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Techno-Economic and Environmental Analyses of Digestate Treatment after Anaerobic Digestion Process

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ABSTRACT

In this study, the impact of digestate treatment after Anaerobic Digestion (AD) process in two scenarios is analyzed in the case of an industrial diary unit in the United States. The first scenario involves production of liquid fertilizer and compost, while the second scenario lacks such a treatment process. Aspen Plus is used to simulate the AD process and evaluate the general properties of biogas and digestate. The results of technical analysis show insignificant changes in the net power production from the CHP unit in Scenario 1. The economic analysis, however, indicates the necessity of digestate treatment for AD systems to be profitable. Furthermore, the results of environmental analysis indicate the mitigation of about 93.4 kilotonnes of greenhouse gas (GHG) emissions in Scenario 1, while AD in Scenario 2 saves only 12 kilotonnes of GHG emissions. In other words, digestate treatment has a more significant environmental impact than the power production and its profitability from CHP unit. The reason could be attributed to the enormous consumption of energy during the production of chemical fertilizers where the digestate treatment process (scenario 1) offsets the utilization of chemical fertilizers in the agriculture industry.

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1. INTRODUCTION

Global industrialization and population growth greatly contribute to higher energy consumption and environmental pollution. The dairy industry has great impact on the environment given its significant expansion throughout the world (David et al., 2021; Houston et al., 2014; Nandhini et al., 2022; Pham et al., 2022). Such an ever-increasing growth results from the income and population growth as well as changes in lifestyle and diet; in this respect, predictions indicate a global 2.5 % annual growth in animal waste (Lukuyu et al., 2019; Outlook for Biogas and Biomethane, 2020). Therefore, mismanaging the treatment of this type of waste causes a series of irreversible damages to water and soil. These damages range from creating environmental contaminations to dispersion of pathogens, accumulation of toxic ingredients, ammonia acidification, and Greenhouse Gas (GHG) emissions (methane (CH_4), oxide nitrogen, and ammonia (NH_3)) (Kozłowski et al., 2019; Thelen et al., 2010; Zeb et al., 2017). Farm-based management approaches can reduce these issues in dairies. Anaerobic Digestion (AD) is one of the most prominent ways based on environmental regulations to reduce the impacts the organic waste caused by different industries (Adiloğlu et al., 2012; Marin-Batista et al., 2020; Rajasimman et al., 2017). One of the main products of AD operation is biogas, which can be used as a fuel for energy production. AD has four stages and in each stage of operation, a group of microorganisms degrade primary substrates and leave them to the next stage of microorganisms (Adiloğlu et al., 2012). Any degradable and organic material can be used as the feedstock of AD. The composition and ingredients of feedstock significantly affect the efficiency of instruments producing the biogas (Outlook for Biogas and Biomethane, 2020; Vindis et al., 2009). Biogas as a product contains two major components: CH_4 and carbon dioxide (CO_2), which are the main causes of global warming with CH_4 consisting of 50 to 60 vol. % and CO_2 consisting of 20 % to 45 % (Karakurt et al., 2012; Moestedt et al., 2013). It is reported that CH_4 has 34 times more potential than CO_2 in the field of GHG emissions. Thus, incineration of CH_4 biogas and CO_2 generation from this phenomenon reduce the effect of GHG emissions of organic wastes (Flesch et al., 2011; Thi Nguyen et al., 2019). Based on the methane volume percentage, biogas Low Heating Value (LHV) varies between 16 to 28 MJ/m^3 (Outlook for Biogas and Biomethane, 2020).

However, AD cannot turn all of its feedstock into biogas and a by-product is produced in digester called digestate (Thi Nguyen et al., 2019). Digestate can be improved by various processes in which bio-fertilizers and composts are produced (Algapani et al., 2019). These products can be utilized in agriculture, aquaculture, and horticulture and their usage not only prevents the over-usage of chemical fertilizers that reduce the fertility of the soil. Further, it can reduce the

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amount of pesticides as well as carbon emissions from the agricultural industry (Ersek, 2021). Moreover, digestate treatment methods for producing compost and bio-fertilizer is a well-known process that satisfies the concept of the circular economy (D'Adamo et al., 2021; Rasapoor et al., 2020).

Due to their physical properties, organic components, and abundance, dairy manures are known as the best type of biomass and feed for biogas units, especially in developing countries (Kaparaju & Rintala, 2011). Carbohydrates, proteins, and lipids are the main compositions of dairy manures (Møller et al., 2004). This type of waste is very attractive due to high water content (acting as a solvent) and low price (Al Seadi et al., 2008). Implementation and simulation of AD is a scientific and complicated process. Hence, many studies have been carried out on the simulation of this process. Betwan et al. developed ADM1, which is a precise and thorough Aspen Plus model over the information, reactions, and kinetic calculations of AD (Batstone & Keller, 2003). Several researches have investigated the economic effects of using a digestate treatment process (Gebrezgabher et al., 2010; Herbes et al., 2020). However, a comprehensive analysis of the environmental aspects of using bio-fertilizers and the composts produced by AD of dairy manure as well as economic effects of the presence of a digestate treatment unit has not been conducted.

Hence, the aim of this study is to investigate the feasibility of integrated management of dairy waste produced in livestock farms and production of value-added streams, including biogas and digestate. Moreover, the economic and environmental impacts of using digestate for further usage are investigated, as well.

2. MATERIAL AND METHOD

2.1. Case study description

An industrial dairy farm is the proposed case study for the integrated management of livestock-made dairy manures. This farm is located in the United States and has 1932 livestock, including cattle and dairy cows. The average weight of cows is around 670 kg, and each one produces approximately 0.048 m^3 manure daily. The keeping system is based on free stalls and the flushed-water system, which consumes 0.01 m^3 of water per animal, is used for waste collection, washing, and sand scratching. It should be noted that before storing the wastes, solid-liquid separation is needed because the solid particles derived from the bed of livestock can create many problems during the pumping of waste and dislocation. Hence, their concentration through time can decrease the capacity of the waste storage system. Also, mechanical separators can facilitate the recycling of wastes and land applications. More information about this diary is illustrated in Table 1.

Table 1. Animal husbandry information

Total number of livestock (head)	1932
Kind of keeping and washing system	Freestall-flushed water system
Bed type	Sand
Daily manure produced per animal (m^3/day)	0.048
Water consumption by animal (m^3/day)	0.01
Yearly produced waste (m^3/year)	40900.4

2.2. Process design and scenarios

The Aspen Process (V10) design was studied in detail in our previous paper (Hosseinpour et al., 2022). Two scenarios are considered to find the effects of using a digestate treatment process. In Scenario 1, the digestate treatment process produces compost and liquid fertilizer, while in the second scenario, Scenario 2, such a unit is omitted (Figure 1). For both cases, there is a Combined Heat and Power (CHP) generation system that generates heat and electrical power from the biogas produced in digester, as well.

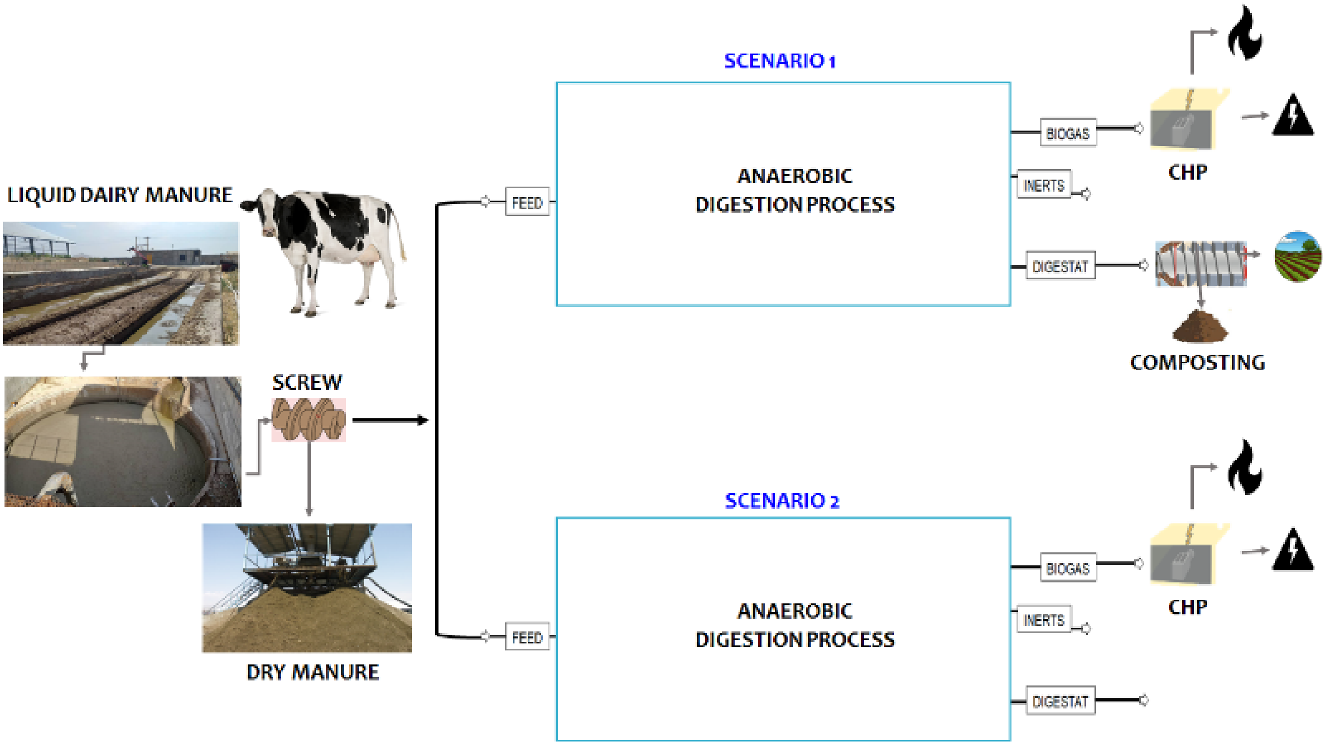

Figure 1. Aspen Plus model for the anaerobic digestion process

Feedstock characteristics, components, and materials in solid fraction are shown in Table 2 (Batstone & Keller, 2003; Ersek, 2021). Since the degradation of lignin is highly difficult and time-consuming, it is considered an inert component. Furthermore, process parameters of AD such as temperature, pressure, load rate, and retention time are illustrated in Table 2 (Pham et al. 2022). Temperature of the digester is in the thermophilic condition, which leads to better digestibility of the feedstock (Labatut et al., 2014).

Table 2. Characteristics of liquid manure and operation parameters of AD process

Liquid dairy manure characteristics	Unit of calculation	Amount
Total solids (TS)	Percentage of feedstock (%)	9.5 [7]
Volatile solid	Percentage of feedstock (%)	4.5 (Rico et al., 2011)
Carbohydrates (cellulose, hemicellulose, lignin, starch)	Percentage of total solids (% TS)	90.2 (Rico et al., 2011)
Fat	% TS	1.5 (Rico et al., 2011)
Cellulose	% TS	20.4 (Rico et al., 2011)
Hemicellulose	% TS	8.6 (Rico et al., 2011)
Glucose	% TS	25.7 (Rico et al., 2011)
Protein (Glycine)	% TS	8.3 (Rico et al., 2011)
Triolein	% TS	1.5 (Rico et al., 2011)
Others	% TS	35.5 (Rico et al., 2011)
Operational condition of the AD process		
Reactor temperature	°C	55 (Labatut et al., 2014)
Reactor pressure	atm	1
Hydraulic retention time	day	15
Load rate	Volumetric m^3 per day	112.056

Digestate treatment process and its impact on the economic situation of AD process are studied by modeling this section. During the digestion process, the majority of organic matter, especially nitrogen, is mineralized and is readily available for plants for their growth. In practice, the digestion rate of dairy waste is about 40 % (Al Seadi et al., 2008). The mineralization process involves the decomposition of carbon bonds and organic acids, resulting in a homogeneous digestate with enhanced nitrogen and phosphorus balance and a lower carbon-to-nitrogen ratio (Ali et al., 2020). Table 3 illustrates the amount of the biogas and digestate used in this research. Moreover, Table 4 shows the composition of the biogas and the digestate used in this research, as well. Biogas methane composition is in good agreement with the results from the experimental research conducted by Kaparaju et al. (Kaparaju et al., 2009) and the model developed by Kozlowski et al. (Kozłowski et al., 2019).

Table 3. Technical results of Aspen Plus model of the previous research

General parameters	Unit	Amount
Feedstock total mass	kilotonne/year	36.500
Biogas generation	million m^3/year	1.2
Digestate production	kilotonne/year	35.300

In the digestate treatment process, solid and liquid fractions of digestate are separated, and the effluent obtained from the AD process comes into the screw press machine for dewatering and separation. Non-Random Two-Liquid model (NRTL) is used as the fluid model in Aspen Plus simulation. The solid phase can be used as compost in agriculture and the liquid phase as the liquid fertilizer (de Baere, 2010). Figure 2 illustrates the digestate treatment process. After digestate production by the digester reactor, it enters a centrifugal pump, which is used for transporting digestate to the screw press unit.

Table 4. Biogas and digestate components and characteristics used for further steps

Compound	Composition (vol%)
Biogas	
CH_4	54
CO_2	37
NH_3	5
H_2O	0.9
H_2S	0.3
C_2H_5OH	0.4
H_2	0.2
Digestate	
Carbon dioxide	1
Glucose	4
Cellulose	1
Hemicellulose	0.6
Ethanol	0.8
Protein	0.1
Ammonia	0.1
Others	6

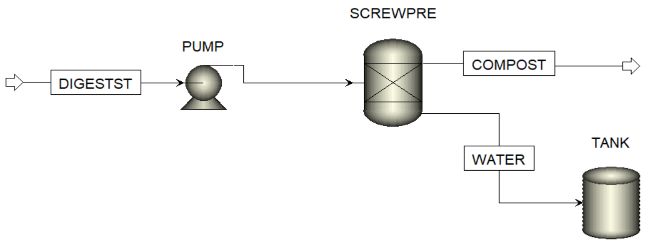

Figure 2. Aspen Plus model for the digestate treatment process (Scenario1)

Figure 3 illustrates the general concept of the CHP unit. In both scenarios, there is a CHP unit using the biogas derived from the digestion of liquid dairy manure and producing electricity and heat. In both scenarios of this research, the heat generated in the CHP unit is used for digester heating as well as other heating purposes in the diary complex. However, in the scenario involving digestate treatment, a portion of the electricity generated in the CHP unit is used for THE digestate treatment process, while the rest of electricity is sold to the general grid for further profitability. In the scenario without digestate treatment process, the entire electricity is sold to the general grid. To have a thorough analysis from the CHP unit, the catalog of the United States Department of Energy (U.S. DOE) is used for modeling the CHP unit (United States Department of Energy, 2016). For the CHP unit of this study, a reciprocating engine is chosen for its operation.

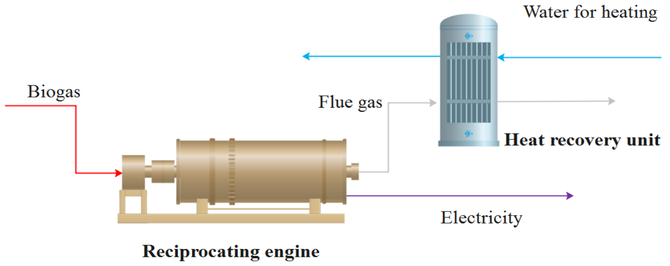

Figure 3. Structure of the combined heat and power unit

2.3. Economic analysis

There are two scenarios considered in this research. In the first scenario, digestate goes through the treatment process, which has been modeled in the previous section of this research. In the second scenario, digestate is untreated and not used for the economic aspect of AD. It is notable that the interest rate is considered to be simple and will not change by the year of operation. To provide the required energy for livestock by the AD process, viable business models are identified with stakeholder consultation. The stakeholders are research organizations, industry, financial institutions, and the government. The heat generated by the CHP unit is used for heating purposes such as maintaining the digestion temperature constant and meeting the thermal needs of the livestock. Table 5 shows the elements of the business model used in this research.

In the case of economic analysis in this research, Seider et al (Seider et al., 2016) considered different economic parameters based on sets of valuable sources and reasonable assumptions concerning economic issues. There are two categories for costs: Capital costs and production costs. There are 4 parameters considered for the capital costs. Direct Permanent Investments (DPI), Total Depreciable Costs (TDC), Total Permanent Investments (TPI), and Total Capital Investments (TCI). All of these parameters are calculated in which the described economic parameters are calculated as a requirement for further parameters to determine TCI for both scenarios. DPI of CHP unit is calculated based on the catalog of U.S. DOE, which covers economic issues of CHP unit ((United States Department of Energy, 2016) in the first step. It is assumed that it takes 50 % of this category of AD operations based on the previous research by Morelli et al. (Morelli et al., 2019). Therefore, DPI of the AD process can be calculated. Since the first scenario involves a digestate treatment unit, DPI of this part has to be calculated and be added to DPI of the AD process whose method of calculation has already been explained, as well. DPI of the digestate treatment unit was calculated by Seider et al. (Seider et al., 2016). Following the calculation of DPI for both scenarios, TDC, TPI, and TCI in both scenarios were calculated and the method of calculation for each element is shown in Table 6.

Table 5. Definition of the business model

Investment	Digester-CHP unit-separator (screw press)
Input	Liquid dairy manure
Output	Electricity-heat-compost-liquid fertilizer

For calculating the production costs of both scenarios, different sets of parameters are considered including maintenance costs, operation costs, depreciation, general expenses, overhead for maintenance and operation cost, and property taxes. Since the first scenario involves an additional unit compared to the second scenario, it requires higher production costs. In the first scenario, there are five operators who work in the complex, while in the second scenario, only 3 operators are present for the AD complex. In the next part of the economic analysis, the sources of income for both scenarios are shown. It is notable that there will be no source of income from compost and liquid fertilizer that can be produced from digestate separation unit in the second scenario. In the next part of the analysis, economic rates including tax rate, inflation rate, and interest rate are required for calculating the level of profitability for both scenarios. Levels of income in each year of operation for both scenarios are deduced by the production costs according to yearly costs of the AD complex. Finally, payback period is measured for both scenarios by considering the effects of the TCI, the results regarding the incomes and production costs of the AD complex, and economic rates. Table 6 presents the calculation method for the production costs, sources of income, and profitability indicators. The basis of the economic assumptions and calculations was derived from the study of Seider et al., in which economic issues were adequately covered (Seider et al., 2016).

Table 6. Parameterization of the business model (Seider et al., 2016)

Cost category	Parameter	Unit	Quantity
Capital costs	DPI	$	-
	TDC	$	115 % of DPC

	TPI	$	107 % of TDC
	TCI	$	115 % of TPI
Production costs	Maintenance cost (M)	$/year	4.5 % of TDC
	Operation costs (O)	$/operator.h	5
	Power plant lifetime	year	25
	Depreciation	$/year	3.4 % of TDC
	General expenses	$/year	5.25 % of incomes
	Property taxes and insurance	$/year	2 % of TDC
	Operation & maintenance overhead	$/year	5 % of M&O
	Operation hour per year	h	7800
Sources of income	Electricity price	$/kWh	0.1
	Heating price	$/kWh	0.02
	Compost price	$ /tonne	70
	Liquid fertilizer price	$/tonne	60
Economic rates	Interest rate	%	5
	Inflation rate	%	4
	Opportunity cost rate	%	3
	Tax rate	%	25

2.4. Environmental analysis

As mentioned in the previous sections, the use of liquid bio-fertilizers and composts in agricultural activities contributes to the intensity of global warming. Therefore, environmental analysis is performed for both scenarios and the impacts of digestate use are considered in this research based on the review and study of valuable resources. However, for establishing a reasonable analysis, carbon emissions should be analyzed through different concepts. In this research, GHG emission savings in both scenarios are studied as in the following three categories:

1- Emission savings achieved by preventing methane emissions from methane use in CHP unit;

2- Prevention of using natural gas for CHP units; and

3- Prevention of emissions caused by producing organic fertilizers and reducing emissions from chemical fertilizer production.

Emission saving achieved by the prevention of methane emission is calculated on the basis that methane has 34 times greater impact than GHG effects (Demirel & Scherer, 2011) and that its incineration inside the CHP unit prevents any methane leak while emitting only CO_2 which is caused by methane incineration. The amount of emissions saved by CHP unit are calculated by the catalog of the U.S DOE for both scenarios (United States Department of Energy, 2016). Since the CO_2 emitted by the CHP unit is renewable unlike natural gas, it is considered as a section for carbon savings. Statistics indicate that 1.2 % of the energy consumption in the world is caused by fertilizer production industry (Ammonia Production: Moving towards Maximum Efficiency and Lower GHG Emissions, 2014). Moreover, 36.4 billion tonnes of CO_2 was emitted in 2019 from the sources that consume much energy (Tiseo, 2023). Additionally, 190 million tonnes (Mt) of fertilizers were consumed in 2019 (Fernández, 2021). Based on the above information, 2.298 tonnes of CO_2 was emitted by the production of chemical fertilizers and it formed the basis of evaluation of GHG emissions in regard to digestate for both scenarios. Although GHG emission from the use of organic fertilizers instead of chemical fertilizers in agriculture can be studied as well, only the emissions caused by activities in AD complex and their impacts are the main issues of this research because of several uncertainties regarding the use of chemical and organic fertilizers (Havukainen et al., 2018). Therefore, this case of investigation is not considered.

3. RESULTS AND DISCUSSION

3.1. General results

In the first step, the general parameters of the AD complex must be measured and then, be used for further required analysis. The amount of produced biogas and digestate effluent affects the scale of the CHP unit as well as economy. Table 7 presents the values of general parameters in this research. According to a report provided by the European Biogas Association, the solid phase accounts for about 8 % of total digestate (de Baere, 2010). This part demonstrates the validity of the Aspen Plus simulation.

Table 7. Technical results of the business model

General parameters	Unit	Amount
Electricity production	GWh/year	1.94
Heat production	GWh/year	2.6
Compost production	kilotonne/year	2.824
Liquid fertilizer production	kilotonne/year	32.476

3.2. Efficiency and power generation analysis

In this section, the economic evaluation of both scenarios is presented. In Scenario 1, investment costs not only increase but also reduce the amount of income that can be earned from electricity production. However, production of compost and liquid fertilizer can offset these points. For calculating the efficiency of CHP unit, the catalog presented by the U.S. Energy Department is consulted to ensure higher precision (United States Department of Energy, 2016). Figure 4a shows the efficiency levels for all parts of CHP unit. As anticipated, CHP enhances the level of efficiency in comparison to the mere power generation. In addition, considering the heating requirements of the dairy industry, the economic aspects of this industry have been improved by reducing or eliminating the need for purchasing natural gas.

It is important to consider that the screw-press unit consumes a portion of electricity generated in the CHP unit.

Figure 4b shows the net amount of electricity produced in the AD complex. Regarding the electricity consumption of the screw-press unit, the results indicate that the screw-press unit does not have a significant effect on the net amount of electricity production of AD complex.

3.3. Economic analysis

Figure 5a shows the impacts of adding a screw-press unit to the total capital costs of AD complex. Results show that the addition of a screw-press unit leads to a 20 % increase in the capital costs of the AD complex as total. However, this figure is not enough to meet the requirement of economic analysis.

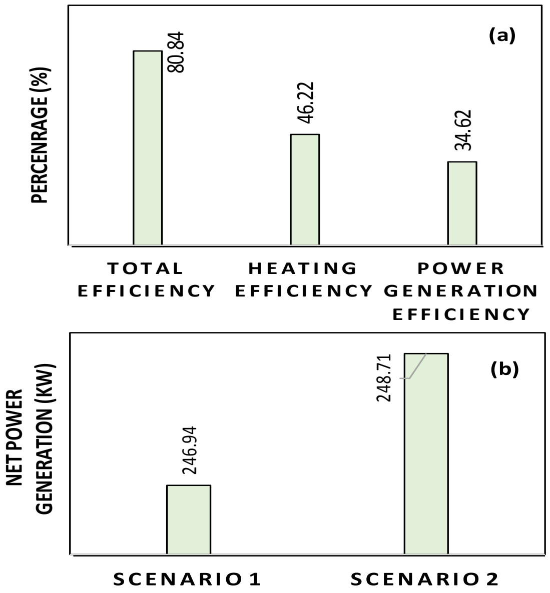

Figure 4. (a) The level of efficiency for the combined heat and power unit for both scenarios and (b) net power production for both scenarios

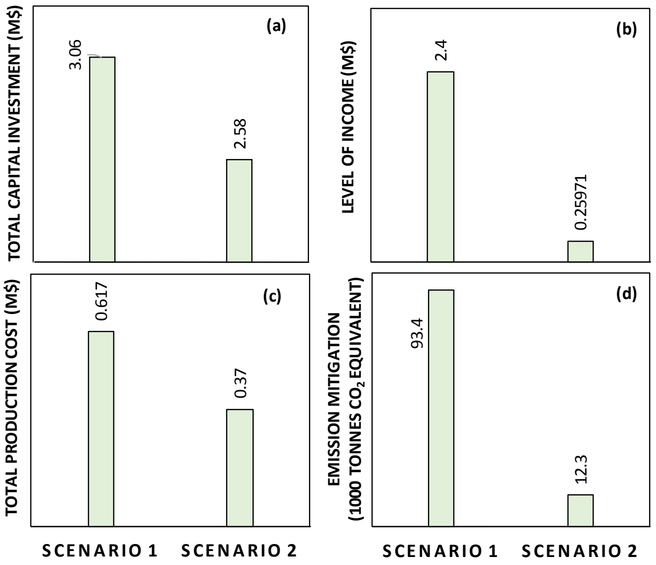

Figure 5. (a) Total capital investment (TCI), (b) level of income, (c) total production costs, and (d) Greenhouse gas emission per annual prevention of both scenarios

Figure 5b and Figure 5c illustrate the levels production costs and incomes of both scenarios. Although the figures show that use of a screw-press unit has a significant effect on the costs of production in AD complex, its positive impact on the incomes of the AD complex is far greater than its impact on the costs of AD complex. Ironically, these results indicate that the absence of a digestate treatment process and, consequently, lacking a stable income from such units cause a negative net economic outcome for the AD complex. However, the AD complex can use subsidies through carbon taxation programs and other governmental subsidies because of its role in reducing health impacts caused by dairy manure. Due to the benefit of the digestate treatment unit, it is profitable enough to eliminate the need for governmental subsidies. Therefore, using a digestate treatment process is of necessity for AD complexes to have an economic outcome for AD. Since incomes of the second scenario could not cover its production costs, the first scenario has another advantage in regard to profitability. However, the profitability of the first scenario is calculated. With the assumption of operation to the full potential of AD complex from the beginning of the operation, the payback period is 2.5 years for the first scenario, while the second scenario does not have a payback period since the level of incomes cannot cover the production costs. Results indicate that the use of a digestate treatment unit in AD complexes ensures profitability while reducing dependency on the governmental help.

3.4. Environmental analysis

AD enjoys various advantages in comparison to other treatment methods for organic-based materials. Its ability to kill pathogens present in the diary manure and the ability of methane for electricity generation are well-established concepts that prove AD efficiency in environmental issues. However, the use of the digestate treatment process and the production of solid and liquid fertilizer is the concept that facilitates further reduction of carbon emissions in the agriculture sector due to the prevention of chemical fertilizers that require energy production from fossil fuels. Figure 5d shows the carbon emission saving levels for different parts as already mentioned. Results indicate that the use of digestate treatment process has a far greater impact on GHG emission reduction than the CHP unit which uses biogas in both scenarios. The reason could be attributed to the production of fertilizers as an energy-intensive industry. Since much of the feedstock from AD turns into digestate, a considerable amount of fertilizer and compost is produced, which reduces the need for chemical fertilizers in agricultural industries (Ammonia Production: Moving towards Maximum Efficiency and Lower GHG Emissions, 2014).

4. CONCLUSIONS

In this research, the techno-economic performance of an AD unit for the treatment of a dairy farm was studied by selecting an industrial livestock unit as a case study using Aspen Plus as a simulation tool. Two scenarios were considered in which different effects of the use of digestate treatment process along the AD system were analyzed in the fields of electricity generation, economy, and environmental issues through these two scenarios to illustrate the true effects of such a unit in the AD process. AD process was implemented at a thermophilic temperature of 55 °C and pressure of 1 atm. According to the results, 3381 m^3 of biogas and 105 tonnes of digests were produced daily under specified operating conditions. In addition, the results of investigating the effects of the digestate treatment process application demonstrate that it does not reduce the net amount of electricity produced on a massive scale, while it significantly improves the economic and environmental aspects of AD systems. Results of this research indicate that the application of a digestate treatment process is necessary for the profitability of the AD complex and the usage of a digestate treatment process eliminates the need for subsidies for the profitability of this technology while reducing the tax burdens on citizens in the case of wastewater management processes. Moreover, while the usage of biogas in CHP systems improves the environmental aspects of the AD process by preventing methane emission, data analysis indicates that a digestate treatment process and the use of bio-fertilizers produced in this unit save 93.4 kilotonnes of GHG emissions by reducing dependence on chemical fertilizer production, which is an energy-intensive industry, while the CHP unit only saves about 12.3 kilotonnes of GHG emissions. Therefore, GHG saving in the scenario containing a digestate treatment unit for bio-fertilizer production is far superior to the one without such a unit. Moreover, the existence of this unit is crucial to an AD complex.

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NOMENCLATURE

GHG	Greenhouse Gas
AD	Anaerobic Digestion
CHP	Combined Heat and Power
DPI	Direct Permanent Investments
TDC	Total Depreciable Costs
TPI	Total Permanent Investments
TCI	Total Capital Investments

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