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Techno-economic assessment of digestate management for full-scale continuous dry anaerobic digestion plant

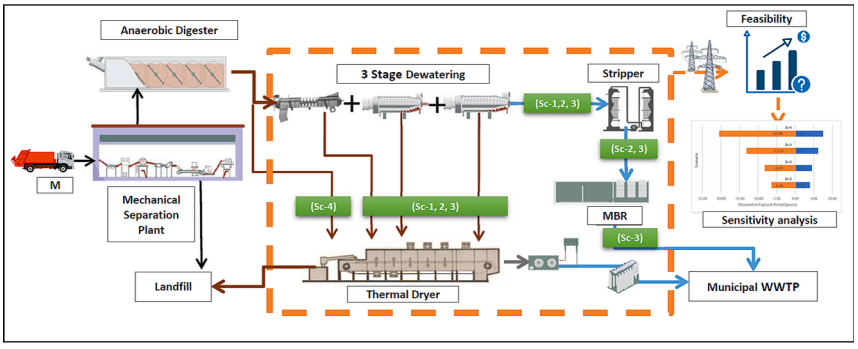
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HIGHLIGHTS

- Digestate treatment for a full-scale dry AD plant was economically feasible.
- CAPEX ranged from $4.2 to $9.8 million for 400 ton/day digestate management system.
- Base scenario had the lowest capital cost but highest NH_4-N in the effluent.
- Direct thermal drying had the highest operating cost of $2.0 million per year.
- Electricity price for 6 years payback in base scenario was found as 15.7 $cent/kWh.

GRAPHICAL ABSTRACT



ARTICLE INFO

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ABSTRACT

This study investigated techno-economic analysis of digestate management systems for a full-scale continuous dry anaerobic digestion plant treating organic fraction of municipal solid waste (OFMSW). A three-stage dewatering system was considered as the baseline scenario (Sc-1) whereas nitrogen removal unit (Sc-2), the incorporation of membrane bioreactor with nitrification downstream (Sc-3) and direct thermal drying of the digestate (Sc-4) were evaluated. The capital cost for the dewatering system with a cake dryer was $4.2 million. For Sc-2, NH_4-N load could be reduced by 60% and Sc-3 would allow for further reduction in COD and NH_4-N loads with capital cost of $5.2 and $9.1 million, respectively. To achieve an additional reduction in TN load, an investment of $9.8 million was required in Sc-4. Sc-1 had the lowest operation cost, consequently resulting in the highest income of $22.6/ton, whereas Sc-4 had the highest operation cost, resulting in the lowest income of $16.6/ton OFMSW.

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1. Introduction

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) on global warming, the global annual emissions must be reduced by at least 43 % by 2030 and to reach net zero by 2050 (IPCC, 2022). Among the available options, reducing greenhouse gas emissions (GHGs) by using organic waste as an energy source represents a proven and viable solution. Anaerobic digestion (AD) is an important technology for overcoming the current challenges involving the trade-off between consuming resources and producing energy (Sganzerla et al., 2021). In addition to promoting the circular economy concept the importance of AD for organic waste has increased from a policy-making perspective and is regarded as a reliable technology (Tyagi et al., 2018).

Analyzing the strengths and weaknesses of each type of AD is necessary to determine its most sustainable application (Lamolinara et al. 2022). AD of the OFMSW minimizes landfilling, reduces greenhouse gas emissions and enhances energy recovery efficiency from waste. However, the application of AD to OFMSW is still relatively limited due to issues faced such as high solids content, large particle size, slowly bio-degradable components and the waste's heterogeneous nature, which makes process control challenging. Furthermore, the contaminated feedstock may also make digestate management even more difficult by being unfit for direct land application or valorizing as compost (Tyagi et al., 2018). From the economic point of view, the implication of AD technology for OFMSW also requires high investment (Morin et al., 2010) and operation costs for the sustainable management of digestate (Kumar et al., 2024). In many cases, difficulties in the treatment or reuse of digestate limit the applicability of AD. Especially in the case of wet AD systems, the amount of liquid digestate is higher than dry AD systems due to the necessity of dilution water at the digester feeding. This makes the application of dry AD systems preferable technology for treating high solid content substrates. The rise in the popularity of continuous dry AD systems are also due to several advantages including lower reactor volume, simpler pre-treatment requirements, high biogas and energy production and less water use resulting in less liquid digestate generation (Chen et al., 2020). Additionally, new technologies like biopolymer production from dry AD plants are getting more attention even though conventional strategies currently have advantages regarding environmental performance (Rossi et al., 2022).

To fully explore the efficiency, it is critical to examine the techno-economic analysis (TEA) of the AD system that combines the technological and economic factors for the purpose to assess the feasibility, viability, and performance of a technology. TEA involves inventory inputs and outputs, assessing their associated impacts, conducting economic evaluations, and interpreting outcomes to help decision-making (Samer et al., 2020). TEA has been used in multiple studies to address different objectives in the field of AD, such as selecting appropriate AD technology, analyzing biogas plant sizes (Wang et al., 2018), evaluating the economics of energy recovery in different forms (Pasciucco et al., 2023), assessing biogas production from various substrates (Lamolinara et al. 2022), and evaluating residue digestate (Samer et al., 2020). More specifically, Vondra et. al. (2019) conducted a comparative TEA for vacuum evaporation of liquid digestate after separation, where they also compared alternative methods for condensate treatment and nutrient recovery. The air-stripping process of ammonia from WWTP sludge digestate was simulated by Alrbai (2024). However, full scale studies are needed to assess the treatment of digestate generated from the AD of OFMSW through a combination of in-situ and ex-situ steps to create an environmentally sustainable and economically viable solution.

The objective of this study was to identify the main pollutant parameters in the digestate and to conduct a TEA of different digestate treatment technologies to reach a final effluent that remained within the capacity limits of the central municipal wastewater treatment plant (WWTP) at the end of the discharged sewer line. Since the effluent after dewatering had an imbalanced carbon-to-nitrogen ratio for a biological nutrient removal system to be built within the mechanical–biological treatment (MBT) plant, a comparative economic assessment was carried out for three scenarios in addition to the baseline scenario which corresponded to the existing dewatering system in the full-scale plant. In the first additional scenario, the dewatering effluent was physio-chemically pre-treated in the MBT plant; in the second additional scenario, it was biologically treated in the MBT before discharge to the sewer line. In the last scenario, the digestate was thermally dried without dewatering, resulting in zero discharge to the sewer line. This study analyzed three years of field data capturing the performance of the dewatering system and effluent characteristics in a full-scale continuous dry AD plant treating OFMSW and nitrogen-rich co-substrates. The results of this study provide valuable guidance for regulatory authorities, planners, investors, and operators in developing technically and economically viable solutions for AD operations.

2. Materials & methods

2.1. Full-scale anaerobic digestion plant configuration

The study focused on a full-scale MBT plant located in the north-west part of Türkiye with a capacity of 1000 ton/day mixed municipal solid waste (MSW). In the facility, recyclable materials such as metal, plastic and paper are separated using manual and automatic separation. The separated organic fraction is fed to a continuous dry AD process consisting of three digesters each having 3000 m^3 volume and operated under mesophilic conditions. Approximately 10 ton/day chicken manure and 30 ton/day sludge from chicken slaughterhouse WWTP as co-substrates are also fed to the digesters. The total capacity of the AD system is approximately 470 ton/day OFMSW producing about 130,000 kWh/day electricity (6.0 MW_{el} installed capacity). Output of the digesters, approximately 400 ton/day of digestate, are processed by the digestate management system.

At the commissioning stage of the facility, the initial configuration of the dewatering system consisted of two steps separation using two screw press separators with a screen size of 5 mm (Bellmer Akupress AM 625, Germany and Biofer VP-400, Türkiye) as the first step and a centrifugal decanter (Haus DDI 5342, Türkiye) without polymer use. The decanter bowl speed was adjusted to 2850 rpm and the differential speed between the drum and the internal screw was set to 4 rpm. Combination of a screw press and centrifugal decanter is a commonly used physio-chemical method to produce a liquid digestate fraction with lower solids content (Feiz et al., 2022). However, this configuration resulted in the final liquid effluent with 9.0 ± 1.2 % total solid (TS) and an average NH_4-N concentration of 4895 ± 573 mg/L. Since the TS load was considerably high to be treated by the WWTP of the municipality, a second stage decanter system with cationic polymer dosage was added. Among the tested five different high density polymer types, the best efficiency was obtained with SNF 4190 SSH and Newfloc 7355C. Moreover, the drum rotating speed was adjusted to 2800 rpm for the first stage decanter and 2930 rpm for the second stage decanter. The differential speed was 9 rpm and 6 rpm for first and second decanter stages, respectively. Since the pollutants not captured in the separation process are predominantly very fine suspended particles (> 1.2 nm) (Akhiar et al., 2021), conditioning with flocculant is usually required to improve the separation efficiency (Chuda and Ziemiński, 2021). Site trials were done with different dosing rates of polymer, where 80–85 % TS separation efficiency were attained with a polymer dosage of 6.8 ± 1.2 g/kg TS_{fed}. The final effluent had a TS content of less than 1.9 ± 0.4 % and 2852 ± 668 NH_4-N mg/L, which presented an acceptable load for the municipal WWTP. The solid fraction from the screw press separator contained high impurities such as textile, plastic, and other inerts and was diverted to a sanitary landfill. The decanter cake produced by the dewatering system included low impurity. After thermal drying it could be disposed of in a landfill as daily cover and could be recovered as additive for soil conditioner.

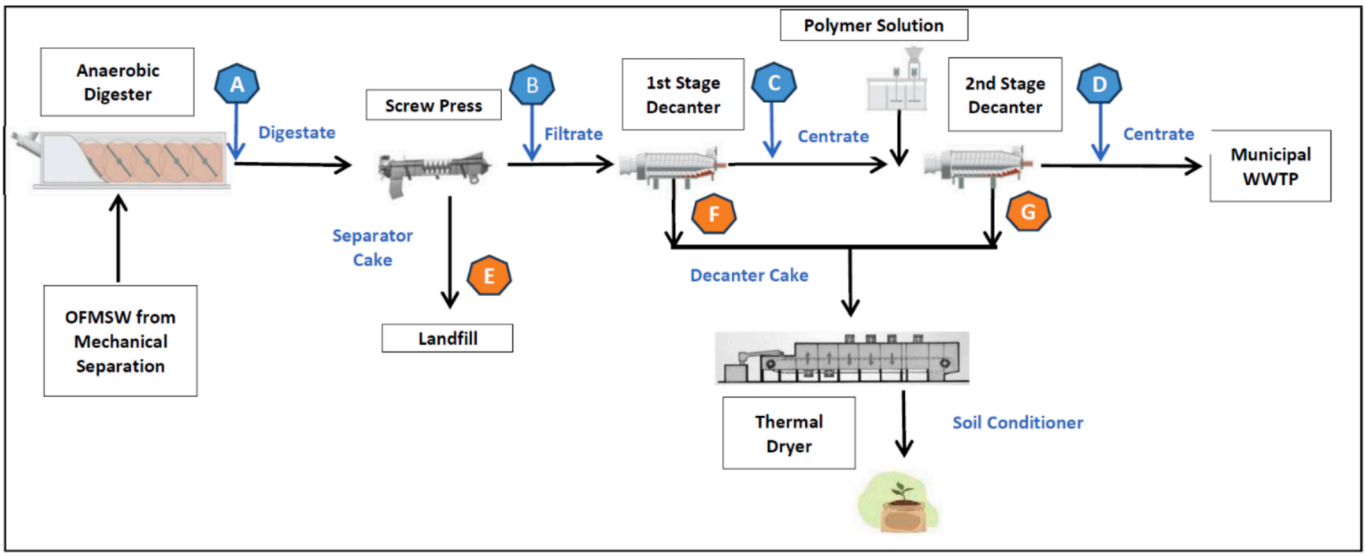


Fig. 1. Flow chart of 3 stages digestate dewatering system (also Sc-1) with liquid stream sampling points A, B, C, D and solid stream sampling points E, F & G.

The flow chart of the digestate dewatering system also defined as Scenario (Sc-1) with the sampling points for the physicochemical analysis is shown in Fig. 1. In order to determine the separation efficiency and pollutant concentrations of each separated stream, samples were taken at the digester outlet, separator outlet, and decanters' outlet. Samples were analyzed for TS, total volatile solids (TVS), total nitrogen (TN), NH_4-N, and chemical oxygen demand (COD) in the plant's laboratory. The analyses were done according to the Standard Methods (APHA, 2005); APHA 2540B for TS and APHA 2540 E for TVS, EN ISO 11905–1, ISO 23697 for TN, AOAC 290.03 for NH_4-N and SM 5220 D for COD. The flow rates were measured by on-line flowmeters of Endress-Hauser (Promag 55S1H, Germany). The results of the analysis were used to generate the mass-balance of the digestate management system.

2.2. Description of scenarios

For the techno-economic analysis covering capital expenditure (CAPEX) and operational expenses (OPEX), the three-stage dewatering system installed in the full-scale plant was referred to as the base scenario and defined as Sc-1. The three scenarios were introduced as alternatives to Sc-1. In scenario 2 (Sc-2), a nitrogen removal unit was added to the Sc-1, while in scenario 3 (Sc-3), a membrane bioreactor (MBR) incorporating nitrification was added to Sc-2. In scenario 4 (Sc-4), the digestate was sent directly to thermal drying, and the evaporated water was condensed and treated in an ultrafiltration (UF) + reverse osmosis (RO).

The scenarios were developed according to the availability of a municipal WWTP treating sewage from the sewer line that the MBT plant is connected to. The discharged pollutant load of the liquid digestate was compared with the design load of an 800,000 person equivalent (P.E.) municipal WWTP. The comparison was made by calculating the magnitude of the additional load in terms of the fraction of the WWTP capacity. Thus, this extra load could be considered in the planning phase of the WWTP by the municipality. It was also assumed that the WWTP had an activated sludge process with biological nitrogen and phosphorus removal steps (anaerobic-anoxic–oxic process).

In all scenarios, the solid fractions were thermally dried to a 50 % TS content, making them a potentially beneficial final product or suitable for disposal in a sanitary landfill. In landfill disposal, a TS content of 50 % or higher allowed sufficient void space to prevent clogging of gas extraction pipes and leachate drainage systems. In Sc-1, Sc-2 and Sc-3, the separator cake and decanter cake mixtures were thermally dried, whereas in Sc-4, the digester outlet was thermally dried directly.

2.2.1. Scenario 1: Dewatering system (existing application)

Sc-1 was based on the existing full-scale plant and a measurement campaign carried out for two years. This scenario included the digestate management practices implemented at the facility including the three-stage dewatering system and liquid digestate discharge to the local sewer line that connects to a municipal WWTP with sufficient extra capacity to handle this load. In the three-stage dewatering system, the first stage involved screw press separation, while the second and third stages used centrifugal decanters, with the third stage assisted by cationic polymer dosing as a flocculant.

2.2.2. Scenario 2: Dewatering system & ammonia removal system

In Sc-2, it was assumed that the municipal WWTP could treat the additional carbon load from the digestate discharge but not the ammonia load. Ammonia air-stripping is one of the most robust methods for recovering nitrogen due to its simplicity and economic feasibility. Other technologies, such as membrane filtration, ion exchange and struvite precipitation are also being explored (Chen et al., 2021; Tao et al., 2024). In this scenario, an air-stripping process was employed to remove ammonia from the liquid digestate, as recommended in literature (Ersahin et al. 2023). Data for Sc-2 were used from a full-scale agricultural waste AD plant with similar capacity in the north-west of Türkiye, where the digestate treatment included polymer- supported decanting, followed by ammonia stripping, and a final MBR step with nitrification.

The efficiency of an ammonia stripping process depends on temperature and pH, as these conditions are necessary to convert ionized ammonia to free ammonia. The system planned in Sc-2 included temperature control at 60 °C and pH adjustment to 9 to convert ionized ammonia to free ammonia in the digestate. In the stripping process, ammonia was first adsorbed by air and then fixed in the form of liquid ammonium-sulphate (ASL). The effluent was discharged to the sewage network after achieving an average ammonia removal rate of approximately 60 %. It was assumed that ammonium-sulfate produced from the ammonia stripping system would be used to enrich the soil conditioner production from the decanter cake (Brienza et al., 2021) and the market value was neglected.

The design and operation parameters of the ammonia stripping system are provided in the supplementary material. The assumed operating parameters such as digestate flow rate, air flow rate, temperature and pH, together with the calculated removal efficiency are comparable to those in similar studies on digestate from OFMSW. Seruga et al. (2020) observed 50.6 % ammonia removal efficiency, where Zhang

et al. (2012) reached 62.6 %, at pH of 9. Limoli et al. (2016) reported removal efficiency of 88.7 % at pH 10. In a recent study of Alrbai et al (2024) used similar design and operation parameters to model the air-stripping process of ammonia from WWTP sludge digestate and found 85 % ammonia removal at 60 °C with pH value of 10——12. In another study, Brienza et al. (2021) reached an ammonia removal rate of 57 % from digestate in a full-scale vacuum stripper installed in an agricultural waste biogas plant running at 90 °C and 9.9 pH.

2.2.3. Scenario 3: Dewatering system, ammonia removal system & membrane bioreactor nitrification system

In Sc-3, it was assumed that the municipal WWTP lacked sufficient capacity either for carbon removal or nitrogen oxidation (nitrification). Therefore, this scenario included both an ammonia removal system and an MBR with nitrification. The MBR was positioned downstream of the ammonia removal system to balance the COD to N ratio of the digestate after ammonia stripping (Malamis et al., 2014). Bamelis et al. (2015) reported the biological treatment of nitrogen in the digestate with activated sludge process as one of the common applications to lower the nitrogen load at the effluent of an AD system. In the MBR system, removal efficiencies of COD and NH_4-N were assumed to be 90 % and 95 %, respectively, comparable to findings from similar study (Gulhan et al., 2022). The design and operation parameters are provided in the supplementary material. It was assumed that the biological excess sludge produced in the MBR system would be dewatered and disposed of in a landfill.

2.2.4. Scenario 4: Thermal drying system & ultrafiltration + reverse osmosis condensate treatment system

In Sc-4, it was assumed that the MBT plant was not connected to a sewer line or the municipal WWTP at the end of the sewer line lacked sufficient capacity for oxidized nitrogen due to limited denitrification capability. In this scenario, the digestate was thermally dried without solid/liquid separation using a belt dryer as the chosen drying technology as it is commonly a preferred process having the advantage of flexible working with wide range of temperatures, especially with the lower ranges such as 55 – 65 °C with the waste heat supplied from the combined heat power (CHP) units (Bamelis et al., 2015). In this study, direct thermal drying without separation was considered as the digestate has high TS content (%27) when leaving the dry AD system. As evaporation systems are negatively affected by high TS and consequent high viscosity (Vondra et al., 2016), thermal drying was chosen in this scenario for reduction of liquid effluent. Bamelis et al. (2015) included in their technical report study a full-scale thermal dryer for digestate directly after the AD system. Waste heat from the CHP plant in the MBT facility would partially cover the thermal energy requirements for digestate drying, with the remaining heat demand supplied by natural gas boilers. To optimize heat demand and vent gas treatment capacity, a portion of the evaporated liquid fraction would be condensed, while the rest would be exhausted as vapor after vent gas treatment. In the calculations, specific heat demand was assumed as 1000 kWh/kg water evaporated, as a typical average value for belt type digestate drying systems (Bolzonella et al., 2018). The condensate from the evaporation would contain much less particulates and organic pollutants than the liquid fraction in the first three scenarios, making it suitable for treatment in an UF and RO system before discharge to sewage or to a receiving body. According to Lebuf et al. (2013), the condensate would mainly consist of ammonia and some volatile compounds, but free of salts. Fuchs and Drosg (2013) recommended in their study that nitrogen and COD values were treated with RO system as these values were higher than discharge values to receiving bodies. The nitrogen-rich concentrate would be added to the solid fraction of digestate to enhance its fertilizing potential or spread on a landfill in a controlled manner. The design and operational parameters, along with the condensate characteristics are provided in the supplementary material.

2.3. Economic analysis

2.3.1. Boundaries of economic analysis

TEA was conducted for the defined system in Fig. 1, starting from the AD until the discharge of the liquid effluent including the biogas utilization part. The mechanical treatment part of the MBT plant was not included in the study. It was assumed that the decision point for the AD investment would start after the production of OFMSW.

2.3.2. Capital expenditures & operating expenditures calculations

To conduct the techno-economic analysis, CAPEX and OPEX for the AD and the digestate treatment system of the MBT plant, three different scenarios were developed in addition to the base scenario. In Sc-1, to calculate the CAPEX and OPEX, the data were collected from the full-scale plant involved in this study. For Sc-2, and Sc-3, data from a full-scale agricultural waste AD plant with a similar capacity of 400 ton/day digestate in north-western part of Türkiye were used. For Sc-4, the data were based on an existing plant in the Aegean Region of Türkiye, where digestate from a sludge digester in a municipal WWTP was thermally dried. For Sc-2, Sc-3 and Sc-4 the data used form the similar full-scale plants in Türkiye was also compared with the full-scale plant data in the literature (Bamelis et al., 2015; Brienza et al., 2021).

For CAPEX calculations, the costs of civil construction, equipment supply, electro-mechanical installation, control and automation systems, and engineering services for the full-scale plants were used by interpolating unit prices from the year of construction to current market prices. The prices used were communicated to the plant owners and with commercial firms providing the goods and services. For OPEX calculations, up to date prices for electricity, natural gas, wear and spare parts, operational personnel labor, and chemicals in Türkiye were used. Biogas-derived electricity sales were considered as the only income for the plant. It was assumed that thermal energy from plant's own biogas CHP's was for free. The energy consumed in the municipal WWTP to treat the residual carbon and ammonia load was included in the OPEX, using the electricity price that is 50 % subsidized by the Turkish Government.

The investment return time for different scenarios was evaluated by varying electricity prices in increments of 8.8, 11.0, 13.3, 19.8 and 27.5 $cents/kWh. For the full-scale plant used in this study, the subsidized electricity selling price will be 13.3 $cents/kWh until the end of subsidy period in 2031 according to the Turkish Renewable Energy Regulation published in Official Gazette, 2023. After this year, the market price will be applied to electricity sales. According to the regulation, consumed electricity during the subsidy period must also be paid at the selling price. The unit prices used in the calculation for operational cost items other than electricity were as follows: 0.035 $/kWh for heat produced from natural gas, 0.013 $/kWh for maintenance cost of the CHP systems, 17.6 $/hour for maintenance costs for each decanter operation, 3 $/ton for NaOH and 187 $/ton for H_2SO_4. It was assumed that the market value of the produced ammonium-sulfate was beyond the scope of the analysis.

2.3.3. Economic evaluation indicators

For economic evaluation of the different scenarios, simple cash flow (CF) and discounted cash flow (DCF) were calculated for 20 years using a discount rate of 3 % according to Equation (1) and (2). It was assumed that the investment was funded with 100 % private equity and that no terminal value was considered at the end of 20 years, as the aim of this study was to compare technological methods rather to optimize the investment model (Herbohn and Harrison, 2002).

$$CF = R - C \tag{1}$$

$$DCF = \frac{CF}{(1+i)^t} \tag{2}$$

where, R is the total revenues and avoided cost ($/year), and C is the operation cost ($/year), i is the interest rate (%), t is the number of years.

For profitability evaluation, five different indicators, which vary from simple indicators such as pay-back period (PBP) and discounted payback time (DPBP) to more detailed and sophisticated indicators such as internal rate of return (IRR), the net present value (NPV) and profitability index (PI) were applied. DPBP, IRR, NPV & PI were used in most of the cases as these parameters consider the actual discount rate, or in other words "the value of money" in the market to compare the profitability (Klammer, 1972; Gitman and Forrester, 1977).

- The Payback Period (PBP) is the period of time required, after start-up, to recover the total capital investment which is calculated using the Equation-(3) (Blank and Tarquin, 2012.).

$$PBP = \frac{I}{CF} \tag{3}$$

where I is the total investment cost ($).

- The Discounted Payback Period (DPBP), which is the time required, after start-up, to recover the total capital investment with all cash flows discounted back to time zero. DPBP is calculated with the Equation (4) (Blank and Tarquin, 2012).

$$DPBP = \frac{\ln\left(\frac{1}{1-\left(\frac{ixr}{CF}\right)}\right)}{\ln(1+r)} \tag{4}$$

- The Net Present Value (NPV), which is the cumulative cash position at the end of the project life, with all cash flows discounted. If NPV < 0, the project is rejected, if NPV > 0, the project is taken into further evaluation. NPV can be represented with the equation (5) (Blank and Tarquin, 2012).

$$NPV = +I + \sum_{t=0}^{n} \frac{CF_t}{(1+\dot{I})^t} \tag{5}$$

- The Internal Rate of Return (IRR), which is the interest rate at which all the cash flows must be discounted in order for the net present value of the project to be equal to zero. It was calculated with the equation (6).

$$IRR = \sum_{t=1}^{n} \frac{CF_t}{(1+\dot{I})^t} \tag{6}$$

- The Profitability Index (PI) is defined as the ratio between the NPV and the initial investment. It is calculated using equation (7). If PI is less than 0, the investment is not recommended, if it is greater than 0, then it can be further evaluated using the other indicators described above.

$$PI = \frac{NPV}{I} \tag{7}$$

2.3.4. Economic assessment

A comprehensive economic analysis was conducted by comparing the profitability evaluation indicators, including PBP, DPBP, IRR, NPV and PI.

To compare the PBP and DPBP of the different scenarios, a moderate investment return timeframe of 6 years was taken as the objective from an investor's perspective (Al-Wahaibi et al., 2020). The electricity price required to achieve this target was calculated and compared. Additionally, the NPV, IRR and PI were evaluated for a 20-year investment period. Sensitivity analysis is a useful tool for understanding how

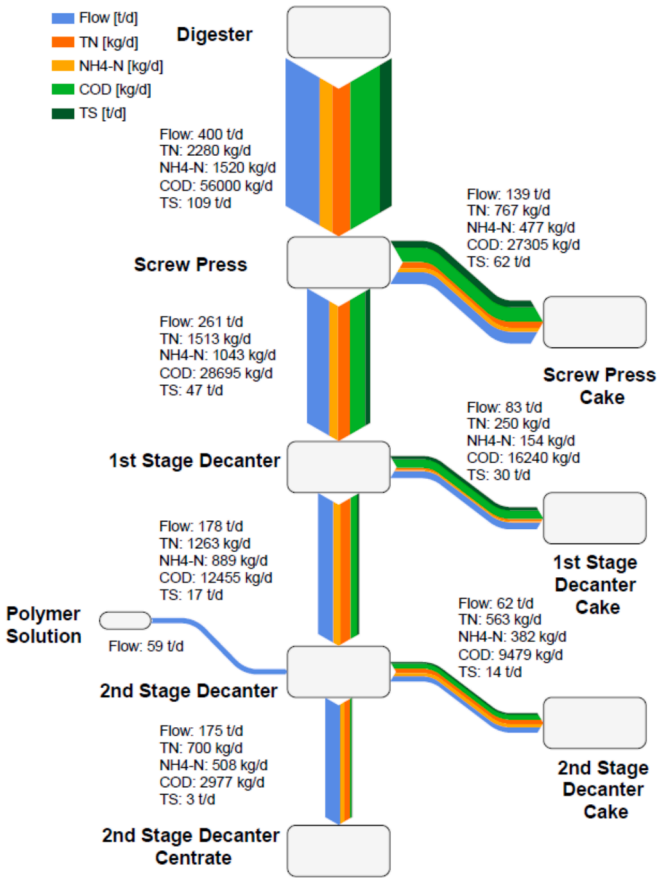


Fig. 2. Mass-balance of main pollutant parameters at each separation step.

Table 1
Pollution discharge loads of scenarios.

Description	Pollutant Load	Additional Load (%)
800,000 (P.E.) WWTP plant inlet load capacity)		
Flow (ton/day)	160,.000	
COD (kg/day)	48,000	
NH4-N (kg/day)	4,000	
TN (kg/day)	6,400	
Scenario 1 (Digestate dewatering only)		
Flow (ton/day)	175	0.11
COD (kg/day)	2,975	6.20
NH_4-N (kg/day)	508	12.69
TN (kg/day)	700	10.94
Scenario 2 (Digestate dewatering + N removal)		
Flow (ton/day)	175	0.11
COD (kg/day)	2,975	6.20
NH_4-N (kg/day)	201	5.03
TN (kg/day)	394	6.15
Scenario 3 (Digestate dewatering + N removal + aerobic MBR)		
Flow (ton/day)	175	0.11
COD (kg/day)	298	0.62
NH_4-N (kg/day)	13	0.33
TN (kg/day)	358	5.60
Scenario 4 (Thermal Drying with Condensate Treatment)		
Flow (ton/day)	80	0.05
COD (kg/day)	120.0	0.25
NH_4-N (kg/day)	12.0	0.30
TN (kg/day)	13.3	0.21

sensitive a profitability indicator may be to a chosen OPEX parameter (Tiller et al., 2024). As the final step of the evaluation, a sensitivity analysis was also performed as part of the TEA study to assess the impact of varying electricity selling prices and discount rates on DPBP. In the sensitivity analysis, electricity selling price was changed by ± 10 % increments, the corresponding DBDP was calculated and plotted by ± 50 % increments against the varying electricity price.

3. Results and Discussion

3.1. Pollutant separation efficiency

The data collected from the three stage digestate dewatering system in the full-scale plant for three years were used to generate the mass balance with average values of COD, TS, TN and NH_4-N (Fig. 2). The findings revealed that the separation process resulted in an overall efficiency of 97 ± 2 %, 95 ± 6 %, 96 ± 2 %, 69 ± 6 % and 67 ± 5 % for TS, TVS, COD, TN and NH_4-N, respectively. Furthermore, the efficiencies of individual steps for each parameter are given in the supplementary material. The findings in this study are higher than those of Chuda and Ziemiński (2021), where TS, TVS and TN removal efficiencies were found as 48 %, 57 % and 39 % respectively in an agricultural waste biogas plant. Rossi at al. (2022) showed 93 % removal in TS for digestate of a continuous dry AD treating OFMSW. The findings revealed that three stage application in the full-scale plant could be an effective method to keep the effluent pollutant concentrations below the municipal WWTP capacity limits in terms of TS, COD, TN and NH_4-N (Table 1). Moreover, the concentrations of 17300 ± 2940 mg/L, 4136 ± 965 mg/L, 2852 ± 668 mg/L for COD, TN and NH_4-N, respectively in the final liquid digestate demonstrate similar characteristics with a medium aged landfill leachate and can be treated biologically after ammonia removal (Gulhan et al., 2022).

3.2. Polymer dosing optimization

The polymer cost being the significant component of OPEX was optimized through various polymer dosing rates, starting from 4 to 11 g polymer per kg TS_{fed}. For optimizing the dosing range, the experiences for the previous similar studies were followed in this study. Polymer dosing rates of 5–8 g/kg TS_{fed} (Recktenwald et al., 2008) and 8–10 g/kg TS_{fed} (Nguyen et al., 2016; Cobbledick et al., 2016) for dewatering of WWTP sludge digestate were reported in the literature. Nguyen et al. (2016) used high density, medium charged cationic polymer Zetag8165, whereas Cobbledick used SNF Clarifloc C-6267, a high density, high charged cationic polymer. A higher dosing range of 10–15 g/kg TS_{fed} was also investigated by Bicudo et al. (2019) for dewatering digested sludge from three different WWTPs using cationic SNF Flopolymer HB 4484 (emulsion) and Flopolymer CA 4600 (powder). In a similar study on dry AD of OFMSW, unit polymer consumption in digestate dewatering was stated as 8 g/kg TS_{fed} to reach an effluent with 1.5 % TS_{fed} (Rossi et al., 2022). Pasciucco et al. (2023) assumed in their life cycle cost analysis for a similar plant a polymer unit consumption of 11 g/kg TS_{fed}. In the full-scale plant study of the current research, the lowest effluent COD and TS results were obtained with SNF 4190 SSH and Newfloc 7355C type polymers. Likewise, higher COD and TS were observed in the effluents of the trials with polymer types SNF Flobind 7541, SNF FB 208, Solenis Floc 7541. The overall results demonstrated that the optimum dosage was 7 ± 1 g polymer/kg TS_{fed}, where the TS removal efficiency was 84 ± 5 %, generating a final effluent with TS content of less than 1.9 ± 4 % and 2852 NH_4-N ± 668 mg/L. The polymer concentration in dosing solution was 0.2 %. Further increase of polymer dosing rate (up to 11 g/kg TS_{fed}) did not result in further removal efficiency and doses below 7 g/kg TS_{fed} (decreased down to 4.0 g/kg TS_{fed}) showed efficiencies between 70–75 %, which would produce a final effluent TS concentration up to 3 % (w/w).

Table 2
Capital costs of scenarios ($).

CAPEX Item Description	Sc-1	Sc-2	Sc-3	Sc-4
Anaerobic Digestion with Electricity Production				
Total ($)	*20,350,000*	*20,350,000*	*20,350,000*	*20,350,000*
3 Stage Dewatering System				
Electro-mechanical Works (Dewatering)	1,600,000	1,600,000	1,600,000	
Electro-mechanical Works (Ther. dryer for cake)	1,540,000	1,540.000	1,540.000	
Civil works	770,000	770,000	770,000	
Engineering & Project Management	280,000	280,000	280, 000	
Total ($)	***4,190,000***	*4,190,000*	*4,190,000*	
Ammonia Removal System				
Electro-mechanical Works		540,000	5400,000	
Civil works		390,000	390,000	
Engineering & Project Management		110,000	110,000	
Total ($)		***1,040,000***	*1,040,000*	
Aerobic MBR System				
Electro-mechanical Works			2,200,000	
Civil works			1,320,000	
Engineering & Project Management			330,000	
Total ($)			***3,850,000***	
Thermal Drying & Condensate WWTP				
Electro-mechanical Works				6,550,000
Civil works				2,750,000
Engineering & Project Management				500,000
Total ($)				***9,800,000***
Grand Total Cost ($)	**24,540,000**	**25,580,000**	**29,430,000**	**30,150,000**

*: All costs are expressed in US $ using the average exchange rate of 33 TL/$ and €/$ rate as 1,10 in August 2024.

3.3. Pollutant loads of different scenarios on municipal waste water treatment plant

For comparing the impact of the discharged pollutants on the municipal WWTP, for each scenario, the pollutant loads and the percentage of additional loads to the WWTP were calculated and given in Table 1. Municipal WWTP's capacity was calculated by using wastewater quantity and pollutant load per person issued by the Ministry of Environment, Urbanization and Climate Change in Türkiye. In Sc-1, the effluent sent to WWTP resulted in additional loads of 6.20 % and 12.69 % for COD and NH_4-N respectively. In case WWTP had spare capacity for these loads, this scenario could be technically applicable for COD and NH_4-N parameters. In case when the WWTP would have enough capacity for the COD load from the MBT but not for the NH_4-N load due to lack of extra nitrification capacity, then with the additional ammonia removal system in Sc-2, the NH_4-N load could be reduced to 5.03 %, and TN load could be decreased to 6.15 %. For the case when the WWTP would not be handle this load in Sc-3, the additional COD and NH_4-N loads could be reduced to 0.62 % and 0.33 %, respectively. However, in Sc-3 TN load would not change significantly and was calculated to be 5.60 % and most of nitrogen would still remain in the form of NO_3-N which had to be denitrified in the municipal WWTP. If the WWTP could not handle this level of NO_3-N load, then Sc-4 would minimum

Table 3
Income and operational costs of AD Plant with operational costs of scenarios **($/year)**.

Income / OPEX Item Description	Sc-1 OPEX	Sc-2 OPEX	Sc-3 OPEX	Sc-4 OPEX
Anaerobic Digestion with Electricity Production				
Electricity Income	6,172,030	6,172,030	6,172,030	6,172,030
Electricity cost	399,000	399,000	399,000	399,000
Chemical cost	33,000	33,000	33,000	33,000
Labour cost	268,210	268,210	268,210	268,210
Maintenance cost	790,280	790,280	790,280	790,280
Total Income	***4,681,540***	***4,681,540***	***4,681,540***	***4,681,540***
3 Stage Dewatering System				
Electricity cost	133,000	133,000	133,000	
Chemical cost	177,100	177,100	177,100	
Labour cost	153,260	153,260	153,260	
Maintenance cost	331,100	331,100	331,100	
WWTP disposal cost	43,410			
Total Cost	***837,870***	*794,460*	*794,460*	
Ammonia Removal System				
Electricity cost		13,300	13,300	
Chemical cost		201,160	201,160	
Maintenance cost		55,000	55,000	
WWTP disposal cost		39,410		
Total Cost		***303,870***	*264,460*	
Aerobic MBR System				
Electricity cost			263,340	
Chemical cost			5,810	
Labour cost			76,630	
Maintenance cost			165,000	
Total Cost			***510,780***	
Thermal Drying & Condensate WWTP				
Electricity cost				608,810
Natural gas cost				828,730
Chemical cost				22,000
Labour cost				76,630
Maintenance cost				445,500
Total Cost				***1,979,670***
Total Net Income	**5,519,410**	**5,779,870**	**6,251,240**	**6,661,210**

*: All costs are expressed in US $ using the average exchange rate of 33 TL/$ and €/$ rate as 1,10 in August 2024.

additional load to the WWTP due to the presence of RO process. The additional TN load was estimated as low as 0.21 % when the concentrate of RO was sent to the sewage network. Besides that, Sc-4 would also cover the case that MBT is not connected to a sewage pipe and effluent needs to be discharged to receiving bodies like surface waters. In this case, RO permeate would be discharged to surface waters and concentrate would be transported to a landfill.

3.4. Results of economic analysis

3.4.1. Capital expenditure & operating expenditure calculations

The results of the CAPEX calculations for scenarios are presented in Table 2. In the base scenario (Sc-1), the capital cost for a 3-stage dewatering system with a cake dryer was $4.2 million. In Sc-2, with an additional CAPEX of $1.0 million (totaling $5.2 million), NH_4-N load could be reduced by 60 %. However, comparing the findings of this study with the previous studies it has been observed that CAPEX for an ammonia removal system with similar capacity was calculated as $0.3 million in the study of Alrbai et al (2024). The difference was mainly due to cost of construction in this study that would be recommended based on climatic conditions and service requirements during cleaning. Moreover, Lamolinara et al. (2022) reported in their review study the CAPEX interval of $0.55 million to $1.65 million. In Sc-3, an additional investment of $3.8 million (totaling $9.1 million) would allow for further reduction of COD and NH_4-N loads. In a study conducted on 175 MBR leachate treatment plants in China, the unit investment cost of leachate was found as approximately 14,300 $/$m^3$ (Zhang et al., 2020), which is comparable with 22,000 $/$m^3$ calculated in this study. Finally, to achieve a reduction in TN load, an investment of $9.8 million was required in Sc-4, corresponding a CAPEX of 24,530 $/$m^3$ digestate. Bolzonella et al. (2018) reported the CAPEX value of 11,000 $/$m^3$ of digestate in their 30 m^3/day capacity dryer. Although this value is lower than our value, it could be explained that our system included a condensate treatment system and installed in a building as differently compared to their system.

For the MBT plant, income and OPEX calculations for AD with different digestate management scenarios are given in Table 3. For the base scenario, yearly $0.8 million digestate treatment OPEX (5.7 $/ton-digestate) was calculated. This OPEX included also the costs for drying the cake up to 50 % TS and the costs of additional electricity consumed in the municipal WWTP to treat the pollution load coming from the MBT plant.

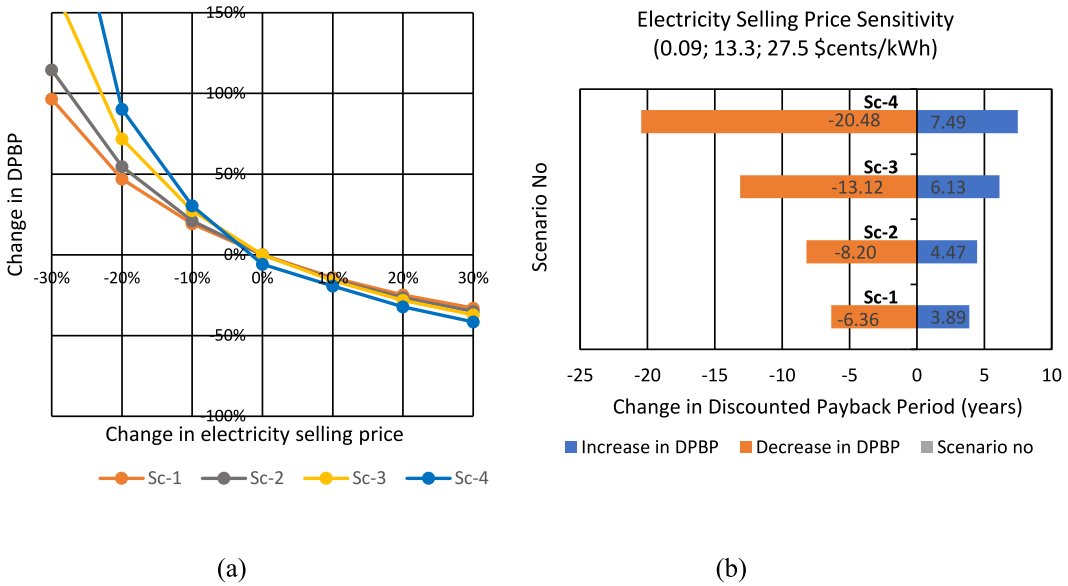
In the dewatering system, polymer cost of the decanter was calculated as 1.3 $/$m^3$ constituting over 20 % of the total OPEX, which was similar to the result of 1.0 $/$m^3$ observed in a study where digestate from an animal manure AD plant was dewatered by decanter system with polymer dosing (Cathcart et al., 2023). The maintenance cost generated 40 % of the total OPEX and was the highest component. The digestate treatment cost in total corresponded to approximately 15 % of the income from electricity. Sc-2 ($1.1 million, 7.5 $/ton-digestate) and Sc-3 ($1.5 million, 11.1 $/ton-digestate) would be financially preferable compared to Sc-4 depending on the availability and capacity of a centralized WWTP close to the MBT plant. OPEX for ammonia removal system used in both Sc-2 and Sc-3 was calculated as 3.2 $/kg $N_{removed}$ which was optimized to 2.4 $/kg $N_{removed}$ by using the waste heat from the biogas CHP's. Lamolinara et al. (2022) reported OPEX values of 2.2 to 4.3 $/ kg $N_{removed}$ in their review study. In our ammonia removal system with the capacity of 175 ton/day digestate inlet, the total OPEX of 264,460 $/year (Table 3) is comparable with the similar study of Alrbai et al (2024) with a total OPEX of 342,630 $/year for a digestate flow rate varying between 40 and 140 ton/day. OPEX for the MBR treatment plant used in Sc-3 was calculated as 3.0 $/ton digestate. Zhang et al. (2020) found 4.8 $/$m^3$ for their study, which is higher than our value due to addition of nano filtration (NF)/RO downstream of MBR systems. As expected, highest OPEX, $8.8 million (12.5 $/ton-digestate), was calculated for Sc-4. The differences in OPEX originated by additional use of chemicals in Sc-2, intensive use of electrical energy in Sc-3 and thermal energy use in Sc-4.

The treatment cost per ton digestate was calculated as 6.1 $/ton for Sc-1, 8.0 $/ton for Sc-2, 11.1 $/ton for Sc-3 and 13.5 $/ton for Sc-4. The overall net income per ton OFMSW was calculated as 23.0 $/ton for Sc-1, 21.2 $/ton for Sc-2, 18.6 $/ton for Sc-3 and 16.6 $/ton for Sc-4. Overall net income was calculated by subtracting the OPEX for AD and digestate management system from the electricity income of the AD plant. Sc-1 had the lowest per ton OPEX and consequently resulting in the highest income per ton OFMSW treated in AD plant with 22.6 $/ton, whereas Sc-4 had the highest OPEX and creating lowest income of 16.6 $/ton OFMSW.

3.4.2. Economic assessment

For the economic assessment, all the four scenarios were compared by calculating the five common evaluation indicators. The complete details of each scenario and indicator are presented in supplementary materials. The findings of all the five indicators showed that the Sc-1 would be a more feasible solution, as long as there would be a municipal WWTP nearby with sufficient capacity to treat the final effluent with varying pollutant content for each scenario.

3.4.2.1. Payback period. Although PBP values of 6.4 and 7.2 years for Sc-1 & Sc-2 respectively at a low electricity selling price of 11 $cent/kWh would economically applicable, DPBP values pointed out that higher electricity prices would be necessary. A similar economic analysis



(a) (b)

Fig. 3. Sensitivity of DPBP for changes in electricity selling price (a) in %; (b) in years.

was conducted by Cheong et al. (2022) for the co-digestion plant using food waste and WWTP sludge with aerobic biological treatment of digestate, where PBP was found to be 6.2 years and was considered to be acceptable for investment. The results depicts that for Sc-1, an electricity selling price of 13.3 $/kWh was needed to reach DPBP of 7.2 years, whereas for Sc-2 same electricity price would cause DPBP rising to 8.2 years. Comparable results were obtained for an AD plant and DPBP calculated with 5 % discount rate was found 6.7 years for co-digestion of olive oil pomace and pig slurry and 9.2 years for mono-digestion of pig slurry (Orive et al., 2016). Vondra et al. (2018), in their techno-economic analysis of vacuum evaporator application as a digestate management method, determined a payback period (PBP) range of 2 to 8 years, depending on the electricity feed-in tariff, which varied between 0.1 and 0. 3 $/kWh.

As a practical decision making tool, the change in PBP and DPBP indicators were plotted versus electricity price (see supplementary material). When PBP was chosen 6 years as commonly observed and accepted in similar investment projects by private sector and plotted on these graphs as an asymptote, the crossing point would give the minimum electricity selling price to reach this target. This price was calculated as 14.4 $cents/kWh for Sc-1, 15.6 $cents/kWh for Sc-2, 18.4 $cents/kWh for Sc-3 and 20.0 $cents/kWh for Sc-4. In the case when DPBP was preferred to be 6 years, then these prices increased to 15.7, 16.9, 19.8, 21.1 $cents/kWh for Sc-1, Sc-2, Sc-3 and Sc-4, respectively. When the electricity selling price decreased, an exponential increase in PBP was observed. This increase was even much higher in the case of DPBP for especially Sc-3 and Sc-4, due to the high CAPEX in these scenarios. DPBP indicator was observed to be very sensitive to the level of the interest rate with which the CAPEX will be financed. (see supplementary material).

3.4.2.2. Net present value and profitability index. NPV and PI indicators showed the minimum electricity selling price where each scenario started to return positive income. NPV could go up to approximately $120 million revenue by the end of 20 years of project life with the highest electricity price of 27.5 $cent/kWh for Sc-1. The NPV would be negative, or in other words PI would be below 1.0 at around 8.8 $cent/kWh for Sc-1 and Sc-2, whereas this value was 11.0 $cents/kWh for Sc-3 and 13.3 $cent/kWh for Sc-4 (see supplementary material). When NPV was calculated with the actual electricity price of 13.3 $cent/kWh, NPV ranged from $10 million (Sc-4) to $33 million (Sc-1), where PI ranged from 1.12 to 1.55. Pasciucco et al. (2023) conducted a life cycle cost analysis for a 563 ton/day co-digestion plant treating WWTP sludge as main substrate and OFMSW as co-substrate. In their results, the NPV for 20 years was up to $11.6 million depending on the chosen energy recovery scenario, where CAPEX was $6.4 million excluding energy recovery systems.

3.4.2.3. Internal rate of return. When IRR was calculated with 13.1 $/kWh, Sc-1 would return a value of 14.6 % and Sc-2 yields 12.7 %. For Sc-3 and Sc-4 all indicators showed that the electricity price in the range of 13.3 $/kWh would bring economical losses and the electricity price should be close to 19.8 $/kWh for an economically favorable AD plant investment. At this price level, IRR for Sc-3 was 19.0 % and for Sc-4 16.5 %. In the previously mentioned study of Pasciucco et al. (2023), an IRR range of 5.9 % to 16.6 % was found for four different scenarios.

3.4.2.4. Sensitivity analysis. The sensitivity of the DPBP towards electricity selling price and discount (interest) rate were studied and the details are presented in the supplementary materials**.** The change of electricity selling price showed different sensitivity in DPBP for each scenario. Sc-4 showed a higher sensitivity to the decreasing electricity selling price. When the current subsidized price decreased by 10 %, then the DPBP increased by 47 %, 55 %, 72 % and 90 % for Sc-1, Sc-2, Sc-3 and Sc-4, respectively. By increasing the price by 10 %, DPBP decreased for all scenarios by 14 % 15 %, 16 % and 19 %. This result indicated that all scenarios showed less sensitivity to price increase compared to price decrease. The magnitude of the sensitivity could be more clearly visualized in Fig. 3. Sensitivity analysis for discount rate showed that a 75 % decrease in discount rate causes a decrease in DPBP by 9 %, 10 %, 13 % and 14 % for Sc-1, Sc-2, Sc-3 and Sc-4, respectively. A 75 % increase in discount rate would increase the DPBP by 11 %, 12 %, 18 %, and 23 % (see supplementary materials). This indicated that Sc-3 and Sc-4 are more affected by the increase in discount rate due to their higher CAPEX.

4. Conclusion

The findings indicated that, for digestate management of a continuous dry AD system treating OFMSW, a three-step dewatering system (Sc-1 as baseline scenario) could be environmentally and economically acceptable under the determined conditions, which are the availability of spare capacity in the central municipal WWTP that will treat the residual pollutants in the effluent of the dewatering system and an

electricity selling price of minimum 15.7 $cents/kWh. Depending on the spare capacity of the municipal WWTP, digestate can be further treated in the AD plant. However, through increasing the electricity selling price up to 16.9, 19.8 and 21.1 $cents/kWh, then the treatment steps of ammonia removal systems (Sc-2), aerobic MBR treatment (Sc-3) or thermal drying (Sc-4) could be applied feasibly, respectively. These results provide a roadmap for regulatory authorities, policy makers and investors for sustainable applications of dry AD systems of treating OFMSW.

CRediT authorship contribution statement

A. Musluoğlu: Writing – original draft, Visualization, Resources, Formal analysis, Conceptualization. **R.K. Dereli:** Writing – review & editing, Supervision, Conceptualization. **O.A. Arıkan:** Writing – review & editing, Supervision, Conceptualization. **H. Guven:** Writing – review & editing, Conceptualization. **K.E. Maçin:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2025.132131.

Data availability

Data will be made available on request.

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