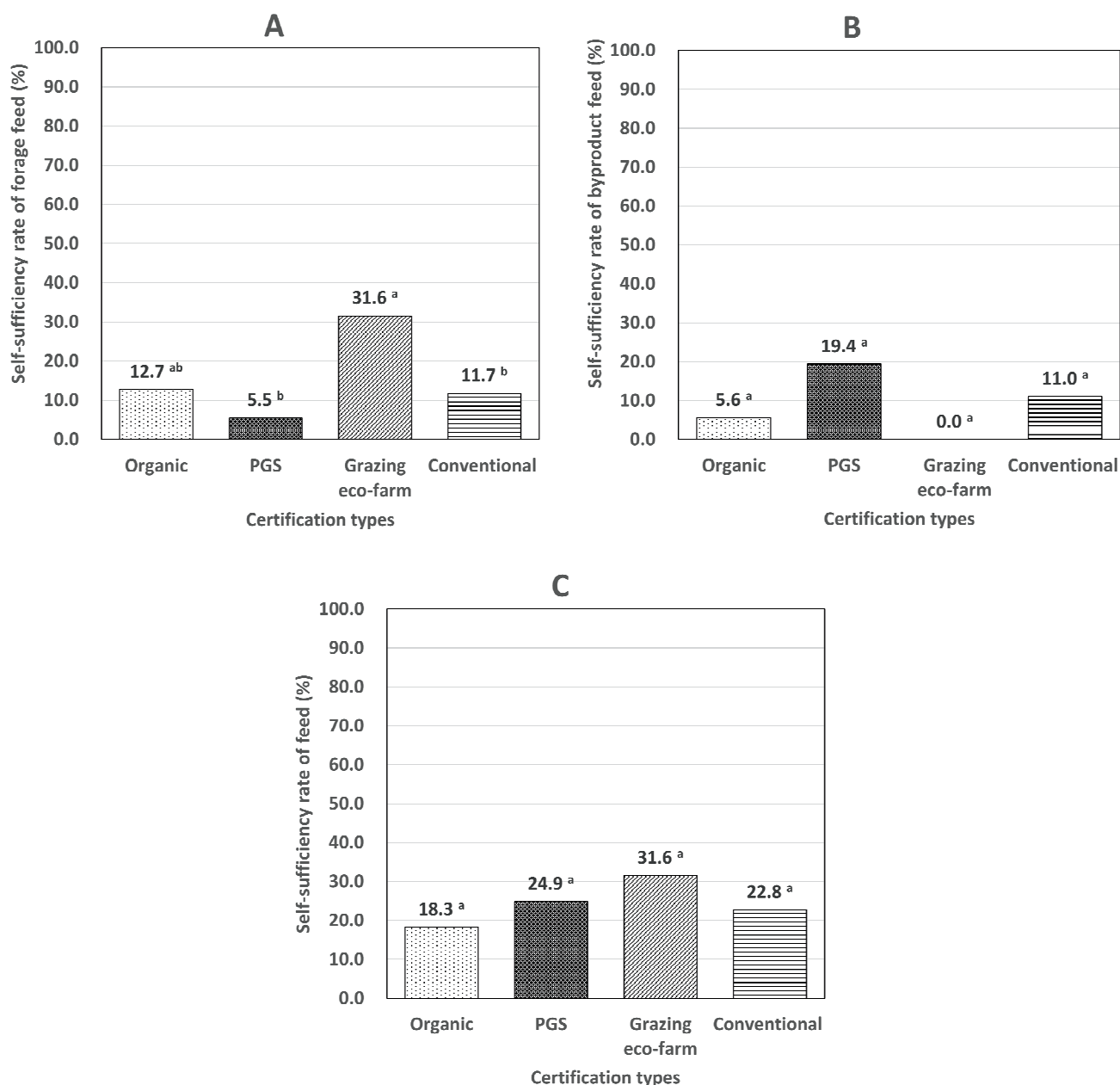


Fig. 1. Self-sufficiency rate by feed source according to the certification types of Hanwoo beef farm: A, Self-sufficiency rate of forage feed; B, Self-sufficiency rate of byproduct feed; C, Self-sufficiency rate of feed.

Means followed by the same letter within a column are not significantly different according to Scheffé’s multiple range test at $p < 0.05$. PGS: Participatory Guarantee System.

Table 3. Crop cultivation area according to the certification types of Hanwoo farm

Farming types	Fodder area (ha)	Grassland (ha)	Rice (ha)	Field crops (ha)	Vegetable crops (ha)	Fruit trees (ha)	Total farm area (ha)
Organic	5.6±1.7 ¹⁾²⁾	0.0±0.0 ^b	2.9±0.7 ^a	0.0±0.0 ^a	0.1±0.0 ^a	0.0±0.0 ^a	8.6±2.2 ^b
PGS ³⁾	1.0±0.4 ^b	0.0±0.0 ^b	1.5±0.3 ^a	0.3±0.1 ^a	0.8±0.2 ^a	0.0±0.0 ^a	3.6±0.7 ^b
Grazing eco-farm	1.2±0.7 ^b	31.9±8.4 ^a	0.0±0.0 ^a	0.0±0.0 ^a	1.3±0.7 ^a	0.1±0.0 ^a	34.5±8.0 ^a
Conventional	2.3±0.6 ^b	0.0±0.0 ^b	3.5±0.8 ^a	0.1±0.0 ^a	0.5±0.1 ^a	0.3±0.1 ^a	6.8±1.0 ^b

¹⁾ All values are means±standard error.

²⁾ Means followed by the same letter within a column are not significantly different according to Scheffé’s multiple range test at $p < 0.05$.

³⁾ PGS: Participatory Guarantee Systems.

certification types. The total proportion of self-produced feed also ranged from 18.3 to 31.6%, showing no significant differences among certification types.

The highest proportion of self-produced roughage in grazing-based ecological livestock farms (31.6%) is considered to result from their larger secured cropland areas, including pastureland, compared to other farm types (Table 3). Although organic livestock farms (12.7%) also showed higher proportions of self-produced roughage than conventional and participatory certification farms, this value was relatively low compared to the national average of 44.4% reported by Lee et al. [14].

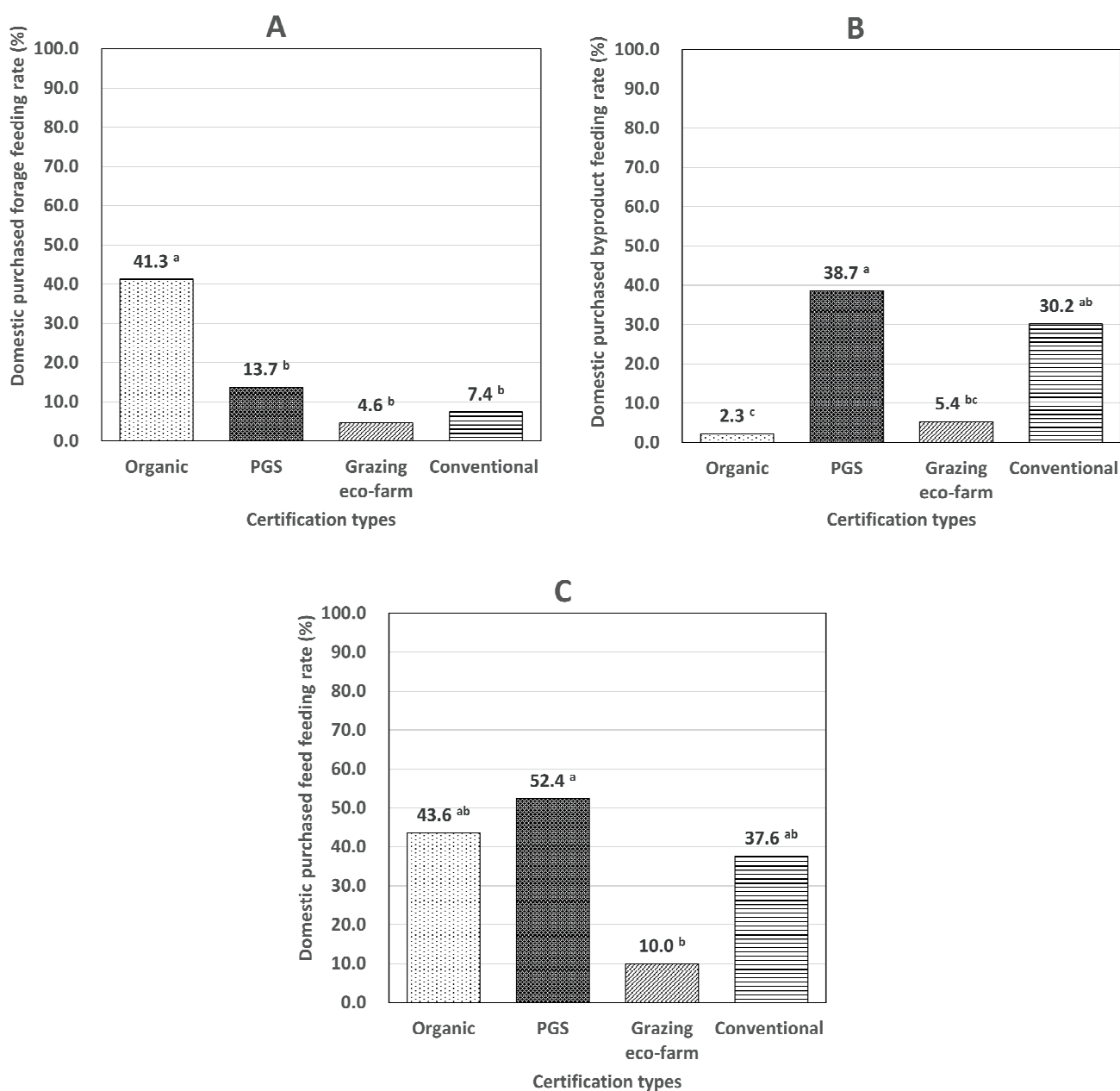


Fig. 2. Self-sufficiency rate by feed source according to the certification types of Hanwoo beef farm: A, Domestic purchased forage feeding rate; B, Domestic purchased byproduct feeding rate; C, Domestic purchased feed feeding rate.

Means followed by the same letter within a column are not significantly different according to Scheffé’s multiple range test at $p < 0.05$. PGS: Participatory Guarantee System.

Proportion of Domestically Purchased Feed Supplied by Certification Type

The proportion of domestically purchased feed supplied by certification type is shown in Fig. 2. The proportion of domestically purchased roughage was highest in organic livestock farms at 41.3%. The proportion of domestically purchased by-product feed was highest in participatory certification farms at 38.7%, followed by conventional farms at 30.2% and grazing-based ecological livestock farms at 5.4%, whereas organic livestock farms showed the lowest value at 2.3%. The total proportion of domestically purchased feed was highest in participatory certification farms at 52.4% and lowest in grazing-based ecological livestock farms at 10.0%, indicating large differences among certification types.

Organic livestock farms showed a high proportion of domestically purchased roughage, whereas participatory certification

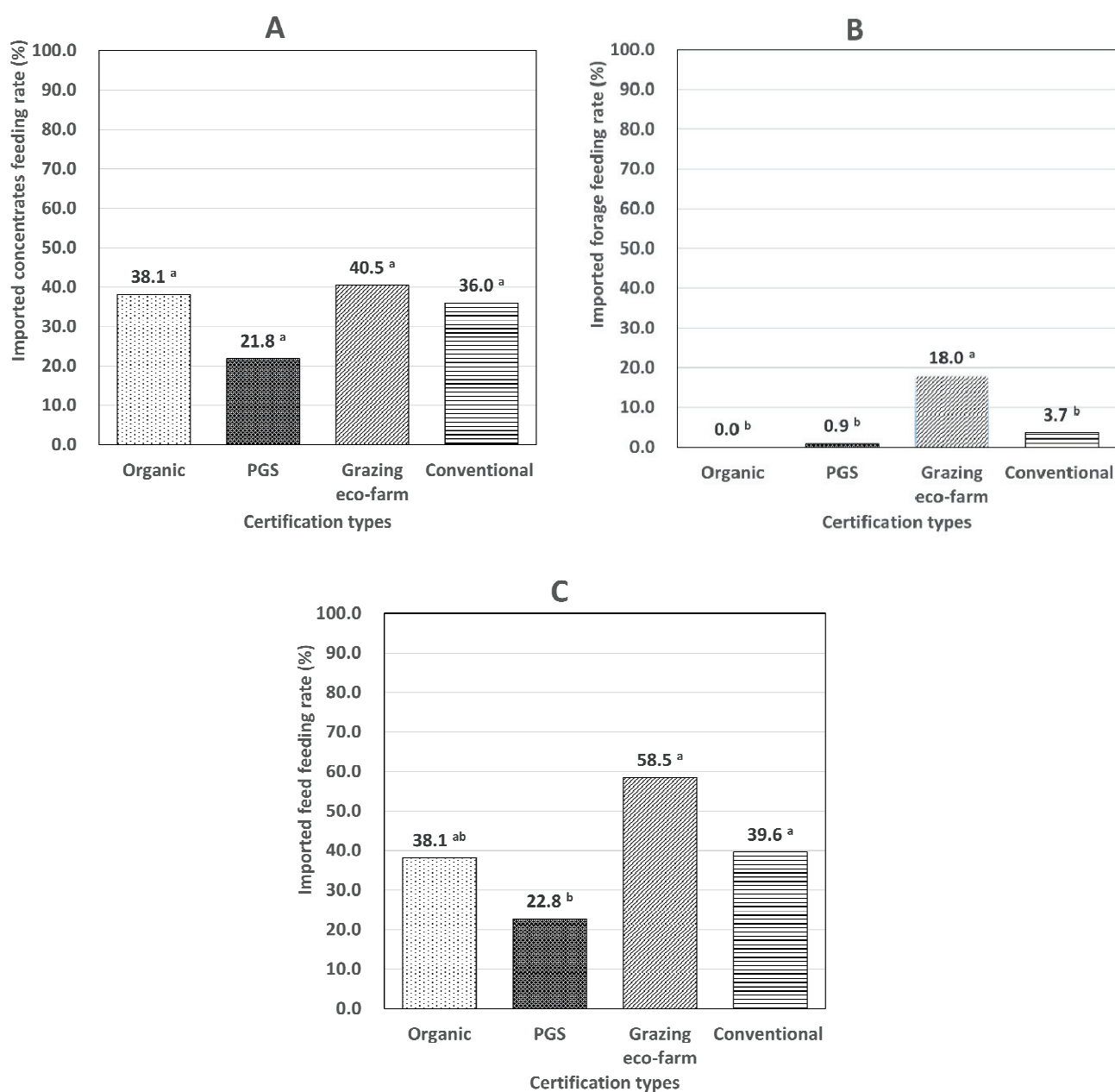


Fig. 3. Self-sufficiency rate by feed source according to the certification types of Hanwoo beef farm: A, Imported concentrates feeding rate; B, Imported forage feeding rate; C, Imported feed feeding rate.

Means followed by the same letter within a column are not significantly different according to Scheffé’s multiple range test at $p < 0.05$. PGS: Participatory Guarantee System.

farms showed a high proportion of by-product feed. As a result, both organic livestock and participatory certification farms exhibited total proportions of domestically purchased feed exceeding 44%. Feed management focused on domestically sourced feed is less susceptible to external uncertainties such as fluctuations in global grain prices compared to reliance on imported feed. Therefore, organic livestock and participatory certification farms are considered capable of achieving more sustainable and stable Hanwoo production systems.

Proportion of Imported Feed Supplied by Certification Type

The proportion of imported feed supplied by certification type is shown in Fig. 3. The proportion of imported concentrate feed ranged from 21.8 to 40.5%, with no significant differences among certification types. In contrast, the proportion of imported roughage was highest in grazing-based ecological livestock farms at 18.0%. The total proportion of imported feed was highest in grazing-based ecological livestock farms and conventional farms, at 58.5% and 39.6%, respectively, followed by organic livestock farms at 38.1%, while participatory certification farms showed the lowest value at 22.8%.

The high proportion of imported roughage in grazing-based ecological livestock farms indicates supplementation of insufficient nutrients in pasture with imported roughage, consistent with the findings of Chang et al. [10], who reported that imported roughage is preferred due to its high nutritional value.

Grazing-based ecological livestock farms and conventional farms, which exhibited the highest total proportions of imported feed (39.6–58.5%), are the most vulnerable to changes in global conditions such as fluctuations in international grain markets. On the other hand, certified participation farms had the lowest total imported feed feeding rate (22.8%), demonstrating that they practice ecological and circular feeding practices, focusing primarily on domestic feed. Organic livestock farms also had a low proportion of imported feed (38.1%), and Lee et al. [14] stated that feeding primarily does domestic feed lowers livestock management costs.

Cultivated Area by Certification Types and Crops

The cultivated area by certification type and crop category is presented in Table 3. Forage crop area was largest in organic livestock farms at 5.6 ha. Pasture area was observed only in grazing-based ecological livestock farms, with an average of 31.9 ha. No differences among certification types were observed for rice, upland crops, vegetables, or fruit crops. The total cultivated area was largest in grazing-based ecological livestock farms at 34.5 ha, with no significant differences among organic livestock, participatory certification, and conventional farms. Most farms secured forage crop cultivation areas, and organic livestock farms maintained more than twice the forage crop area of other farm types, at 5.6 ha. This suggests that organic livestock farms are reducing their dependence on imported roughage and transitioning toward feeding systems centered on self-produced roughage.

Rice cultivation following forage crops indicates extensive use of rice straw as feed, consistent with previous reports that rice straw accounts for approximately half of the domestic roughage supply [14].

Table 4. Compost production and compost recycling according to the certification types of Hanwoo farm

Farming types	Compost production (kg/LSU ¹⁾)	Compost disposal modes		
		On-farm use (kg/LSU)	Local farm use (kg/LSU)	Off-farm use (kg/LSU)
Organic	2,776.1±174.8 ^{2)a3)}	2,247.3±221.5 ^a	521.0±171.4 ^a	7.9±4.3 ^b
PGS ⁴⁾	3,026.6±170.7 ^a	2,191.7±297.8 ^a	733.6±190.2 ^a	101.2±43.3 ^a
Grazing eco-farm	2,157.7±75.4 ^a	1,376.5±277.4 ^b	781.2±212.6 ^a	0.0±0.0 ^b
Conventional	2,446.1±78.2 ^a	1,913.2±151.8 ^a	446.1±126.1 ^a	86.9±32.5 ^a

¹⁾ LSU: Livestock Standard Unit.

²⁾ All values are means±standard error.

³⁾ Means followed by the same letter within a column are not significantly different according to Scheffé's multiple range test at $p < 0.05$.

⁴⁾ PGS: Participatory Guarantee Systems.

Compost Production and Circulation by Certification Types

Compost production and circulation by certification type are presented in Table 4. Compost production per head ranged from 2,157.7 to 3,026.6 kg, with no significant differences among certification types. Compost self-circulation per head was relatively high in organic livestock, participatory certification, and conventional farms, ranging from 1,913.2 to 2,247.3 kg, whereas grazing-based ecological livestock farms showed a lower value of 1,376.5 kg. Compost transported off-farm per head was relatively high in conventional and participatory certification farms, at 86.9 and 101.2 kg, respectively, whereas organic livestock and grazing-based ecological livestock farms showed low values ranging from 0 to 7.9 kg.

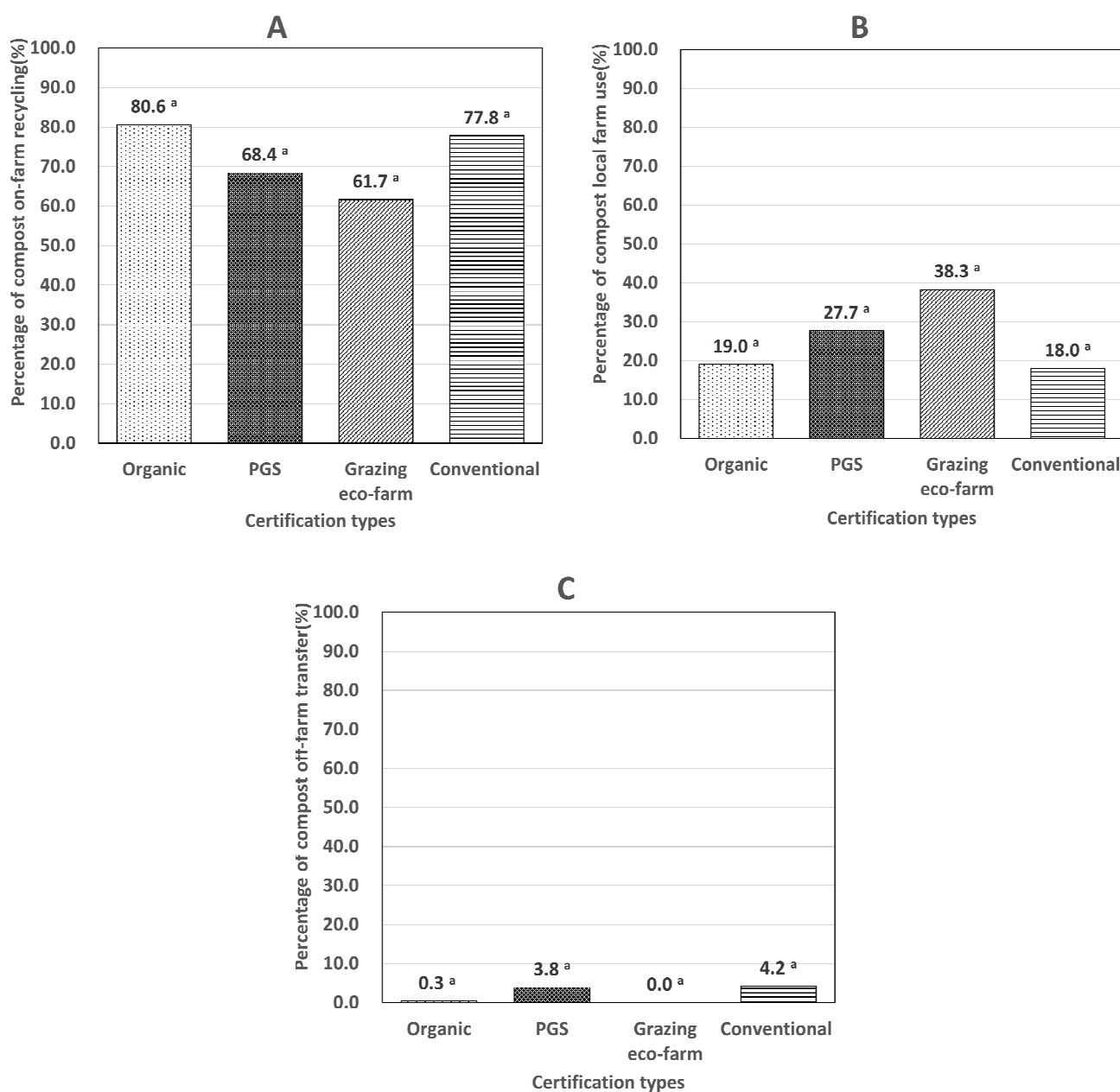


Fig. 4. Self-sufficiency rate by feed source according to the certification types of Hanwoo beef farm: A, Percentage of compost on-farm recycling; B, Percentage of compost local farm use; C, Percentage of compost off-farm transfer.

Means followed by the same letter within a column are not significantly different according to Scheffé’s multiple range test at $p < 0.05$. PGS: Participatory Guarantee System.

Self-circulation accounted for the largest proportion of compost circulation in all farm types because all farms cultivated forage crops. Participatory certification and conventional farms showed higher levels of off-farm compost transport due to limited or absent cropland in some cases, whereas grazing-based ecological livestock farms exhibited no off-farm transport because of lower overall compost production.

The compost self-circulation rate by certification type is shown in Fig. 4. The self-circulation rate ranged from 61.7 to 80.6%, which was numerically higher than village-level circulation or off-farm transport rates, although the differences were not statistically significant. It is considered that securing an appropriate level of cropland area, together with efficient manure treatment and application management, could enhance compost self-circulation rates and expand self-produced feed supply. This would reduce surplus nitrogen loads within farms and improve the economic, environmental, and ecological sustainability of organic livestock farming [12]. Therefore, it is necessary to secure farmland appropriate for the scale of the farm and maximize the efficiency of compost nutrient management to continuously increase the self-recycling rate.

Nitrogen and Phosphorus Balance by Certification Types

Nitrogen and phosphorus balances by certification type are presented in Table 5. Surplus nitrogen and surplus phosphorus per kg of beef produced ranged from 8.6 to 14.6 kg and from 5.2 to 14.5 kg, respectively, with no significant differences among certification types. In general, nutrient inputs tended to be slightly higher than outputs. Nitrogen use efficiency ranged from 23.5 to 44.6%, and phosphorus use efficiency from 50.9 to 65.7%, with no significant differences among certification types.

Considering nutrient losses through volatilization and leaching during crop and livestock production, it is generally necessary for nutrient inputs to exceed outputs to maintain appropriate production levels. However, the absence of differences in surplus nutrients among certification types suggests that, despite management efforts under organic livestock and participatory certification (PGS) systems, current levels of control over external feed inputs and requirements for securing cropland are insufficient to induce meaningful differences in nutrient balances among farms [5, 12].

In particular, the finding that nitrogen utilization efficiency was lower than that of phosphorus demonstrates the importance of nitrogen management from an agricultural environmental perspective, which can be improved through precise management of surplus nutrients. Therefore, to improve nutrient balances, a key indicator of environmentally friendly agriculture, it is necessary to consider ways to more effectively supplement the certification system's criteria for self-forage production and securing farmland areas.

Carbon Balance by Certification Types

Carbon footprints by certification type are presented in Table 6. Baseline carbon emissions per head were highest in organic livestock farms, at 6,764.8 kg CO₂-eq, reflecting their high feed supply levels. Participatory certification farms and conventional farms followed with values of 6,284.8 and 6,134.9 kg CO₂-eq, respectively, whereas grazing-based ecological livestock farms showed

Table 5. N-P balance according to the certification types of Hanwoo farm

Farming types	N balance		P balance	
	N balance per kg meat (Input-Output, kg/meat kg)	N-use efficiency (Output/input, %)	P balance per kg meat (Input-Output, kg/meat kg)	P-use efficiency (Output/input, %)
Organic	10.1±1.2 ^{1)a2)}	27.6±2.5 ^a	5.2±0.7 ^a	62.6±2.8 ^a
PGS ³⁾	8.6±1.0 ^a	44.6±4.4 ^a	10.5±1.9 ^a	65.7±2.8 ^a
Grazing eco-farm	14.6±2.6 ^a	23.5±3.5 ^a	13.6±3.0 ^a	50.9±7.0 ^a
Conventional	12.9±1.7 ^a	35.6±2.7 ^a	14.5±2.4 ^a	55.8±3.0 ^a

¹⁾ All values are means±standard error.

²⁾ Means followed by the same letter within a column are not significantly different according to Scheffé's multiple range test at $p < 0.05$.

³⁾ PGS: Participatory Guarantee Systems.

Table 6. Carbon footprint according to the certification types of Hanwoo farm

Farming types	Baseline carbon emissions (kg CO ₂ -eq)		Carbon reduction (kg CO ₂ -eq)			Carbon footprint (kg CO ₂ -eq)	
	Carbon emissions per LSU ¹⁾ (kg CO ₂ -eq/LSU)	Carbon emissions per kg meat (kg CO ₂ -eq/meat kg)	Carbon reduction per LSU (kg CO ₂ -eq/LSU)	Carbon reduction per kg meat (kg CO ₂ -eq/meat kg)	Carbon reduction rate (%)	Carbon emissions per LSU (kg CO ₂ -eq/LSU)	Carbon emissions per kg meat (kg CO ₂ -eq/meat kg)
Organic	6,764.8±211.7 ^{2)a3)}	14.8±0.5 ^a	1,039.4±39.9 ^a	2.3±0.1 ^a	15.3±0.3 ^a	5,725.4±176.3 ^a	12.5±0.4 ^a
PGS ⁴⁾	6,284.8±191.0 ^{ab}	13.8±0.4 ^{ab}	885.7±116.2 ^a	1.9±0.3 ^a	13.6±1.6 ^{ab}	5,399.1±166.0 ^a	11.8±0.4 ^a
Grazing eco-farm	4,994.3±155.0 ^b	10.9±0.3 ^b	113.7±15.4 ^b	0.2±0.0 ^b	2.3±0.3 ^c	4,880.5±156.0 ^a	10.7±0.3 ^a
Conventional	6,134.9±173.1 ^{ab}	13.4±0.4 ^{ab}	578.0±57.7 ^{ab}	1.3±0.1 ^{ab}	9.0±0.8 ^{bc}	5,556.9±142.4 ^a	12.2±0.3 ^a

¹⁾ LSU: Livestock Standard Unit.

²⁾ All values are means±standard error.

³⁾ Means followed by the same letter within a column are not significantly different according to Scheffé's multiple range test at $p < 0.05$.

⁴⁾ PGS: Participatory Guarantee Systems.

the lowest emissions at 4,994.3 kg CO₂-eq. Carbon emissions per kg of carcass weight were also highest in organic livestock farms at 14.8 kg CO₂-eq, followed by participatory certification farms (13.8 kg CO₂-eq) and conventional farms (13.4 kg CO₂-eq), while grazing-based ecological livestock farms exhibited the lowest value at 10.9 kg CO₂-eq.

Baseline carbon emissions per head and per kg of carcass weight were higher in organic livestock farms, which supplied larger amounts of feed (Table 2), consistent with reports that greater feed supply leads to higher carbon emissions [2]. The carbon emissions per kg of carcass weight in conventional farms (13.4 kg CO₂-eq) were similar to values reported in previous studies [15]. In contrast, organic livestock farms showed higher emissions per kg of carcass weight (14.8 kg CO₂-eq) than those reported by Kim et al. [15], likely due to increased feed supply and associated emissions from feed production and enteric fermentation. Grazing-based ecological livestock farms exhibited the lowest carbon emissions, which can be attributed to lower feed supply, reduced emissions from enteric fermentation, decreased compost production and manure management emissions, and reduced energy use resulting from approximately six months of pasture grazing, as reported by the Ministry of Agriculture, Food and Rural Affairs in 2016.

Carbon reduction per head was highest in organic livestock farms and participatory certification farms, at 1,039.4 and 885.7 kg CO₂-eq, respectively, reflecting the use of organic feed and agricultural by-products. Conventional farms followed with 578.0 kg CO₂-eq, whereas grazing-based ecological livestock farms showed the lowest reduction at 113.7 kg CO₂-eq. Carbon reduction per kg of carcass weight was also highest in organic livestock farms (2.3 kg CO₂-eq) and participatory certification farms (1.9 kg CO₂-eq), followed by conventional farms (1.3 kg CO₂-eq), while grazing-based ecological livestock farms showed the lowest value at 0.2 kg CO₂-eq. The reduction rate was highest in organic livestock farms at 15.3%, followed by participatory certification farms at 13.6% and conventional farms at 9.0%, with grazing-based ecological livestock farms showing the lowest rate at 2.3%.

Higher carbon reductions in farms supplying organic feed and by-product feed are consistent with reports that crop–livestock circular agriculture reduces carbon emissions through decreased use of chemical fertilizers and recycling of agricultural by-products [16]. Lim et al. [3] also reported increased carbon reduction under organic farming systems. After accounting for carbon reductions, carbon emissions per head ranged from 4,880.5 to 5,725.4 kg CO₂-eq, with no significant differences among certification types. Carbon emissions per kg of carcass weight also showed no significant differences among certification types, ranging from 10.7 to 12.5 kg CO₂-eq. Kim et al. [15] reported higher values (13.0–13.9 kg CO₂-eq per kg of carcass weight) than those observed in this study, likely because their analysis did not incorporate carbon reductions from organic feed production, nitrogen reduction through compost return to cropland, substitution effects of by-product feed, or emission reduction rates associated with manure management.

Overall, the results of this study suggest that a sustainable crop–livestock circulation model for Hanwoo farms can be achieved

through the integration of ideal environmental structures and institutional implementation capacity. Grazing-based ecological livestock farms, supported by the largest cropland area (35.7 ha) and the highest self-produced roughage self-sufficiency rate (31.6%), recorded the lowest baseline carbon emissions (4,994.3 kg CO₂-eq per head), presenting an ideal model of environmentally friendly livestock production. In contrast, organic livestock and participatory certification farms, despite higher baseline emissions, achieved the highest carbon reduction rates (13.6–15.3%) through the use of organic feed and compost circulation, demonstrating the potential for environmental improvement through institutional efforts. Taken together, these findings indicate that establishing an economically and environmentally sustainable Hanwoo production model requires integrating the institutional implementation capacity of organic livestock and participatory certification systems with the strengths of grazing-based ecological livestock farms in self-produced feed production. Expanding cropland area, improving compost circulation, and increasing self-produced forage supply are key factors for effectively reducing nutrient surpluses and carbon footprints. Therefore, it is necessary to strengthen certification criteria related to farm-level self-produced roughage targets and to implement policy measures, such as land lease support, to alleviate difficulties in securing cropland and establish a foundation for environmentally friendly livestock production. Ultimately, a Korean style integrated circular model will achieve both economic and environmental sustainability when certification systems that entail high levels of environmental effort are combined with a robust self-produced forage production base.

Materials and Methods

Classification of Hanwoo Farms by Certification Type and Surveyed Farm Status

Certification types of Hanwoo farms were classified into organic livestock certification, participatory certification, grazing-based ecological livestock farming, and conventional farming systems. The surveyed farms included 11 farms that had obtained organic livestock certification as of March 2024, according to data provided by the National Agricultural Products Quality Management Service. Organic livestock certification requires that 100% organic feed be supplied, adequate forage crop cultivation areas be secured, and livestock manure be fully composted or processed into liquid manure and returned to grassland or cropland, thereby maintaining an organic circular relationship between soil and plants, as stipulated by the Korean Law Information Center in 2024.

Participatory certification is a certification system in which producers and consumers jointly participate to realize sustainability and process-oriented values. It operates under independent Hanwoo production standards that emphasize environmentally friendly practices, animal welfare, the use of non-GMO feed, and local circular agriculture. In this study, a total of 17 farms affiliated with organizations operating participatory certification systems were surveyed, including the Catholic Farmers' Movement, Hansalim Cooperative, and Dure Consumer's Cooperative, based on information provided by each organization between 2023 and 2024.

Grazing-based ecological livestock farms refer to farms that produce roughage on pastureland and raise ruminants (beef cattle and dairy cattle) under grazing systems, with milk or meat production as their primary source of income. Farms that graze livestock on pastureland or grassland grazing areas of at least 1 ha are designated by the Ministry of Agriculture, Food and Rural Affairs [17], and six such farms were surveyed in this study. Conventional farms included 24 farms that raise livestock under conventional practices without any certification.

Survey of Livestock Cycle Indicators

The number of cattle, cropland and forage crop area per farm and per head, livestock density, and forage crop self-sufficiency rate were investigated through on-site visits to each farm. The livestock density index was calculated by dividing the livestock units (LSU) by the cropland area, following the method of Eurostat (2022), using the following Eq. (1).

$$\text{Livestock unit density (LSU/ha)} = \frac{\text{total livestock unit (LSU)}}{\text{total crop area (ha)}} \quad (1)$$

LSU were calculated based on the number of adult cattle, standardizing growth stages to enable comparable livestock unit values. For Hanwoo cattle, adult cattle aged 14 months or older were defined as 1 LSU. Growing cattle aged 6–14 months were converted to 0.5 LSU, middle calves aged 3–6 months to 0.15 LSU, and calves younger than 2 months to 0.05 LSU [18].

The forage crop self-sufficiency rate (%) was calculated by dividing the forage crop area per head (m^2/LSU) by the standard forage crop area requirement of $825 \text{ m}^2/\text{LSU}$ established by the National Agricultural Products Quality Management Service in 2024 and multiplying by 100, as shown in Eq. (2).

$$\text{Forage self-sufficiency rate (\%)} = \frac{\text{forage area per head (m}^2/\text{LSU)}}{\text{standard forage area (825m}^2/\text{LSU)}} \times 100 \quad (2)$$

Nutrient Balance Assessment

Nutrient balance was calculated as the difference between total nutrient inputs and total nutrient outputs within each farm. Nutrient inputs included the number of livestock produced on-farm and purchased, the amount of feed supplied, the amount of bedding materials such as sawdust and rice husks purchased—which are used on barn floors to absorb moisture, provide thermal insulation and comfort for animals, maintain barn cleanliness, and promote manure fermentation—as well as the amount of fertilizers purchased for cropland application and the amount of self-produced compost applied.

Nutrient outputs included the sale of calves, shipment and mortality of beef cattle, the amount of self-produced feed and rice straw feed, the production and sale of polished rice and other agricultural products, the amount of compost returned to on-farm cropland, and the amount of compost transported off-farm. Nutrient (N, P) balance per unit of live beef weight was calculated by dividing the total nutrient balance per farm [kg N(P)] by the live weight of beef cattle (kg), expressed as $\text{kg N(P)/kg live weight}$, using Eq. (3).

$$N(P) \text{ balance (kg N(P)/live weight)} = \frac{\text{input} - \text{output (kg N or kg P)}}{\text{live weight (kg)}} \quad (3)$$

Nutrient use efficiency was calculated as the ratio of nutrient output (kg) to nutrient input (kg), converted to a percentage (%), as shown in Eq. (4).

$$N(P) \text{ - use efficiency (\%)} = \frac{N(P) \text{ output (kg)}}{N(P) \text{ input (kg)}} \times 100 \quad (4)$$

Carbon Emission Assessment

The carbon footprint per farm was estimated by including enteric fermentation, manure management, and energy use, in accordance with the low-carbon livestock product certification standards [15]. The system boundary was defined as “Cradle-to-Farm gate,” extending to the feed production and transportation stages based on Life Cycle Assessment (LCA) methodology [19].

Greenhouse gas emissions were calculated by multiplying activity data for each emission source by country-specific emission factors, based on the IPCC (2019) guidelines, and were integrated as carbon dioxide equivalents ($\text{CO}_2\text{-eq}$) using global warming potentials (GWP). The calculation formula is shown in Eq. (5), and all results were expressed as $\text{kg CO}_2\text{-eq per kg of beef}$

produced to allow objective comparison of emission efficiency among farms.

$$\text{Carbon footprint (kg CO}_2\text{-eq/kg)} = \frac{\Sigma(\text{activity data} \times \text{emission factor})}{\text{total beef production (kg)}} \quad (5)$$

Carbon emissions per head were calculated by dividing the total emissions per farm by LSU. For calculating the carbon footprint per kg of carcass weight, the national average carcass weight of male Hanwoo cattle from 2022 to 2023 (457.02 kg) reported by the Korea Institute for Animal Products Quality Evaluation (2024) was applied as the denominator.

The final carbon footprint by farm resource circulation type was calculated by subtracting carbon reduction amounts by item from the baseline emissions, as shown in Eq. (6). Here, baseline emissions refer to the sum of emissions calculated under conventional farming conditions without the application of resource circulation technologies, based on the same LCA perspective as in Eq. (5).

$$\text{Final carbon footprint} = \text{baseline emissions} - \Sigma \text{ carbon reductions} \quad (6)$$

Carbon reduction amounts included reductions in external inputs through the production and use of organic feed, substitution of synthetic nitrogen fertilizers through the return of compost to cropland, and reductions in soil nitrogen emissions, in order to quantify the resource-circulating value of the Hanwoo industry [20]. In addition, emission offsets from the utilization of agri-food by-product feeds during raw feed production and transportation stages, as well as greenhouse gas reduction rates by manure treatment method, were comprehensively applied to standardize and present the final carbon balance.

Statistical Analysis

ANOVA analysis of crop–livestock circulation indicators by certification type was performed using the *aov* function in the R program, and multiple comparisons were conducted using the *scheffe.test* () function of the “agricolae” package (P=0.05). All statistical analyses were performed using R software (ver. 4.4.2).

Data Availability: All data are available in the main text or in the Supplementary Information.

Author Contributions: J.L. and J.R. conducted the experiments, performed investigation and data curation, and wrote the manuscript; D.C. provided overall supervision and critical feedback on the manuscript.

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Additional Information:

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