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Waste management strategies for dairy farms of varying capacities

Umut Kılıç İlker Kılıç*

Department of Biosystems Engineering, Bursa Uludağ University, 16110, Bursa, Türkiye

***Corresponding author e-mail:** ikilic@uludag.edu.tr

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Abstract: Dairy cattle farms must plan effectively for waste management due to the high volume of manure produced by the animals they keep. A well-designed waste management plan not only creates a healthy environment for all stakeholders but also generates an additional source of income to support the dairy farm's sustainability. In this study, a general waste management plan was developed for 24 dairy cattle farms, and various scenarios (plant production, composting, biogas) that could be used as alternatives for the reuse of manure were comparatively evaluated. Calculations show that, if dairy cattle farms use manure for plant production in the first scenario, 38 tons of manure per hectare would need to be applied in the Bursa region, and across the 24 farms evaluated, the total manure available could be applied to an average of 21.45 hectares of land. In the second scenario, the total compost production across all dairy cattle farms was calculated to be 425.74 m3 per day. Approximately 80% of this amount belongs to dairy farms with large capacity (6 dairy farms). In the third scenario, biogas calculations indicate that the total manure from all dairy farms can generate 1,830,853 kWh of electricity annually. 70% of this figure (1,261,835.49 kWh) is obtained from large-capacity dairy farms, and 4% (67,663.61 kWh) is obtained from small-capacity dairy farms. When all the scenarios examined in the study were analyzed economically, the compost scenario yielded the highest economic gain and the shortest payback period across all groups. On small-capacity dairy farms, the annual profit is 104,758 TL, and the payback period is 8.49 years. Large-capacity dairy cattle farms, on the other hand, have the shortest payback period with an annual profit of 2,271,812 TL and a payback period of 5.24 years.

Keywords: Biogas, Compost, Plant Production, Pollution, Sustainability

Farklı kapasitelerdeki süt sığırı çiftlikleri için atık yönetimi stratejileri

Öz Süt sığırı işletmeleri içerisinde bulundurdukları hayvanların gübre üretme miktarlarının yüksek olması nedeniyle atık yönetimi konusunda iyi bir planlama gerçekleştirmek zorundadırlar. İyi tasarlanmış bir atık yönetim planı yalnızca tüm bu paydaşlar için sağlıklı bir ortam oluşturmakla kalmaz, aynı zamanda işletmelerin sürdürülebilirlikleri için ek bir kazanç kaynağı da ortaya çıkarır. Bu çalışmada 24 adet süt sığırı işletmesi için genel bir atık yönetim planı oluşturulmuş ve gübrenin yeniden kullanılabilirliği amacıyla, birbirlerinin alternatifi olarak kullanılabilecek çeşitli senaryolar (bitkisel üretim, kompost, biyogaz) karşılaştırmalı olarak değerlendirilmiştir. Hesaplamalar sonucunda işletmelerin gübreyi birinci senaryoda bitkisel üretim amacıyla kullanması durumunda Bursa bölgesinde hektar başına 38-ton gübre uygulanması gerektiği ve değerlendirilen 24 işletmeden elde edilecek toplam gübrenin ortalama 21.45 hektar araziye uygulanabileceği belirlenmiştir. İkinci senaryoda tüm işletmeler için toplam kompost üretimi günlük 425,74 m3 olarak hesaplanmıştır. Bu miktarın yaklaşık %80'lik kısmı büyük kapasiteye sahip işletmelere (6 adet) aittir. Üçüncü senaryo da ise biyogaz hesaplamaları sonucunda toplamda tüm işletmelerden elde edilecek gübre miktarı ile yıllık olarak 1.830.853 kWh elektrik üretimi gerçekleştirilebilmektedir. Bu rakamın %70'lik kısmı (1.261.835,49 kWh) büyük kapasiteli işletmelerden, %4'lük kısmı (67.663,61 kWh) küçük kapasiteli işletmelerden elde edilmektedir. Çalışmada ele alınan tüm senaryolar ekonomik olarak incelendiğinde tüm gruplar için en yüksek ekonomik kazanç ve en düşük amorti süresi kompost senaryosunda elde edilmiştir. Küçük kapasiteli süt sığırı çiftliklerinde yıllık kazanç 104758 TL' dir ve amorti süresi 8.49 yıl olarak belirlenmiştir. Büyük kapasiteli süt sığırı çiftlikleri ise 2271812 TL yıllık kazanç ve 5.24 yıl amorti süresi ile en kısa süreye sahiptir.

Anahtar kelimeler: Biyogaz, Kompost, Bitkisel Üretim, Kirlilik, Sürdürülebilirlik

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1. Introduction

Environmental pollution refers to the contamination of air, water, and soil, and the disturbance of the natural ecological balance caused by human activities. Pollution levels are increasing globally due to rapid population growth, industrial expansion, inadequate waste management, insufficient environmental awareness, and other related factors. Livestock production is a major contributor to environmental pollution due to the substantial organic waste generated on farms. Livestock manure can lead to various environmental problems, including excessive bacterial and algal growth in water bodies, fish mortality, odor emissions around farms, and soil and plant degradation. Although these impacts are often first observed in the immediate vicinity of livestock farms, they may extend over much larger areas through interconnected water systems (Özek, 1994; Atılgan et al., 2006; Karaman, 2006; Varol, 2017).

Türkiye hosts a large livestock population, consisting of 17.19 million cattle and 58.2 million sheep as of 2025 (Anonymous, 2025a). The number of farms—directly proportional to the number of animals—has resulted in significant environmental pressures associated with manure management. Therefore, implementing appropriate measures to minimize pollution originating from livestock activities is essential. Among these measures, waste management practices play a crucial role in controlling and reducing the environmental impacts caused by manure.

According to Anonymous (2015), waste management encompasses reducing, collecting, storing, recycling, and disposing of waste at its source. For livestock operations, reducing manure at the source is not feasible; therefore, the focus shifts to recycling and reusing manure and other waste streams. Manure recycling provides environmental advantages in addition to economic benefits for animal farms. Common methods of manure recycling include agricultural land applications, composting, and biogas production (Taban et al., 2020).

Manure obtained from dairy farms can be applied to agricultural soils after appropriate storage or fermentation. Composting, which involves the microbial decomposition of organic waste under optimal levels of oxygen, temperature, moisture, and C/N ratio, provides another environmentally friendly means of manure utilization (Külcü, 2016). Biogas production, in contrast, enables energy generation through the anaerobic digestion of organic materials, producing a gas mixture consisting primarily of methane, carbon dioxide, nitrogen, oxygen, and hydrogen sulfide (Şenol et al., 2017; Kurt, 2021). Electricity generated by biogas systems can be used for various farm operations, contributing to sustainable production.

This study aims to determine the most suitable strategies for manure recycling and waste management across 24 dairy farms with varying herd sizes in the Bursa region by comparing scenarios involving land application, composting, and biogas methods. This study makes a scientific contribution by comparing the economic and environmental feasibility of different waste management methods rather than focusing on a single method. Similar studies in the literature focus on regional scales, particularly on determining biogas potential. However, the number of studies that examine different methods within the scope of waste management plans by grouping animal shelters by capacity (small, medium, large) is quite limited. This approach focuses on selecting capacity-specific, feasible, and economical waste management methods for both existing and newly established animal farms.

2. Materials and Methods

2.1. Study area and scope

This study was conducted in Bursa province of Türkiye. Bursa Province is an important region for the livestock sector, with 9,988 animal farms and 224,002 cattle (Anonymous, 2023; Anonymous, 2024). To accurately and comparatively evaluate waste management scenarios across enterprises with different capacities and sizes, the number of animals and land area were considered. Within this scope, 24 dairy cattle farms in the region were selected using a purposive sampling method. The dairy farms are in six different districts of Bursa province. Figure 1 shows a map of Bursa Province, with the districts where the dairy cattle farms are located and marked.

The smallest of the 24 dairy cattle farms selected for the study have a capacity of 4 animals, while the largest has a capacity of 225. A waste management plan has been established for dairy farms. Within the scope of the waste management plan, plant production, compost, and biogas production potentials of each dairy farm were determined. The animal capacities of the farms selected for the study are shown in Figure 2.

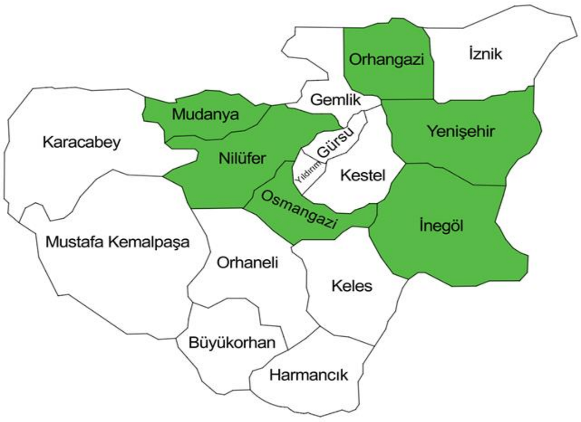

Figure 1. Map of Bursa province and the districts where the dairy farms are located

2.2. Waste management plan in animal husbandry

A waste management plan can be defined as the planning of practices used to protect the health of living beings and the environment, and to increase economic profitability at all stages, such as collecting, storing, recycling, or disposing of the resulting waste, starting from its source (Yılmaz & Bozkurt, 2010; Bilgili, 2020). The first step in waste management is to prevent waste formation at its source. However, in situations where waste generation cannot be prevented, recycling or using it for energy production has been identified as the second- and third-priority options. As a final option, waste must be disposed of most appropriately, considering environmental and human safety. Using the correct equipment and methods is crucial at all stages of waste management (Tezel & Yıldız, 2020; Dağdelen Türkyılmaz, 2024).

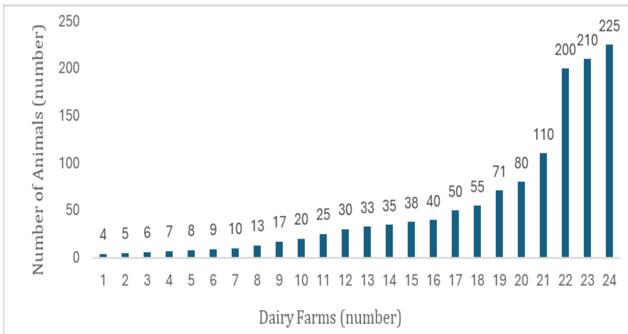

Figure 2. Capacities of the dairy farms where the study was conducted

The livestock sector has high potential for generating waste. Examples of waste generated in livestock farms include solid manure, urine, manure leaching water, and pharmaceutical and feed packaging. Considering the environment, human and animal health, and the sustainability of animal farms, these wastes need to be managed properly. In this context, under the waste management regulation numbered 29134, definitions for the recycling and disposal processes of waste produced on dairy farms have been established (Anonymous, 2015). After identifying the waste generated on dairy cattle farms, all waste has been categorized as hazardous or non-hazardous. In the waste management plan, a disposal scenario has been added for hazardous and non-recyclable waste, while various reuse scenarios have been added for recyclable waste.

A large portion of the waste produced on dairy farms consists of manure, and its reuse offers significant economic benefits. When creating the waste management plan, since there are limited possibilities to prevent the formation of manure in dairy farms, its management and recycling have been emphasized. Cattle manure can be reused in plant production, composting, or biogas production due to its high organic matter, carbon, and nitrogen content (Dağdelen Türkyılmaz, 2024).

In this study, plant production, composting, and biogas scenarios were incorporated into the waste management plan to reuse manure. The calculation steps for each scenario have been detailed. The feasibility of the scenarios added to the waste management plan has been evaluated using decision criteria such as the number of animals and land area. Before detailing the scenarios, the basic parameters to be used in plant production, compost, and biogas calculations have been elaborated.

Cattle can produce 30 kg of solid manure and 15 liters of liquid manure daily (Olgun, 2011). While performing the calculations, the daily fresh manure amounts per animal reported in the literature were considered. The application rate of the obtained manures to the land has been calculated.

The amounts of N, P, and K to be applied for plant production vary depending on soil nutrient levels, the type of plant to be produced, and the type of manure to be applied. However, in the Bursa region, the average N, P, and K values that can be practically applied to the land to prevent nitrate pollution and contamination of underground water sources are 170 kg/ha. In this context, the manure application norm has been calculated based on this value. The characteristics of manures from different animal types are provided in Table 1 based on the literature (Brady, 1991; Kızılgöz, 2012; Kılıç & Amet, 2017).

Table 1. The characteristics of manures from different animal types

Animal Types	N (kg/tons)	P (kg/tons)	K (kg/tons)
Dairy Cattle	4.5	1.2	3.4
Beef Cattle	5.4	2.1	3.2
Chicken	13.6	6.5	3.2
Sheep	10.4	3.2	9.8

In the study, compost production was planned to consist of two components: manure and a modifier. Calculations were carried out with three different components, namely rice husk, straw, and sawdust, to determine the modifier that would create the best combination with dairy cattle manure. The volume reduction of compost during the maturation period is approximately 20%-60% (Lalremruati & Devi, 2021). In this study, the compost volume reduction factor was also set at 20%. The characteristics of dairy cattle manure and modifiers based on literature are given in Table 2 (Öztürk, 2017; Saedd et al., 2021; Anonymous, 2021; Kınık, 2023).

Table 2. The characteristics of dairy cattle manure and modifiers.

Parameters	C (%)	N (%)	C/N	Moisture Content (%)
Dairy Cattle Manure	43.47	4	10	70
Rice Husk	78	1.06	73.58	10
Sawdust	50	0.125	500	25
Straw	42.09	0.48	87.69	7.5

The basic parameters used in biogas calculations, as reported in the literature, are provided in Table 3 (Ekinci et al., 2010; Kaynarca et al., 2021). Additionally, the energy conversion coefficient (10 kWh/m^3) and system electrical efficiency (35%) have been used (Yağlı & Koç, 2019)

Table 3. Variables used in calculating biogas potential with cattle manure

Animal Type	Useful Manure Rate (%)	Dry Matter Ratio (%)	Volatile Solid Matter Ratio (%)	Methane Production (m^3 CH_4/kg-VSR)
Cattle	100	17.27	83.36	0.18
Calf	100	3.71	44.23	0.33

2.3. Scenarios of manure use in the waste management plan

2.3.1 Use of manure as organic fertilizer in plant production

Recycling and reusing manure generated in cattle farms as part of waste management not only prevents environmental pollution but also provides significant benefits for the economic and administrative sustainability of dairy farms. The manure collected from dairy cattle farms needs to be properly stored after fermentation before being used for plant production. Improper storage of these manures results in both environmental and visual pollution and causes the loss of up to 50% of their nutrients. This situation leads to yield losses when manures are reused for plant production, resulting in significant economic losses. Therefore, in the first scenario, when performing plant production calculations, it is necessary to accurately determine the capacities of the liquid manure tank and the solid manure storage tank (Anonymous, 2017).

In the study, under the scenario of using manure from 24 selected dairy farms for plant production purposes, the liquid manure tank and solid manure storage capacities were determined using equations 1, 2, 3, 4, 5, 6, and 7 (Anonymous, 2016; Anonymous, 2025b).

$$TLMV = NA \times LMA \times SP \quad (1)$$

$$WWW = TLMV \times 0.01 \quad (2)$$

$$SCV = MSA \times AG \quad (3)$$

$$RV = MSA \times ARDTP \quad (4)$$

$$TLMTV = TLMV + WWW + SCV + RV \quad (5)$$

$$TSMV = NA \times SMA \times SP \quad (6)$$

$$TSMSV = TSMV + SCV \quad (7)$$

Where; TLMV Total liquid manure volume (m^3), WWV: Washing water volume (m^3), SCV: Security clearance volume (m^3), RV: Rainfall volume (m^3), TLMTV: Total liquid manure tank volume (m^3), TSMV: Total solid manure volume (m^3), TSMSV: Total solid manure storage volume (m^3), NA: Number of Animals (number), LMA: Liquid manure amount (m^3/week), SP: Storage period (weeks), MSA: Manure storage area (m^2), AG: Air gap (m), ARDTP: Average rainfall during the storage period (mm), SMA: Solid manure amount (m^3/week).

After manure from livestock farms undergo fermentation during storage, it becomes suitable for use in plant production. The amount of manure stored in storage that can be applied to fields per hectare for plant production purposes, and the usable land sizes in the Bursa region, were determined using equations 8 and 9.

$$\mathrm{MAA} = \frac{H}{Y} \tag{8}$$

$$\mathrm{LSA} = \frac{\text{Total amount of manure (tons)}}{\text{Manure application amount } \left(\frac{\text{tons}}{\text{ha}}\right)} \tag{9}$$

Where: H: The amount of N, P, and K to be applied per hectare on agricultural land (kg/ha), Y: N, P, K values of dairy cattle manure (kg/tons), MAA: Manure application amount (tons/ha), LSA: Land size where manure will be applied (ha)

2.3.2. Composting

In the second scenario, one method for using manure obtained from livestock farms is composting. Composting is the decomposition of manure by microorganisms under suitable conditions (ideal C/N ratio, moisture, oxygen, and temperature). To prevent odor formation and spoilage in the compost mixture and to achieve high yield, the ideal C/N ratio should be 25-30, and the ideal moisture content should be 50-60%. Equations 10 and 11 were used to determine the modifiers and substance content amounts to be used in the compost content (Öztürk, 2017; Anonymous, 2021; Kumaş et al., 2024).

Calculation based on moisture content

$$x = \frac{\mathrm{nb-N}}{\mathrm{N-na}} \tag{10}$$

Calculation based on the C/N ratio

$$x = \frac{\%\mathrm{Nb} \times (\mathrm{R-Rb}) \times (1-\mathrm{nb})}{\%Na \times (Ra-R) \times (1-na)} \tag{11}$$

Where, x: amount of substance a (modifier) required per kg of substance b (manure) (kg), na, nb: moisture content (%) of substances a and b (manure and modifier), respectively, N: desired moisture content in the compost mixture, %Na, Nb: nitrogen percentage (%) of substances a and b (manure and modifier), respectively. R: desired C/N ratio in the compost mixture, Ra, Rb: C/N ratio of substances a and b (manure and modifier), respectively.

2.3.3. Biogas production

A third scenario for the reuse of dairy manure within the scope of waste management is biogas production. Biogas is an energy source produced by the anaerobic fermentation of animal manure. Biogas is produced from various gas mixtures (CO_2, CH_4, H_2S, H_2O, H_2, N_2). The most used component for biogas production worldwide is cattle manure (Cestonaro et al., 2015; Gülen & Çeşmeli, 2012). The biogas potential for 24 dairy cattle farms examined in the study was calculated using equations 12, 13, 14, and 15 (Ekinci et al., 2010; Kaya & Öztürk, 2012; Görmüş, 2018; Yağlı & Koç, 2019; Kılıç Erikgenoğlu et al., 2023; Kaynarca et al., 2021; Coskun, 2025).

$$\mathrm{UMA} = \mathrm{AWC} \times \mathrm{NA} \times \mathrm{T} \times \mathrm{SMR} \times 365 \tag{12}$$

Where, UMA: Useful manure amount (kg/year), AWC: Amount of waste to be collected (kg/day.animal), NA: Number of animals (number), T: Usefull manure rate (%), SMR: Solid matter rate (%)

$$\mathrm{Mmethane} = \mathrm{FG} \times \mathrm{VSR} \times \mathrm{MM} \tag{13}$$

$$\mathrm{Q} = \mathrm{Mmethane} \times \mathrm{Hmethane} \tag{14}$$

$$\mathrm{E} = \mathrm{Mmethane} \times \eta\mathrm{e} \times \mathrm{W} \tag{15}$$

Where; M_{metan}: Total annual methane amount (m^3/year), VSR: Volatile solids ratio (%), MM: Amount of methane obtained from 1 kg VSR, E: Annual electricity production of CHP engine (MWh/year), Q: Energy equivalent of methane gas (MJ/year), $H_{Methane:}$ Heating value of methane gas (MJ/m^3) (The thermal energy value of methane gas has been taken as 36 MJ/m^3 based on the literature), W: kWh equivalent of methane gas (kWh/m^3) (The energy value of methane gas in kWh has been taken as 10 kWh/m^3 based on the literature), ηe: Electrical efficiency of the CHP engine (Due to the efficiency of the motors used in electricity generation being accepted as 35% in the literature, the ηe value has been taken as 0.35) (Blas, 2006; Görmüş, 2018; Yağlı & Koç, 2019; Coskun 2025).

2.4. Statistical Analysis

The 24 dairy cattle farms where the study was conducted were divided into three groups based on their capacities. In similar studies found in the literature, dairy farms are divided into 4 different groups: 1-10, 11-50, 51-100, and ≥101 (Öztürk & Sipahi, 2021). However, in this study, the last 2 groups were combined because the capacities and distributions of the selected businesses were also considered. The necessary information regarding the groupings is presented in Table 4. Analysis of variance was applied to assess the significance of parameters calculated in the study for livestock farms, divided into groups, including storage capacities, land sizes where manure is applied in plant production, compost, and biogas potential. Additionally, the effect size indicator (eta-squared - η^2) of capacity-based differences has been calculated. Statistical analysis was performed using SPSS 29 software.

3. Results and Discussion

3.1. Waste management plan

A general waste management plan was developed to manage waste generated by dairy farms included in the study. Various scenarios for the reuse and disposal of all waste generated by the farms, including manure, paper, plastic packaging, and liquid waste, were included in the waste management plan. The rapid disposal of hazardous waste is planned. While only recycling options are included in the waste management plan for manure management, small quantities of manure generated in environments where sick animals are kept and that encounter foreign matter will be disposed of quickly. Table 5 presents the waste management plan for dairy farm waste.

Table 4. Information on the grouping of dairy farm cattle

Group	N (Number of Animlas)	Number of Dairy Cattle Farms	Distribution Ratio of Dairy Cattle Farms (%)
Small	0-10	7	29
Medium	11-70	11	46
Large	71-225	6	25

Table 5. Waste management plan created for dairy cattle farms

Waste Type	Waste Code*	Waste Content	Waste Management Method	Explanation
Solid Waste	02 01 06	Animal manure, urine, and dung	Recycling operations	Use for plant production purposes
	02 01 06	Animal manure, urine, and dung	Recycling operations	Use in composting
	02 01 06	Animal manure, urine, and dung	Recycling operations	Use as biogas
Liquid Waste	02 01 06	Flowing liquids (Dangerous)	Disposal procedures	Disposal of hazardous liquids
	02 01 06	Flowing liquids (non-hazardous)	Recycling operations	Recycling of non-hazardous liquids
Paper Packaging	15 01 01	Paper or cardboard packaging	Recycling operations	Regular storage and recycling of packaging
Plastic Packaging	15 01 02	Hazard-free packaging	Recycling operations	Regular storage and recycling of packaging
	15 01 10	Packaging containing hazardous material or its residue	Disposal procedures	Disposal of packaging without storage

*Taken from the Republic of Türkiye Ministry of Environment, Urbanization and Climate Change Waste Management Regulation (Anonymous 2015).

The meticulous implementation of waste management practices on dairy cattle farms is crucial to the health of the environment, people, and animals. In this context, it is necessary to raise awareness among employees working on animal farms. Furthermore, having dedicated staff responsible for waste management is essential to the system's healthy operation. A waste management template, understandable to everyone at the farm, is planned to be displayed in visible locations. The waste management template created for dairy farms is shown in Figure 3.

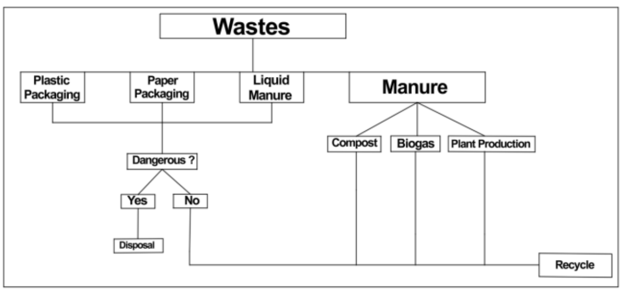

Figure 3. Waste management plan for dairy farms

3.2. First scenario: plant production calculations

The manure generated on dairy cattle farms, which falls within the scope of the study, will be separated into solid and liquid components using a separator. For this reason, two different manure storage capacity calculations were carried out, ideal for all dairy farms: solid and liquid. Considering that the manure obtained from dairy cattle farms will not be used in agricultural production during the winter months, and considering the initial investment costs and land requirements. It was planned that the manures would be stored for a period of six months; therefore, the calculations were made with this period in mind. In dairy cattle farms, solid manure storage is generally constructed at heights of 2-5 meters, while liquid manure storage tanks are built at heights of 3-6 meters (Olgun, 2011). Based on the literature and equipment requirements, the storage height for solid and liquid manure has been set at 4 m in this study. The manure storage facilities are designed as open-topped reinforced concrete tanks for liquid manure and as enclosed reinforced concrete structures with leak-proof floors for solid manure.

The ideal manure storage and tank capacities calculated for all dairy cattle farms in the study are given in Figure 4.

a)

b)

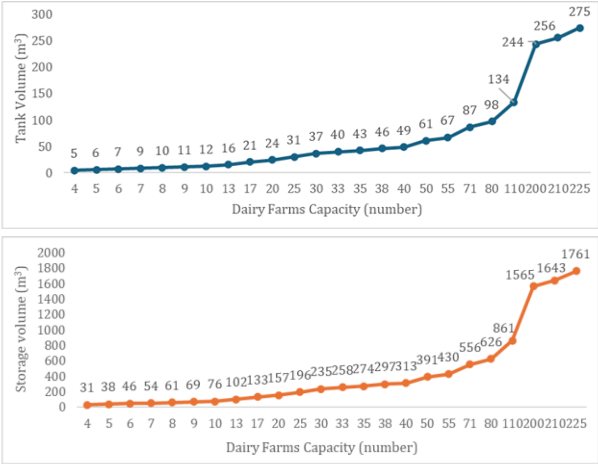

Figure 4. Ideal storage capacities for dairy farms. (a) Liquid manure (b) Solid manure

In the study, the ideal liquid manure tank capacity on the farm was approximately 5 m^3, serving four animals, while the ideal solid manure tank capacity was approximately 31 m^3. As the number of animals on the farm increases, so does the capacity of the manure storage and tanks. In this context, the dairy farm with the highest capacity, housing 225 animals, had solid and liquid manure storage capacities of 1,761 m^3 and 275 m^3, respectively. On large-capacity dairy farms, there is a need for land to construct such large manure storage facilities and for the mechanization investment required to facilitate loading and unloading operations during the operational phase.

Altınbilek and Kızıl (2019) determined the liquid tank volume to be 180 m^3 for a 90-day storage period in a dairy cattle farm with a total of 162 animals, 100 of which were milking animals, while the solid manure tank volume was determined to be 1,032 m^3. Kılıç et al. (2018) determined the lagoon volume in which liquid manure would be stored as 2,775 m^3 for a 180-day storage period in a dairy cattle farm with 1,000 animals. In their studies, they determined that 1,050 tons of solid manure would be produced monthly and stored in 6 manure piles, each with a volume of 141 m^3. The results of these studies in the literature show parallelism with the storage capacities determined for cattle farms with similar capacities in our study.

The statistical analysis comparing dairy cattle farms and the ideal liquid and solid manure storage is presented in Table 6. When the differences in liquid and solid manure storage volumes were examined by farm group, they were found to be significant ($p<0.05$). Especially since the storage capacity of newly established small-capacity cattle farms is sufficient, they can be constructed in a simpler, lower-budget manner, whereas large-capacity cattle farms, due to their very large storage capacity, should be more detailed and higher-budget. This statistical analysis provides an important criterion for economic sustainability, in proportion to dairy farms' capacities, by correctly selecting storage volumes. When looking at the effect size of capacity-based differences, an eta-squared value above 0.14 is considered a 'large effect' in the literature (Cohen, 1988). In this context, the eta-squared value for the differences in the capacities of manure storage facilities in the study was 0.741. This value indicates that capacity differences in cattle farms have a significant impact on storage requirements. In small-capacity dairy cattle farms, liquid manure tanks have an average volume of 8.57 m^3, while solid manure storage tanks should have an average volume of 53.57 m^3. There is approximately a 21.5-fold difference between the liquid and solid manure storage capacities of large and small capacity cattle farms. When comparing the storage capacities of large and medium-capacity cattle farms, there is approximately a 4.5-fold difference. Given this situation, it is not particularly challenging to allocate storage space in such small-capacity dairy farms.

Table 6. Statistical analysis of groups of dairy cattle farms and ideal manure storage

Storage Type	Group	N	Average*	Standard Deviation	Min.	Max.
Liquid	Small	7	8.57^c	2.63	5	12
	Medium	11	39.54^b	16.05	16	67
	Large	6	182.33^a	85.26	87	275
Solid	Small	7	53.57^c	16.35	31	76
	Medium	11	253.27^b	103.13	102	430
	Large	6	1,168.66^a	547.25	556	1761

* Means expressed with different letters are statistically significant ($P<0.05$).

However, on large-capacity dairy farms, a large land area of 300 m^2 is required, especially since the average solid manure storage volume is 1,169 m^3. The required land size is easier to obtain for newly established dairy farms, but especially for existing dairy farms, acquiring new land within the current operations and constructing on it is quite challenging from an agricultural management perspectiveThe total amount of manure from all dairy farms in the study, the manure application rates per hectare, and the land area that can be fertilized per farm have been determined. As a result of the calculations, approximately 59 tons of manure are obtained annually from the dairy cattle farms with the smallest capacity. In the highest-capacity dairy farms, approximately 3,367 tons of manure are produced annually. To meet the soil's N, P, and K needs, 38, 142, and 50 tons/ha of manure must be applied, respectively. The use of 142 and 50 tons/ha of manure to meet the soil's P and K needs results in nitrate pollution due to excess N introduced. This situation causes environmental impacts, including groundwater pollution, decreased soil fertility, increased soil salinity, and reduced product quality (Cüre, 2022). Therefore, it has been decided to apply 38 tons/ha of manure and supplement the missing soil nutrients (P and K) with chemical fertilizers. The use of these manures in plant production significantly reduces dependence on chemical fertilizers and, by integrating animal production with agriculture, makes agricultural management more economical and environmentally friendly. On average, all dairy cattle farms produce enough manure for 21.45 hectares of land. The amount of manure produced annually by the smallest capacity farm in the study could be used to fertilize 1.55 hectares of land, while the amount of manure collected annually from the largest capacity farm could be used on 89.11 hectares of land. However, in all dairy farms, there is a high land requirement to meet these manure quantities. Therefore, when farms lack sufficient agricultural land to meet their needs, selling these manures for waste management to achieve economic gain is an option. The annual amounts of manure to be obtained per dairy cattle farm and the size of land that can be fertilized are given in Table 7.

Kızılgöz (2012) stated that an average of 20-30 tons/ha of barnyard manure should be used to meet the soil's nutrient needs. Jing et al. (2016) conducted a study in Shandong Province, China, to monitor maize and wheat yields and soil nitrate levels when dairy cow manure was applied at different rates (0, 15, 30, 45, 60, 75 tons/ha). Their studies resulted in the highest efficiency and lowest environmental pollution rates, reaching 45 tons/ha. Dönmez Özyakar and Yılmaz (2021) conducted an analysis on capacity differences in the use of barnyard manure in plant production in 102 dairy cattle farms in Burdur province. In their studies, they identified animal farms with a capacity of 5-20 animals as Group 1 (60 dairy cattle farms), and dairy cattle farms with a capacity of more than 20 animals as Group 2 (42 dairy cattle farms). The study determined the average intensity of manure use in plant production as 7.3, 14.4, and 11.1 tons/ha for Group 1, Group 2, and all farms, respectively. They calculated the nutrient uptake rates of this barnyard manure used in plant production as 29.9%, 58.9%, and 45.2%, respectively, and concluded that uptake rates increase as animal capacity on farms increases. The value of 38 tons/ha we found in our study is within safe limits and consistent with similar studies in the literature.

Table 7. Annual manure amount and usable land size in dairy cattle farms

No	Capacity	Amount of Manure Collected (tons/year)	Size of Land to be Fertilized (ha)
1	4	58.68	1.55
2	5	73.35	1.94
3	6	88.02	2.33
4	7	102.69	2.72
5	8	117.37	3.11
6	9	132.04	3.50
7	10	146.71	3.88
8	13	194.51	5.15
9	17	254.36	6.73
10	20	299.24	7.92
11	25	374.06	9.90
12	30	448.87	11.88
13	33	493.761	13.07
14	35	523.68	13.86
15	38	568.57	15.05
16	40	598.49	15.84
17	50	748.12	19.80
18	55	822.93	21.78
19	71	1,062.33	28.12
20	80	1,196.99	31.69
21	110	1,645.87	43.57
22	200	2,992.49	79.21
23	210	3,142.12	83.17
24	225	3,366.55	89.11

Statistical analysis of the relationship between livestock farm groups, the amount of manure to be collected from the farms, and the size of the land that can be fertilized is given in Table 8. While there is a 4.65-fold difference in the required land area for fertilization between small-medium and large-medium capacity enterprises, there is a 21.75-fold difference in land requirements for large- and small-capacity cattle farms. The analysis shows cattle farm capacities have a significant impact on the land requirements (η^2 = 0.741). Additionally, it was determined that the amount of manure produced on dairy cattle farms and the size of the land on which this manure can be applied were statistically significant parameters among farm groups (p<0.05). Driven by these statistically significant requirements of large-capacity dairy farms, this provides an additional source of economic income for dairy farms that do not have such large land areas by selling the excess manure produced.

Table 8. Statistical analysis between livestock farm groups and the amount of manure to be collected from the farms, and the size of the land that can be fertilized.

Parameters	Group	N	Average*	Std. Deviation	Min.	Max.
Amount of Manure (tons)	Small	7	102.70[c]	31.69	59	147
	Medium	11	484.24[b]	197.63	195	823
	Large	6	2,234.83[a]	1,046.59	1062	3367
Size of Land to be Fertilized (ha)	Small	7	2.72[c]	0.84	2	4
	Medium	11	12.82[b]	5.23	5	22
	Large	6	59.15[a]	27.70	28	89

* Means expressed with different letters are statistically significant (P<0.05).

3.3. Second scenario: composting calculations

In the study, calculations were performed using manures obtained from dairy farms for composting as a second scenario. As a result of the calculations, the optimal mixing ratio was achieved with sawdust as the modifier, which had a C/N ratio of 27 and a moisture content of 56%. The proportions of compost mixtures are given in Table 9.

Table 9. Ratios of different compost mixtures

Mixtures	C/N	Moisture (%)
Manure and rice husk	27	51
Manure and sawdust	27	56
Manure and straw	27	43

The compost maturation period at the dairy farm is 30 days. After this period, the mixture is planned to be stored for 60 days before moving on to the application phase. It has been calculated that 2.17 kg of sawdust modifiers should be used for one kg of manure in the compost mixture. Due to their high volume-to-weight ratio, sawdust modifiers constitute a large portion of the total mixture volume. This situation creates a high land requirement for storing sawdust before composting and the mixture after composting. While the smallest dairy farm in the study produced 1.28 m^3/day of compost mixture, the largest produced 73.68 m^3/day. The daily compost mix potential for all dairy farms is given in Figure 5.

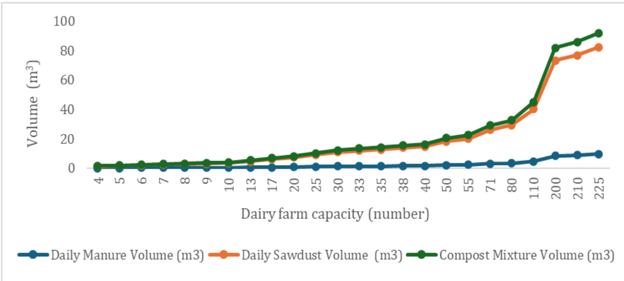

Figure 5. Daily compost mix potential for all dairy farms

There are many composting studies in the literature that use animal manure and various modifiers. Öztürk (2017) achieved the ideal compost mixture with a C/N ratio of 29 and 55% moisture content on a livestock farm with a capacity of 4,213 cattle, using manure and sawdust in a 1.4:1 ratio. The company has determined its composting and storage capacities to be 590 m^3/day and 14,160 m3, respectively. Kılıç et al. (2018) tested the effect of different regulatory agents on manure collected from a dairy cattle farm with a capacity of 1000 animals and identified the most ideal compost mixture ratios using the manure + rice husk combination. The researchers determined that the compost mixing capacity of the dairy farm where they conducted their study was 392 m^3/day. Özbek and Uçaroğlu (2022) conducted a study to obtain a compost mixture with optimal ratios of manure from three types of livestock farming (cattle, horses, and chickens), along with sunflower stalk modifiers. In their studies, they used manure and modifiers in a 4:1 ratio. The study determined that the combination of dairy cow manure and sunflower stalks provided optimal conditions, with a temperature of 58.7 °C and a C/N ratio of 22.4. All these studies, consistent with our research, show that by combining cattle manure with various regulatory agents in appropriate proportions, a high-quality compost mixture can be obtained under optimal conditions.

All dairy farms within the scope of the study (24 dairy farms, comprising 1,301 animals) have a total compost mixture potential of 425.74 m^3/day. Approximately 80% of the total amount of compost mixture is owned by large-capacity dairy farms (6 dairy farms). Volume calculations were performed for the area where the compost mixture will be stored during the maturation period and for the areas where it will be stored after maturation. On small-capacity dairy farms, maturation and storage areas have average capacities of 33.72 m^3 and 67.43 m^3, respectively. In contrast, medium and large-capacity dairy farms have volumes ranging from approximately 100 m^3 to 2,200 m^3. This clearly shows that for dairy farms with small capacities, the facility is manageable and requires fewer infrastructure investments, whereas for dairy farms with large capacities, developed infrastructure and a large land area are required. The maturation area and storage volume sizes of all dairy farms are given in Figure 6.

The statistical analyses used in the compost production calculations are presented in Tables 10 and 11. To determine the significance of all these calculations for compost production relative to the operating capacity, analysis of variance was applied. It was determined that there were statistically significant differences ($p<0.05$) in capacity, compost potential, compost maturation areas, and storage volumes among livestock farms. It has been determined that the capacities of dairy cattle farms have a significant impact on the capacities of compost maturation and storage areas ($\eta^2 = 0.741$). In large and small dairy farms, there is an approximately 21-fold difference in the required compost storage areas. This situation indicates that the method can be used with minimal land use and labor on small-capacity dairy farms, but on large-capacity dairy farms, commercial-sized structures are required. This situation has particularly highlighted the need for substantial investment in newly established large-capacity dairy farms.

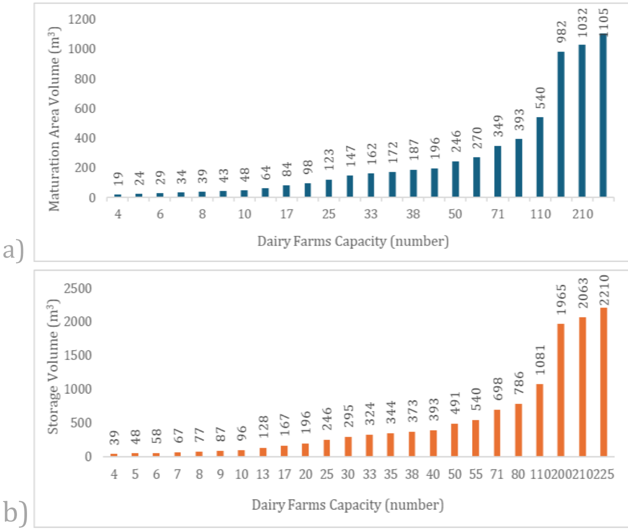

Figure 6. Compost area capacities for dairy farms. (a) Maturation area (b) Storage

Table 10. Statistical of the relationship between animal capacity, compost maturaion, and storage area volume.

Parameters	Group	N	Mean*	Standard Deviation	Min.	Max.
	Small	7	33.71c	10.42	19	48
Maturation Area (m^3)	Medium	11	159.00b	64.83	64	270
	Large	6	733.50a	343.54	349	1,105
	Small	7	67.43c	20.68	39	96
Storage Area (m^3)	Medium	11	317.91b	129.64	128	540
	Large	6	1,467.17a	686.93	698	2,210

* Means expressed with different letters are statistically significant (P<0.05).

Table 11. Statistical analysis of animal capacity and composting potential.

Parameters	Group	N	Mean*	Standard deviation	Min.	Max.
	Small	7	281.00c	86.41	161	401
Amount of Compost (tons)	Medium	11	1,324.82b	540.64	532	2,251
	Large	6	6,112.83a	2,863.19	2,906	9,210

* Means expressed with different letters are statistically significant (P<0.05)

3.4. Third scenario: biogas calculations

One method for reusing manure from dairy farms is to produce biogas. In this context, annual manure production from 24 dairy farms was used to calculate the farms' energy production. While approximately 70% (1,261,835.49 kWh) of the total energy to be produced with biogas from dairy farms is realized from large-capacity dairy farms, dairy farms with small capacities meet only 4% (67,663.61 kWh) of the total potential. As a result of the analysis, the relationship between the capacity differences among dairy cattle farms and their biogas production potential was statistically significant (P<0.05), and an eta-squared value of 0.741 was reached. This situation shows that differences in the capacity of dairy cattle farms have a significant impact on their biogas production potential. In this context, on large-capacity dairy farms, there is potential to generate additional economic gains through external sales in addition to meeting internal energy needs with biogas. However, the energy produced by small-scale dairy farms remains insufficient for in-house applications. Table 12 presents a statistical analysis of the average annual biogas production potential for dairy cattle farms, grouped by capacity.

Table 12. Statistical analysis between animal capacity and biogas production potential.

Parameters	Group	N	Mean	Standard deviation	Min.	Max.
Methane Production (m^3-CH_4/year)	Small	7	2,762	852	1,578	3,945
	Medium	11	13,022	5,315	5,231	22,130
	Large	6	60,087	28,145	28,568	90,533
Energy Value (MJ/year)	Small	7	99,424	30,683	56,814	142,034
	Medium	11	468,799	191,324	188,310	796,695
	Large	6	2,163,147	1,013,216	1,028,460	3,259,205
Electricity Value (kWh/year)	Small	7	9,666	2,983	5,524	13,809
	Medium	11	45,578	18,601	18,307	77,556
	Large	6	210,306	98,507	99,989	316,867

a-c Means expressed with different letters are statistically significant (P<0.05).

The biogas potentials determined for all operations included in the study are given in Table 13. Twenty-four dairy farms (1,301 animals) in the Bursa Region have the potential to generate 18,308,853 kWh of electricity annually. There are many studies in the literature similar to this one, in which biogas potential is calculated using animal manure. In their study, Salihoğlu et al. (2018) determined that if the manure from the 512,487 head of cattle and 991,521 head of small ruminants in Balıkesir province were used in biogas production, 389,233,320 kWh of electricity could be generated annually. Their studies indicated that a very high percentage (91%) of this production would come from cattle manure, while a lower percentage (19%) would come from small ruminants' manure.

Yağlı and Koç (2019) determined that if the manure obtained from all the livestock (3,062,992 head) in Adana province in 2018 were used in biogas production, the amount of energy that would be produced annually would be 3,181,227 GJ. They concluded that approximately 89.11% of the total energy produced, amounting to 2,834.854 GJ, could be obtained from cattle manure. Hacısalihoğlu (2023) calculated the biogas production potential of Karacabey district of Bursa province as 121,146, 218,790, and 187,345 GJ/year, respectively, taking into account the cattle population in 2019, 2020, and 2021. Coskun (2025) determined that if biogas production were carried out using the manure collected from the 221,665 head of cattle in Yozgat province in 2023, 26.06 GWh of electricity would be produced annually. They concluded that electricity generated by the biogas method could meet 2.54% of the city's annual electricity needs. All these studies, in line with our results, reveal that the use of cow dung in biogas production is not only a high-energy source but also an important resource for regional energy independence and sustainable waste management strategies.

3.5. Economic analysis

In the waste management of dairy cattle farms, there are initial investment and operating costs for implementing compost and biogas scenarios. For the establishment of a compost facility, the average initial investment costs for small, medium, and large-capacity dairy cattle farms are, respectively, 888,957 TL, 3,182,830 TL, and 11,911,037 TL. The payback period for the compost facility was 8.5 years for small-capacity dairy farms, while the shortest, 5.2 years, was achieved for large-capacity dairy farms. In all dairy farm groups, the short payback period indicates that the system is economically viable. The economic analysis for establishing a compost facility for dairy cattle farms is presented in Table 14 (Bilgili et al. 2011; Anonymous, 2026b).

Table 13. Biogas potentials were for all dairy farms included in the study

No	Capacity	Methane Production (m^3-CH_4/year)	Energy Value (MJ/year)	Electricity Value (kWh/year)
1	4	1,578.16	56,813.77	5,523.56
2	5	1,972.70	71,017.21	6,904.45
3	6	2,367.24	85,220.65	8,285.34
4	7	2,761.78	99,424.10	9,666.23
5	8	3,156.32	113,627.54	11,047.12
6	9	3,550.86	127,830.98	12,428.01
7	10	3,945.40	142,034.42	13,808.90
8	13	5,230.82	188,309.63	18,307.88
9	17	6,840.31	246,251.06	23,941.08
10	20	8,047.42	289,707.13	28,165.97
11	25	10,059.28	362,133.91	35,207.46
12	30	12,071.13	434,560.69	42,248.96
13	33	13,278.24	478,016.76	46,473.85
14	35	14,082.99	506,987.48	49,290.45
15	38	15,290.10	550,443.54	53,515.34
16	40	16,094.84	579,414.26	56,331.94
17	50	20,118.55	724,267.82	70,414.93
18	55	22,130.41	796,694.60	77,456.42
19	71	28,568.34	1,028,460.31	99,989.20
20	80	32,189.68	1,158,828.52	112,663.88
21	110	44,260.81	1,593,389.21	154,912.84
22	200	80,474.20	2,897,071.29	281,659.71
23	210	84,497.91	3,041,924.85	295,742.69
24	225	90,533.48	3,259,205.20	316,867.17

In the economic analysis of the biogas facility, the initial investment and operating costs are quite high. On small-capacity dairy farms, the initial investment for a biogas facility is 1,186,570 TL, whereas on large-capacity dairy farms, it rises to 8,426,825 TL. The economic analysis conducted to establish the biogas facility is presented in Table 15 (Yaldız & Sözer, 2005; Bilgili et al., 2011).

Table 14. Initial investment in the compost facility

Parameters	Dairy Cattle Farms		
	Small	Medium	Large
Ground (TL)	270398	1003487	3407640
Machine and Equipment (TL)	546573	1934212	7540963
Unexpected Expenses (TL)	71986	245132	962435
Operating Costs (TL/Year)	15480	92995	336830
Modifiers Material (TL/Year)	674148	3178672	14669983
Total initial cost (TL)	888957	3182831	11911038
Net Profit (TL/year)	104758	493599	2271812
Payback Period (years)	8.49	6.45	5.24

* The calculations have been made based on the current Central Bank of the Republic of Turkey exchange rate (1 € = 51.40 TL).

The revenue from the electricity generated by the biogas facility to be installed at the enterprises has also been calculated. The calculations were based on the current purchase price of 4.19 TL/kWh, determined by YEKDEM (Anonymous, 2026a). In this context, the annual profit from biogas in small-capacity enterprises is insufficient to cover the facility's annual operating expenses, rendering its economic viability infeasible. In medium- and large-capacity enterprises, the payback periods are approximately 20 and 14 years, respectively.

Table 15. Biogas facility investment costs

Parameters	Dairy Cattle Farms		
	Small	Medium	Large
Construction Cost (TL)	857684	1568964	6635459
Producer Costs (TL)	82041	375047	1210238
Generator Costs (TL)	26853	77042	361136
Measurement and Control Dev. (TL)	219992	219992	219992
Operating Costs (TL/Year)	43851	81448	284772

* The calculations have been made based on the current Central Bank of the Republic of Turkey exchange rate (1 € = 51.40 TL)

When evaluated for investment feasibility, the compost scenario is preferred for all dairy farm groups due to its short payback period and high economic returns. In the biogas scenario, while it is economically unsustainable for small-group dairy farms, the payback period for medium- and large-sized dairy farms is similar to the facility's lifespan.

In addition to producing large amounts of energy and generating economic gains, these scenarios are critical for ensuring environmental sustainability through positive effects, such as preventing soil and groundwater pollution and reducing the carbon footprint (Maj, 2022).

4. Conclusion

This study identified potential methods for managing waste from dairy farms of varying capacities and developed a comprehensive waste management plan. It was planned that all plastic, paper, and cardboard waste used on the farms, including feed, medicine, and similar materials, should be disposed of promptly if deemed hazardous; otherwise, they should be stored and recycled. To recycle manure, the largest waste source in livestock farming, calculations were carried out for three scenarios that dairy cattle farms could use: plant production, composting, and biogas. In addition to studies in the literature that focus on determining regional biogas potential, this study makes a scientific contribution by evaluating, on an animal-farm-by-animal-farm basis and in groups, the economic and environmental impacts of different waste management methods.

In the first scenario, calculations were performed for liquid manure tanks and solid manure storage to store manure for 6 months, during which fermentation occurs before the manure is reused for plant production. Among the dairy cattle farms examined in the study, the smallest-capacity farm requires a 5 m^3 liquid manure tank and a 31 m^3 solid manure storage tank. On dairy farms with large capacities, an average of 182 m^3 of liquid manure and a solid manure storage with a volume of 1,169 m^3 should be available. Considering the amount of manure obtained from all dairy farms, manure can be applied to an average of 2.72 hectares in small-capacity dairy farms, 12.82 hectares in medium-capacity dairy farms, and 59.44 hectares in large-capacity dairy farms.

In the second scenario, calculations were performed for composting, another method for reusing manure. After the composting process, 1.28 m^3/day of mixture is obtained from the dairy farm with the smallest capacity, and 73.68 m^3/day from the dairy farm with the highest capacity. The total daily amount of compost mixture produced across all dairy farms is 425.74 m^3. While the maturation area and storage area volumes for small-capacity dairy farms are 33.72 and 67.43 m^3 on average, respectively, these amounts increase to an average of 733.56 and 1,467.11 m^3 in large-capacity dairy farms, respectively.

In the third scenario, calculations were performed for the biogas method to produce energy from dairy cow manure. As a result of the calculations made within this scope, a total of 1,830,853 kWh of electricity can be produced annually with the manures obtained from the 24 dairy farms within the scope of the project. While 70% of this value comes from large-capacity dairy farms, 4% comes from small-capacity dairy farms.

In the study, an economic analysis was conducted for compost and biogas scenarios. On small-capacity dairy farms, the initial investment cost for a compost facility is 888,957 TL, and with an annual profit of 104,758 TL, the cost can be amortized over 8.49 years. On medium- and large-capacity dairy farms, the initial investment costs for compost facilities are amortized over 6.45 and 5.24 years, respectively, while for biogas facilities, these values are 20 and 14 years, respectively

When evaluated across all groups included in the study's scope, it is not economically feasible to use a biogas facility on small-capacity dairy farms because annual operating costs exceed annual returns. Therefore, the compost scenario is recommended for small-capacity dairy farms. For medium- and large-scale dairy cattle farms, the composting scenario is recommended because the payback period for biogas plant investments approaches the facility's physical lifespan. Furthermore, given economic gains and operational sustainability, composting yields higher profits.

In livestock farms, proper waste management planning not only has economic benefits but also makes a significant environmental contribution. The use of biogas on the cattle farms included in the study can make a positive contribution to mitigating climate change by preventing the emission of 523,100.97 m^3/year of methane into the atmosphere. In plant production, applying fertilizer within the legal limit (170 kg/ha) as part of the waste management plan provides environmental benefits by improving soil structure and reducing the carbon footprint, thereby offsetting the use of 370 kg of additional chemical fertilizer.

The study's results demonstrate that supporting waste management plans with appropriate policy development and sustainable livestock management strategies positively contributes to the economic and environmental impacts on dairy cattle farms. In this context, it is of great importance to increase the necessary incentives, training, and grant support from the government to promote the widespread adoption of methods such as composting and plant production on dairy farms. Additionally, the establishment of centralized facilities for the biogas method, which is economically unsustainable, especially for small-capacity dairy farms, should be encouraged. Implementing waste management systems through necessary legal inspections, along with incorporating these strategies into agricultural and livestock policies, provides strong support for establishing a robust circular economy and reducing dependence on imported chemical fertilizers.

Ensuring that waste management, a significant issue for livestock farms, is applicable to farms of all sizes, offers numerous benefits. This study concludes that implementing waste management in farms can prevent pollution and disease problems in and around the farm, and that high energy and economic profitability can be achieved through methods that reuse manure. This study has some limitations. Although the environmental benefits of implementing waste management plans are emphasized, a comprehensive analysis has not been provided. The economic analysis section of the study has been conducted based on the current region and economic conditions. In this context, regional differences and potential economic changes can affect the payback period and profitability. At the same time, economics analyzes and supports the establishment of a centralized biogas facility, which can be used especially by small-capacity cattle farms, and provides guidance for future studies.

Authorship contribution statement

U.K: Writing – original draft, Investigation, Methodology, Data collection and curation, Conceptualization.

İ.K: Writing – review & editing, Methodology, Project administration Validation, Supervision, Conceptualization.

Conflict of interest

The authors declare no conflicts of interest.

Ethical Statement

There is no need to obtain ethics committee approval for this study.

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