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Assessment of the domestic sewage sludge by different drying methods: solar radiation and thermal energy source

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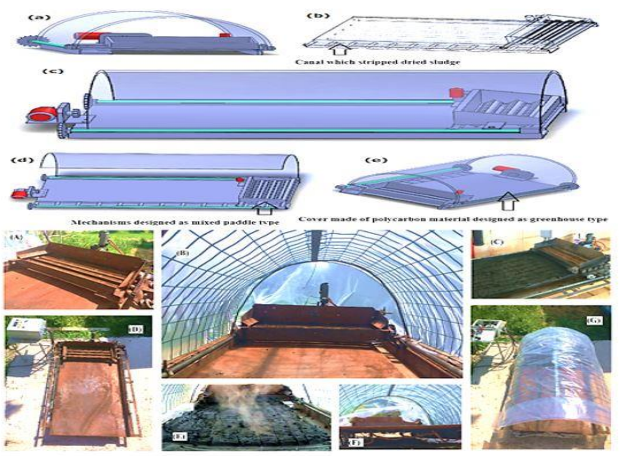
Graphical abstract



Pilot scale hybrid sludge drying system. (a) side views (b) resistances (c) front views (d) mechanisms designed side by side and like mixer paddle type (e) polycarbonate material that can pass the sun rays easily. (A) The mixer-paddle mechanism of system (B) inside of dryer (C) the moment the dewatered sludge is laid in the dryer (D) electrical resistances (E) drying sequence (F) the appearances of the sludge in the drying area (G) external view of the system

Abstract

The amount and properties of the sludge produced in wastewater treatment plants depend on the composition of the wastewater, the type of wastewater treatment used and the disposal method applied to the mud. The sludge that occurs during mechanical, biological and chemical treatment methods must be subjected to some pre-treatment in terms of both environmental problems and the threat of human health. Sludge samples were taken from the sludge dewatering station, which is the last point of a wastewater treatment plant sludge treatment, and tested in pilot scale hybrid sludge drying system. In the study, drying methods were investigated in the context of urban wastewater treatment plants in Ankara province under the final disposal of sludge from urban wastewater treatment plants. The most suitable solution would be to dry the sewage sludge in Ankara in a hybrid system with solar radiation and thermal energy sources (cogeneration with solar panels) in a system that will provide uninterrupted power to the drying system. This thermal source can be provided from the existing cogeneration system in the plant. Addition of solar panels to the sludge drying system is an important option in order to obtain better efficiency than solar radiation-based drying system.

Keywords: Domestic sewage sludge, drying methods, hybrid drying system, solar radiation

1. Introduction

Sewage sludge is a substance which comprises of solid and liquid mixtures, emerges as a result of the water and wastewater treatment, has to be made harmless by passing through various treatment processes due to its properties (Andres *et al.,* 2018; Carneiro *et al.,* 2020). Sewage sludge is also called as "biosolids" in some countries. In particular, because the organic matter content is high and the percentage of solid matter is low in the sewage sludge emerging at the end of the biological treatment processes, this type of sludge tends to decompose and putrefy (Alves *et al.,* 2022; Xiaochun *et al.,* 2021; Uysal & Boyacioglu, 2021; Yılmaz *et al.,* 2018; Zaidi *et al.,* 2021). The amount and characteristics of sludge produced in wastewater treatment plants (WWTPs) depend on the composition of wastewater, type of the used wastewater treatment and the disposal method applied to the sludge (Bolognesi *et al.,* 2021; Jatav *et al.,* 2018; Kelessidis & Stasinakis, 2012; Morandi *et al.,* 2018; Morgano *et al.,* 2018; Zhang *et al.,* 2018). Because of the environmental problems and as well as because it poses a threat to human health, sludge that occurs during the mechanical, biological and chemical treatment methods must be subjected to pre-treatment (Janusevicius *et al.,* 2024). The aim of the pre-treatment for sludge is to reduce volume, stabilize sludge, eliminate water and kill pathogenic organisms (Alisawi, 2020; Al-Gheethi *et al.,* 2018; Chaea et al., 2016; Flores-Trujillo et al., 2021; Slim *et al.,* 2008). The high moisture content and biological gel structure of the sludge may lead to difficulties in dewatering as well as increased processing costs (Bozym *et al.,* 2021; Wang *et al.,* 2018).

Examining the previous studies related to the sewage sludge, it is seen that drying tests for the sludge from wastewater treatment plants have been carried out by using two types of paddle dryer, and the difference in the type of dryer gives information about the heating process and drying speed period of the sewage sludge (Onaka, 2000). In the literature, it is recommended to use existing incineration plants for the disposal of the sewage sludge by burning (Onaka, 2000). Indirect drying and mechanical mixing of the sewage sludge provides many advantages (Ferrasse *et al.,* 2002). The effects of biosolids emerging from urban wastewater treatment plants, in which physical and biological treatment were applied, on plant yield and quality and soil structure have been investigated and as a result, it was observed that it increased the protein rate of wheat and had positive effects on the quality of it (Bux & Baumann, 2003). For drying beds, there may be differences in facilities according to the needs of the regions and there may be also differences in terms of cost (Bux & Baumann, 2003). Lee & Lui (2004) have stated that within the scope of the management of the sludge emerging from wastewater treatment plants, a "local sewage sludge management plan" should be made for the sludge whose physical, chemical, biological properties, local conditions and final disposal methods can change. In another study, the energy rate consumed by the sewage sludge dryers (with thermal resource) and the energy value of the dry sludge were compared and the feasibility of drying were evaluated, and solar drying technologies were suggested as the best drying method (Arjona Ciseros, 2005). Since drying of the sewage sludge directly with thermal resource (non-renewable resource) will consume a lot of energy, it is recommended to dry sludge with a resource (renewable resource) such as biogas obtained through sludge stabilization in wastewater treatment plants (An & Liu, 2017). Scharenberg & Pöppke (2010) examined the solar drying and reuse possibilities of the sewage sludge emerging from the treatment plants and suggested the solar sludge drying system as a result of their studies. In the study of Lin *et al.* (2012), the material created by solid materials added to the concrete at low rates was burned at high temperatures for long periods and the obtained data were investigated. The drying of sewage sludge by solar drying systems is advantageous in terms of cost and generally provides solid matter (SM) up to 70%; moreover, this ratio can be increased with additional heat Kurt *et al.,* 2015). Güven *et al.* (2016) investigated the grass growing possibility in ericaceous compost in which different proportions of leather treatment sludge compost were added. Kurt *et al.* (2016) examined the use of greenhouse-type dryers and solar panels in the drying of sewage sludge in terms of cost-effectiveness. An & Liu (2017) introduced some innovative approaches to the solar drying systems and gave information about advanced solar sludge drying, such as waste flue gas heat/solar capacity system use, and presented the characteristics of solar systems related to the sludge drying process. Depending on the final disposal type of the wastewater sewage sludge, sludge treatment technologies and thereby treatment costs vary as well. A study by Cicco *et al.* (2020) found that when examining a large wastewater treatment plant in southern Italy with a traditional active sludge process scheme and electricity as an exclusive source of energy, it encourages research in the field of energy efficiency for the wastewater industry and is useful for comparison with international data. According to Zhang & Ma (2021), sewage sludge treatment systems had investigated, calculated, and analyzed, including the conventional treatment system and improved reuse system, respectively. In this study, drying and burning (thermal) methods which are of the final disposal methods were evaluated for the sewage sludge originated from the wastewater treatment plant of Ankara province (Tatlar Wastewater Treatment Plant). Since putrefaction and degradation occur in sludge from treatment sources due to their content, both pre-treatments and different drying methods are applied in the literature. In this study, a hybrid drying method was tested by considering the individual advantages of solar and thermal drying methods. In the literature, there is limited research on the hybrid use of both methods. For this purpose, a pilot-scale drying unit was prepared for the final disposal of the sludge of the urban wastewater treatment plant in Ankara province by hybrid (thermal and solar) drying method. Experimental studies were conducted in the pilot-scale hybrid sludge drying unit, analyses of the sludge samples were carried out, the obtained results were examined in the context of the sludge originated from the urban wastewater treatment plant of Ankara province, and finally, the findings were discussed and evaluated.

2. Materials and methods

Ankara Central Wastewater Treatment Plant was activated in 1997 and it has created a great relief especially for Ankara Creek which had become a sewerage and for the aquatic environment to which it is connected. The location of the plant was chosen considering that it would be out of town until 2025. The topography of the city and the treatment plant made it possible to design the treatment plant in a way that did not require a pump station in the transportation of the wastewater to the plant. All waste collected in the sewage system reaches the plant with a strong gravitation. General layout and satellite image of Tatlar Wastewater Treatment Plant are given in **Figure 1**.

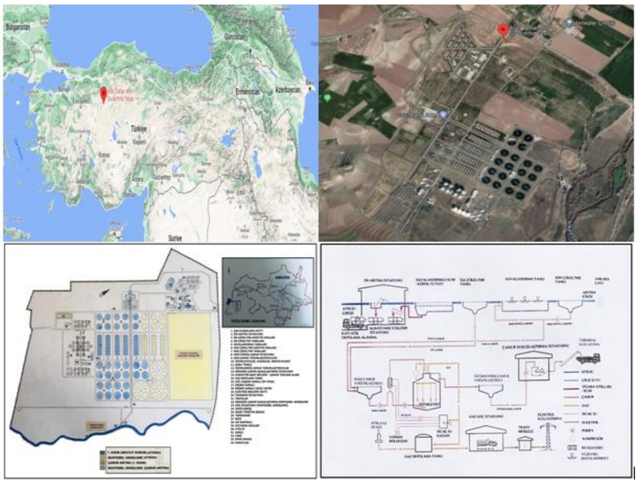


Figure 1. General layout and satellite image of Tatlar Wastewater Treatment Plant

The plant was designed according to the classical activated sludge system. In order for the solid content of the sludge taken from pre-sediment (pre-sludge) and aerobic tanks to reach the desired value, it is first taken into the raw sludge thickeners to thicken them with gravity and then it is expected to be thickened with sufficient waiting time. After that, raw sludge reaching the desired density is fed to the digestion functioning under anaerobic conditions for the purpose of stabilization, and biogas production is carried out under mesophilic conditions. The sludge decomposed in the digestion tanks are taken into the thickening tanks and here, the density of it is brought to desired values before the sludge dewatering process and then the rate of dry matter is increased to 26-30% by centrifugal decanters. Tatlar Wastewater Treatment Plant was designed and built in the classical activated sludge system. It was identified that there was an organic matter input more than 66% in the wastewater input values of the plant on a monthly basis. This situation indicates that it contains the most suitable conditions for obtaining energy through the production of biogas from wastewater. It also indicates that an investment for the purpose of obtaining energy (etc., burning, drying-burning) can be considered in the context of the final disposal of the dewatered sewage sludge.

The analyses and methods performed during the study are as follows: The international TS EN ISO 10523 standard was used to determine the pH value in municipal and industrial wastewater and liquid sludge. Electrical conductivity was measured with TS 9748 EN 27888 standard. Suspended Solid (SS) was determined by the SM 2540 D method. Chemical oxygen demand (COD) was determined by the SM 5520 D method. Biological oxygen demand (BOD) was determined by the SM 5210 B method. Organic Matter Quantity was determined by the SM 2540 E method. Characterization of wastes - Solid extraction analysis - Suitability test for solid extraction of granular solid wastes and sludges was carried out according to TS EN 12457 method. The analyses of various heavy metals which have priority to be considered as mentioned in the relevant legislation (Regulation on the Use of Domestic and Urban Sewage Sludge in the Soil, 2010) regarding the use of sewage sludge in the soil due to anaerobic stabilization in wastewater treatment plant are given in **Table 1**.

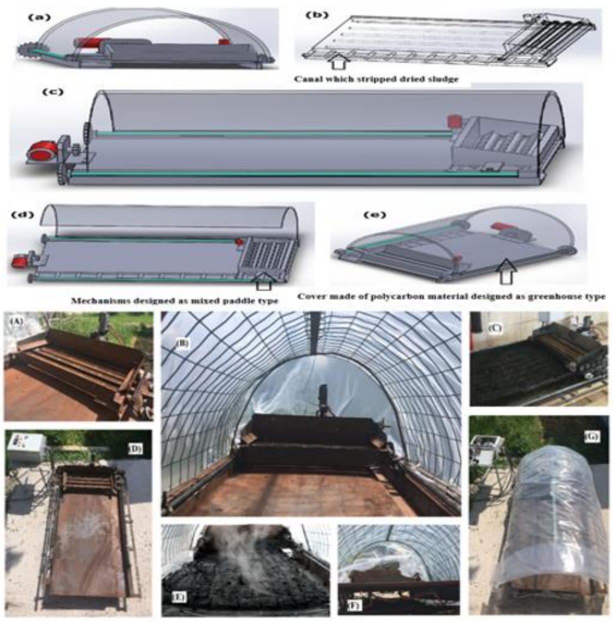


Figure 2. Pilot scale hybrid sludge drying system. (a) side views (b) resistances (c) front views (d) mechanisms designed side by side and like mixer paddle type (e) polycarbonate material that can pass the sun rays easily. (A) The mixer-paddle mechanism of system (B) inside of dryer (C) the moment the dewatered sludge is laid in the dryer (D) electrical resistances (E) drying sequence (F) the appearances of the sludge in the drying area (G) external view of the system

Table 1. Heavy metal levels of dehydrated sludge of the WWTP

Heavy Metals	Sample values taken in winter period (mg/kg)	Sample values taken in Summer period (mg/kg)	Permissible maximum heavy metal contents in stabil sewage sludge which used in soil (mg/kg oven dry soil)
Copper (Cu)	219.4 ± 1.75	311.6 ± 5.8	1000
Chromium (Cr)	222.56 ± 0.53	372.1 ± 2.4	1000
Zinc (Zn)	1932 ± 3.3	2418 ± 23.7	2500
Cadmium (Cd)	5.7 ± 0.07	9.5 ± 0.04	10
Lead (Pb)	72.76 ± 0.04	92.6 ± 0.4	750
Nickel (Ni)	73.62 ±0.08	141.5 ± 1.2	300
Mercury (Hg)	< 1	< 1	10

2.1. Pilot scale hybrid sludge drying system design

The sludge samples were taken from the sludge dewatering station of the Tatlar Wastewater Treatment Plant, which was the final point in which the sludge treatment was performed, and they were tested in the pilot-scale hybrid sludge drying system. The sewage sludge that has been stabilized before the dewatering is dehydrated at the sludge dewatering station up to an average rate of 26-30% dry matter. After the dewatering process is completed, the saturated sludge is sent to the storage areas. In terms of sewage sludge, sludge drying beds with an open-top structure used in previous years can be shown as the first example of the use of solar drying systems. Solar sludge drying systems are able to vaporize water up to 70% of water in the sludge. Considering that drying efficiency varies depending on climate conditions in the mentioned system, in this study, it was thought that the drying system should be hybrid type in order to minimize this problem (**Figure 2**). Although **Figure 2** shows the real images of our pilot-scale sludge drying system and photos of drying process.

In this context, in order to increase the drying rate above 90%, in addition to the solar radiation source, a thermal drying source (electrical energy) was also installed in our sample dryer. (a) and (c) also have side and front views. In this context, 5 resistances of 550 W power placed under the sludge drying area are shown in (b). The dryer tray heated by the help of resistances warm the sewage sludge up. Our dryer carries out the sludge drying process by directly contacting the surface tray which is heated with the help of resistance. The sewage sludge is exposed directly to high heat. The pilot-scale sludge drying system was designed to dry the spread sludge by means of electric energy as a renewable energy source and instant solar radiation as a thermal source. In this way, a reduction close to 4 times in the amount of waste sludge will be ensured in a safe manner. In addition, the obtained sludge will be in a consistence that can be easily managed or stored. As layout and drying area, our dryer has been designed in the dimensions of 60 × 120 cm. On the dryer, there are mechanisms (d) designed side by side and like mixer paddle type. The mixers perform two separate functions and therefore, each moves in two directions. The first function is running upside down process of the sludge for ventilation, fragmentation and homogenous mixture of dry and wet sludge. In addition, the mixer mechanism moves forward and backward in the drying area and ensures equal and uniform distribution of sludge in the drying area, and thus creating of an ideal sludge bed is ensured. The speeds of the mixer have been changed due to the need and a significant decrease in sludge drying time has occurred. As the basic requirement of the use of solar radiation in the sludge drying process, dryingenvironment and top of it were prepared in a greenhouse type. As the coating material, polycarbonate material that can pass the sun rays easily (e) was used. This material is water resistant product which minimizes heat loss. The thermal isolation of the material, which has a very high rate of thermal insulation, is also very high. The temperature of the pilot system is kept under control with the help of thermometers which measure the ambient temperature inside the dryer and the floor temperature of the sludge drying area.For the purpose of making the sludge as granules in one dimension at the end of the drying, by continuously moving back and forth on the dryer area, the mixer paddle mechanisms that perform the laying process both increase the drying speed of the sludge and provide the decomposition of the sludge that is drying. The sludge reaching sufficient dryness is discharged to the 'dried sludge canal' seen in (b) by the help of a stripper positioned under the mixer paddles. The stripper system is moving perpendicular to the motion of the mixer mechanism. (A) shows the mixer-paddle mechanism of our system. This mechanism both serves as new sludge laying function along the drying area and enables the mixing of sludge in drying phase. It realizes this situation on the shafts with the help of the wheels positioned on the side of the dryer area. This movement is repeated as forwards and backwards on the area on which the sludge has been laid and throughout the sludge laying borders. Our sludge stripper system is located under the mixer – paddle mechanism and ensures the sludge, which reaches enough dryness, to be carried to the channel positioned on the drying surface edge. (C) and (F) shows the appearances of the sludge in the drying area. Our sludge drying system has a structure that can use electrical energy in terms of thermal resource. (E) shows 5 electrical resistances installed on the lower part of the dryer area. In the same **Figure 1**, the vapors rising from the sewage sludge due to the effect of heat during the drying process are seen. While the drying study was performed, the sludge laying thickness was applied as 4 cm. The reason for this was that because our plant had a small size and capacity, this height was determined as optimum based on the mixer-paddle mechanism in our drying system. When the sludge with less volume was laid (in a way in which laying height was not exceed 4 cm), it was observed that drying rate increased according to normal time and energy consumption decreased.

Sewage sludge was taken from the outlet of the decanter of the facility. Then, the sludge, which reached a dryness of approximately 90% and above, was made into a uniform granule for analysis. Moisture and organic-inorganic matter (%) determinations of the sludge obtained as granules were made. After drying the sludge, sludge samples were taken from the dryer for laboratory analysis.

2.2. Drying studies of the sewage sludge

In our pilot-scale hybrid sludge drying system, before the sludge drying operation was performed, periodic averages of the analysis results of the percentage values of the dry matter, organic matter and inorganic matter belonging to the sewage sludge to be used as sample were calculated.

In our hybrid-scale sludge drying system, for the drying operation, the sewage sludge dewatered by cationic polyelectrolyte and centrifugal decanter in the dewatering unit, which is the next stage of the digested sewage sludge discharged from the digester after anaerobic digestion in wastewater treatment plant, was used. The analyses values of the dewatered treatment sludge obtained by drying in pilot scale drying system were analyzed as spring semester, summer semester, autumn semester and winter semester. Analysis related to drying of dewatered sewage sludge in pilot-scale drying system was carried out as spring, summer, autumn and winter periods. The sludge drying process was performed by using both solar radiation source (sun) and thermal drying source (electrical energy). Experimental studies with sludge samples after drying were carried out according to international analysis methods.The samples taken monthly from the sewage sludge which was the output of the wastewater treatment plant and dewatered by means of Decanter centrifuge were dried in our pilot sized sludge treatment plant. The seasonal 3 month average of these dried sludge samples was processed as the final.

3. Results and discussion

In this study carried out to determine the final disposal of the sewage sludge originated from Ankara Wastewater Treatment plant, samples from inlet and outlet waste water of the plant were taken on monthly basis during 2017 for revealing of the wastewater composition which constitutes the basic nature of sewage sludge. COD, BOD_5, SS were analyzed in the taken samples. The removal efficiencies obtained as the results of the analyses are presented in **Figure 3**. Looking at the results, it is observed that the rate of removal efficiency for each parameter is over 88%.

According to **Figure 3**; in 2017, the lowest removal efficiency average based on the parameters was achieved in COD, and the highest removal efficiency was achieved in AKM parameter. The period when the removal efficiency was lowest in all three parameters during the year was in September 2017.

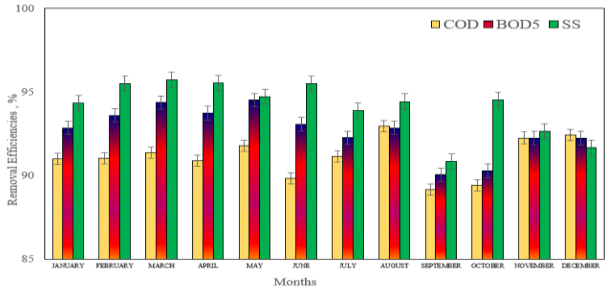


Figure 3. COD, BOD5, and SS (%) removal efficiencies

Table 2. WWTP sludge and output wastewater analysis values

Period	Sewage Sludge Types	Raw Sludge	Digested Sludge	Dewatered Sludge	Exit Wastewater
January-February-March	Solid Matter Ratio (%SM)	3.57	3.93	25.9	-
	Organic Matter Content (%)	66.1	47.6	42.8	-
	Inorganic Matter Content (%)	33.9	52.4	57.2	-
	pH Values	7.91	7.33	8.21	8.03
	Electrical Conductivity	-	-	-	1330
April-May-June	Solid Matter Ratio (%SM)	4.19	3.09	28.2	-
	Organic Matter Content (%)	67.2	46.4	47.3	-
	Inorganic Matter Content (%)	32.8	53.4	52.7	-
	pH Values	7.88	7.46	8.18	7.93
	Electrical Conductivity	-	-	-	1214
July-August-September	Solid Matter Ratio (%SM)	3.03	3.11	26.7	-
	Organic Matter Content (%)	63.2	48.2	50.5	-
	Inorganic Matter Content (%)	36.8	51.8	49.5	-
	pH Values	8.15	7.54	8.47	7.89
	Electrical Conductivity	-	-	-	1105
October-November-December	Solid Matter Ratio (%SM)	4.09	2.74	27.1	-
	Organic Matter Content (%)	68.4	51.9	51.0	-
	Inorganic Matter Content (%)	31.6	48.1	49.0	-
	pH Values	8.07	7.41	8.30	7.98
	Electrical Conductivity	-	-	-	1255

Table 3. Seasonal analysis results of the sludge drying studies

Sewage Sludge types	Spring		Summer		Fall		Winter	
	Dewatered Sludge Values	Dried Sludge Values	Dewatered Sludge Values	Dried Sludge Values	Dewatered Sludge Values	Dried Sludge Values	Dewatered Sludge Values	Dried Sludge Values
Solid Matter Ratio (% SM)	24.37	91.53	26.18	95.87	28.05	88.32	25.73	90.06
Organic Matter Content (%OM)	54.32	53.70	49.45	48.74	53.35	52.41	48.76	49.48
Inorganic Matter Content (% IOM)	45.68	46.30	50.55	51.26	46.65	47.59	51.24	50.52
Total Organic Carbon(% TOC)	7.43	-	8.10	-	7.82	-	7.36	-
Total Nitrogen	1.72	-	2.61	-	1.93	-	1.76	-
Total Phosphorus	1.38	-	1.09	-	1.27	-	1.65	-

In our pilot-scale hybrid sludge drying system, before the sludge drying study was performed, three-month averages of the analysis results of the percentage values of the dry matter, organic matter and inorganic matter belonging to the sewage sludge to be used are given in **Table 2**. In order for the sludge to reach the desired % SM (Solid Matter) ratio, before the anaerobic stabilization process, the pre and extra sludge emerging in the plant are taken into "raw sludge thickening tanks" and thickening of them is expected. It was observed that raw sludge (non-digested sludge) obtained from sludge samples from different units of the plant had an average rate of 3.72% SM on the basis of the year. It was identified that the average annual value of pH was 8. Organic matter content was found to have an average rate of 66.225%. The high organic content of raw sludge before anaerobic digestion suggests that the production of good amounts of digestion and biogas may be high. Looking at the organic matter changes between digested sludge and dewatered sludge, the fact that after the anaerobic stabilization process, the bacteria in the tank continues to use organic matter while waiting for the desired percentage of SM in the sludge thickening tanks can be shown as the reason for the falling of organic matter.

Therefore, the waiting time should be well adjusted in the sludge thickening tanks (Frutuoso *et al.,* 2025). The change in the amount of organic matter is important in terms of the disposal type of sewage sludge. Although the sludge was subjected to anaerobic digestion, it is observed that the amount of organic matter is between 42.8% and 51.4%. The situation reveals that in terms of the final disposal of it, the sludge is suitable for both disposal and obtaining energy by burning. Samples from the wastewater treatment plant which were dewatered by decanter centrifuge and were taken 3 times per month during the year were dried in our pilot scale sludge drying plant and seasonal averages were determined (**Table 3**).

When the results obtained in the spring period were examined, it was observed that the rate of SM% was 24.37 before the drying process of dewatered sewage sludge and it increased to 91.53 after drying activity. İf the summer period were examined, it was observed that the rate of SM% was 26.18 before the drying process of dewatered sewage sludge and it increased to 95.87 after drying activity. During the summer period, there was an increase in the values of TOC and TN compared to the spring period. In addition, TP content of sewage sludge decreased compared to the spring period. Examining the results obtained in the fall period, a volume decrease of approximately 3.15 times occurred in the sewage sludge. When the results obtained in the winter period were examined, a volume decrease of approximately 3.50 times occurred in the sewage sludge. According to the result obtained during the same study, although it was observed that there was no significant change in total organic matter averages of sewage sludge during the all periods, a slight increase occurred. As compared to the fall period, it was observed that there was a decline in the contents of TOC and TN . However, compared to the summer period, the increase in the TP content of the sewage sludge was observed. The graph was drawn by taking the averages of the mean of the final data obtained during sludge drying studies on the seasonal basis (**Figure 4**).

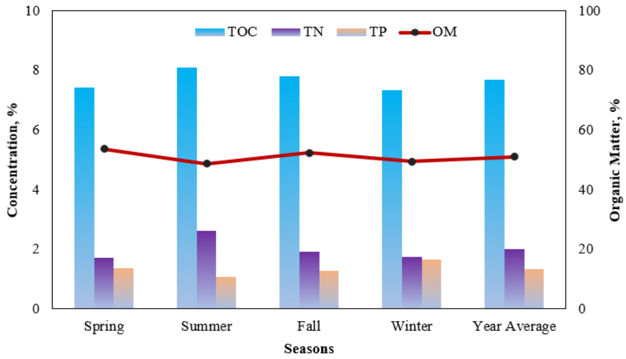


Figure 4. WWTP results based on seasonal basis

It is seen that the amount of organic matter in question is high; this value is the decomposed sludge average of the organic matter content that is subjected to the digester. When looking at the parameters TN and TP, there was an opposite situation. Looking at the TOC release, it was observed that it showed parallel changes with the TN parameter. On an annual average, the TOC value is 7.69%.In accordance with the “Criteria for the Regular Storage of Non-Hazardous Wastes” given in Annex-2b of the “Regulation on the Regular Storage of Wastes”, it was observed that it had a slightly higher value than the relevant limit value (50 g/kg = 5%). It can be thought that the reason of the changes in TN and TP content in sludge cake samples may be the input wastewater feature, the commercial activity structure of the region, consumption habits and the treatment process. It was determined that the TOC contents of the sludge cake samples taken from the dewatered sewage sludge samples taken from the Tatlar Wastewater Treatment Plant for representing winter and summer seasons were 225 g/kg in winter and 250 g/kg in summer. In accordance with the “Criteria for the Regular Storage of Non-Hazardous Wastes” given in Annex-2b of the “Regulation on the Regular Storage of Wastes”, it was observed that it had a very high value than the relevant limit value (5%) (MEU, 2015). Water content, amount of organic matter, calorific value, TOC, Cl, N and P analyses were performed in the wastewater treatment plant for both summer and winter period averages after sludge drying activities (**Table 4**).

Table 4 Analysis results obtained in dried sludge

	Water Content (%)	Organic Matter (%)	Calorific Value (kcal/kg dm)	TOC (% SM)	Cl (ppm)	N_d* (ppm dm)	P_d* (ppm dm)
Summer	7.31	49.9	2579	28.51	1279.6	797	264
Winter	6.79	55.21	3073	33.24	6757.9	1923	326

**dissoluble*

Table 5. Heavy metal quantities obtained in dried sludge, ppm

	Al	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	Co	Mo
Summer	15126	0	0	237	232	12380	377.6	0	167.46	1305	0	0
Wınter	14084	0	0	185.26	147.12	12538	384.2	0	145.62	1725.2	0	0

The summer season, it was seen that dried sludge reached the rate of 92.69% SM. The amount of organic matter was found as a very good value for an anaerobic digested sewage sludge. The calorific value of sewage sludge, which was treated in the anaerobic digester, then dewatered and finally dried in our hybrid sludge drying system, was measured as 2579 kcal/kg sm. The winter period, it was observed that there was a slight increase in these values compared to the summer period. After the sludge drying activities in the wastewater treatment plant, heavy metal analyses were carried out for the sewage sludge dried in summer and winter periods (**Table 5**).

For both periods, As, Cd, Zn, Co were not detected in the sludge samples. During the winter season, there was a decrease in Al, Cr, Cu and Pb values compared to the summer period. On the other hand, an increase in Fe, Mn and Zn values was observed compared to the summer period. At the same time, the high values of Al and Fe are striking. At the wastewater treatment plant, wastewaters are subjected to physical and biological treatment. There is no chemical treatment in the plant. In spite of this, the presence of a chemical that is used at certain intervals and rates during the treatment process may be considered as the cause of high rates of soil-group heavy metals (Chernysh *et al.,* 2024). For the agricultural use of sewage sludge, the maximum permissible heavy metal content in stabilized sludge has been informed by the U.S. Environmental Protection Agency’s Part 503 rule, European Union directive (86/278/EEC), and Annex 1-B of the “Regulation on the use of domestic and urban sewage sludge in the soil”. our heavy metal analysis results are compared with the aforementioned maximum permissible heavy metal content in stabilized sludge that can be used in soil (**Table 6**).

Table 6. Comparison of the quantities of heavy metals in dried sludge

Parameters	Unit	ABD	AB	TÜRKİYE	Results	
					Summer	Winter
Arsenic (As)	mg/kg	41	-	-	0	0
Cadmium (Cd)	mg/kg	39	20 – 40	10	0	0
Chrome (Cr)	mg/kg	-	-	1000	237	185.26
Copper (Cu)	mg/kg	1500	1000- 1750	1000	232	147.12
Manganese (Mn)	mg/kg	-	-	-	377.6	384.2
Nickel (Ni)	mg/kg	420	300- 400	300	0	0
Lead (Pb)	mg/kg	300	750- 1200	750	167.46	145.62
Selenium (Se)	mg/kg	100	-	-	-	-
Zinc (Zn)	mg/kg	2800	2500- 4000	2500	1305	1725.2

Table 7. The use of dried sludge as additional fuel

Parameters	Unit	Communication Limit Values	Summer	Winter
Calorific Value	kcal/kg	> 2500	2579	3073
Humidity Rate	%	<35	7.31	6.79
Total Heavy Metals	mg/MJ	<2500	2319. 06	2587.4

The heavy metal contents found in both summer and winter periods in this study, it was observed that they did not exceed the maximum metal content allowed in the stabilized sludge that can be used in the soil indicated in the aforementioned Regulation. It may be thought that this dried sewage sludge will be appropriate for the use of it in the soil (Khanlari *et al.,* 2025). In the context of the use of wastes as alternative raw materials and the preparation of refuse-derived fuel; in terms of the use of sewage sludge as refuse-derived fuel (RDF) and/or additional fuel, the comparison of the results with the limit values in Annex-3 of “Refuse-Derived Fuel, Additional Fuel, and Alternative Raw Materials Communiqué" is given in **Table 7**.

When we examine the calorific value, humidity rate and chlorine content parameters, it is observed that the obtained results are appropriate in terms of the use of the sewage sludge for the preparation of refuse-derived fuel and/or additional fuel. When the average of both periods was taken, this value was below the relevant limit value. The Wastewater Treatment Plant is the largest wastewater treatment plant in the region in terms of the established power. when the results of heavy metal are examined, it can be interpreted that there is no more interference to the wastewater other than domestic pollution. In addition, as can be understood from the results on the basis of years, heavy metal ratios in wastewater content are in a certain order. This can provide significant assurance for the investments to be made within the scope of final disposal of sewage sludge on the basis of heavy metals in sewage sludge.

The evaluations made according to the samples showed that the sewage sludge (samples taken from the outlet of the sludge dewatering unit) from Ankara Tatlar Wastewater Treatment Plant was in the group that can be used in the agricultural applications. It was stated in the relevant report that the sewage sludge from Ankara Tatlar Waste Water Treatment Plant was in the medium risk group. This result showed similarities with those found by us. According to this opinion; considering the number of domestic wastewater treatment plants in Ankara province and its districts and the sludge amounts they produce and considering the cement factories in the region and their production/need capacities, the amount of produced sludge will be able to meet the amount of the additional fuel needed by these plants (Düzgün, 2015).

4. Conclusions

The calorific value is very high for sewage sludge. In this way, in terms of obtaining energy, it is possible to evaluate the sewage sludge by burning. Looking at these results, the high calorific value of dried sewage sludge reveals the possibility of burning it within the context of final disposal of the sludge. As can be understood from the conducted analyses, it is possible to use dried sewage sludge in the soil (etc., soil strengthening agent, compost use and fertilizer production). Taking into account all of these results, it can be said that drying of sewage sludge with a system having hybrid structure running by both solar radiation and thermal energy resources integrated to the system for uninterrupted power will be the most appropriate solution. As a result of the study, the costs of the treatment plant are also minimized. The use of these drying methods, which are evaluated separately in the literature, in hybrid form and will provide advantages in the elimination of pathogens in the structure of the sludge will be a reference for future research.

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.

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Availability of data and materials

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