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Effect of biogas waste applications on soil moisture characteristic curve and assessment of the predictive accuracy of the Van Genuchten model

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Abstract

Biogas production has recently become an important issue in countries where alternative energy sources are gaining importance. The study investigates the use of waste, the final product of production, as a soil conditioner and fertilizer for sustainable soil management. The study examines the effects of different amounts of biogas waste [0 (B0), 1 (B1), 2 (B2), 3 (B3) and 4 (B4) ton da^{-1}] on some soil properties and soil moisture characteristic curve (pF). In addition, the van Genuchten model, which has been long and widely used in many studies for the prediction of hydraulic properties, was compared with the pF curves that were obtained using the predicted and real values obtained from the applications. The results of the study showed that although biogas waste applications were more effective in the wet region of the moisture characteristic curve, B3 was the most effective dose that improved the physical properties of the soil. The B4 application had a decrease of about 16% in the penetration resistance and an increase of about 21% in the wilting point compared with those of the control group. The decrease in the macro pore volume due to biogas waste applications was not statistically significant, while biogas waste applications caused a statistically significant increase in the micro pore volume ($P < 0.05$). Among the van Genuchten model parameters, the moisture content in saturation (θ_S) and residual water (θ_r) had realistic results in all biogas waste applications. Moreover, the air entry value ($1 / \alpha$) was estimated to be 41.667 cm in the B0 application and 55.556 cm in the B4 application. In conclusion, high-accuracy estimates were obtained using the van Genuchten model with a R^2 value of 0.901 and root mean square error (RMSE) value of 0.061 cm^3 cm^{-3} in the moisture characteristic curve of the control (B0) soil.

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Introduction

In recent years, available water amount has decreased due to global warming and unconscious water consumption. Thus, its importance is increasing day by day. Furthermore, its increasing consumption due to rapidly increasing population will inevitably cause drought. The scenarios of climate change point to growing risks of drought and land degradation due to the limited use of technological developments in agricultural production as opposed to excessive resource consumption (IPCC, 2019). Turkey, which has a surface area that is mostly dominated by arid, semi-arid or semi humid climatic characteristics, uses 70% of its fresh water resources for agricultural activities (TUIK, 2012). The unconscious and unplanned use of these resources can lead both to the decrease of the already scarce water supply and land degradation (salinification, runoff, etc.). Therefore, knowing the soil-plant-water relationships in soils on which

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agricultural activities are carried out especially in regions with arid and semi-arid ecosystems are highly important to improve issues such as the preservation of soil water and development of irrigation programs.

The soil-water dynamic and soil-water potential can considerably change depending on texture, structure and compaction (Liyanage and Leelamanie, 2016; Fashi et al., 2017). The soil-water dynamic includes the entry of water to soil, water storage, water losses and water use by plants and is evaluated using the water retention curves of soils. Water can move or be retained in the pores of soils. The water retention characteristics of soils change depending on the pore structure of soils, infiltration rate and hydraulic conductivity. The water retention curve explains the relationship between the amount of water held in the soil and retention forces. In their study on the effects of organic material applications on water retention and water-entry value, Liyanage and Leelamanie (2016) reported that the soil water content significantly and linearly increased with increasing organic material content. Again, Müjdeci et al. (2020) reported that stable manure and green manure applications increased volumetric water content at all retention pressure. Barzegar et al. (2002) stated that organic material applications increased the water content held at levels below 100 kPa.

Various numerical models have been developed to predict soil water retention curves due to the difficulty and cost of determining the curves. The applicability of the models varies depending on the region and soil properties (Alaboz and Işıldar, 2019). The model developed by van Genuchten (1980) is one of the most used equations. Retc and Rosetta are widely used programs for the prediction of the parameters of the van Genuchten equation. Unguraşu et al. (2012) reported that they successfully predicted all hydraulic properties (water retention parameters, hydraulic conductivity values under saturated and unsaturated conditions) within the scope of the Rosetta neural network using the parameters of sand, clay and silt contents, bulk density and water contents at 33 kPa and 1500 kPa.

Energy need and consumption are constantly increasing due to the increasing population in Turkey and the world. There is a need for different energy resources and biogas is one of these alternative energy resources. Organic wastes of animal and plant origin are generally used in biogas production (Şenol et al., 2017). Biogas production involves an anaerobic degradation process and the wastes of its production are turned into valuable organic fertilizers (Kılıç, 2011). Yaraşır et al. (2018) reported that biogas waste applications had a positive effect on wheat yield and quality parameters. Again, Islam et al. (2010) reported that biogas applications positively affected the yield and quality parameters of corn silage.

The study investigates the effect of biogas waste applications on water retention characteristic curve and assesses the predictive accuracy of the van Genuchten equation, a model widely used for the prediction of soil-water dynamic.

Material and Methods

Study Area

The study area is located in the east of the Isparta–Burdur Highway within the borders of Isparta Applied Sciences University. Its coordinates are WGS 1984 UTM Zone 36N 283100- 282921 North longitude and 4190355-4191399 East latitude (Figure 1). The study area is on a land opening to the Isparta plain in the southeast direction and surrounded by high hills and ridges in the other direction. According to the long-term meteorological data (1974-2017) of the study area, the region has a semi-arid climate. The annual mean temperature and precipitation are 12.3ºC and 467 mm, respectively. According to the Newhall simulation model (Figure 2) for the soil climate regime, the soil temperature and moisture regime of the study area are mesic and xeric (dry xeric in the subgroup) (van Wambeke, 2000).

Application material and experimental setup

The study was carried out in accordance with the randomized block experimental design. The biogas waste (B) used as the organic material was obtained from a biogas production facility. Farmyard manure was used in biogas production and the waste that contain 15% moisture and leave the Separator Press as an end product was used as the organic material. Different ratios of biogas waste were used [0(B0), 1(B1), 2(B2), 3(B3), 4(B4) ton da^{-1}] and the waste was applied in 5 repetitions to parcels of 3*5 m^2. The study area was ploughed and seed bed was prepared using a rotary harrow at the time of harvest. The experiment was set up on 19.11.2019 and B was mixed into a depth of about 0-20 and, then, 2 rows of barley (Tarım-92) was planted using a 6-split row planter with an automatic piston. As the main fertilizer, 10 kg da^{-1} N, 8 kg da^{-1} P and 8 kg da^{-1} K were applied. The trial was harvested on 05.07.2020. Prior to the harvest, disturbed and undisturbed soil samples were collected in three repetitions and brought to the laboratory. Then, preparations were made for the soil analyses.

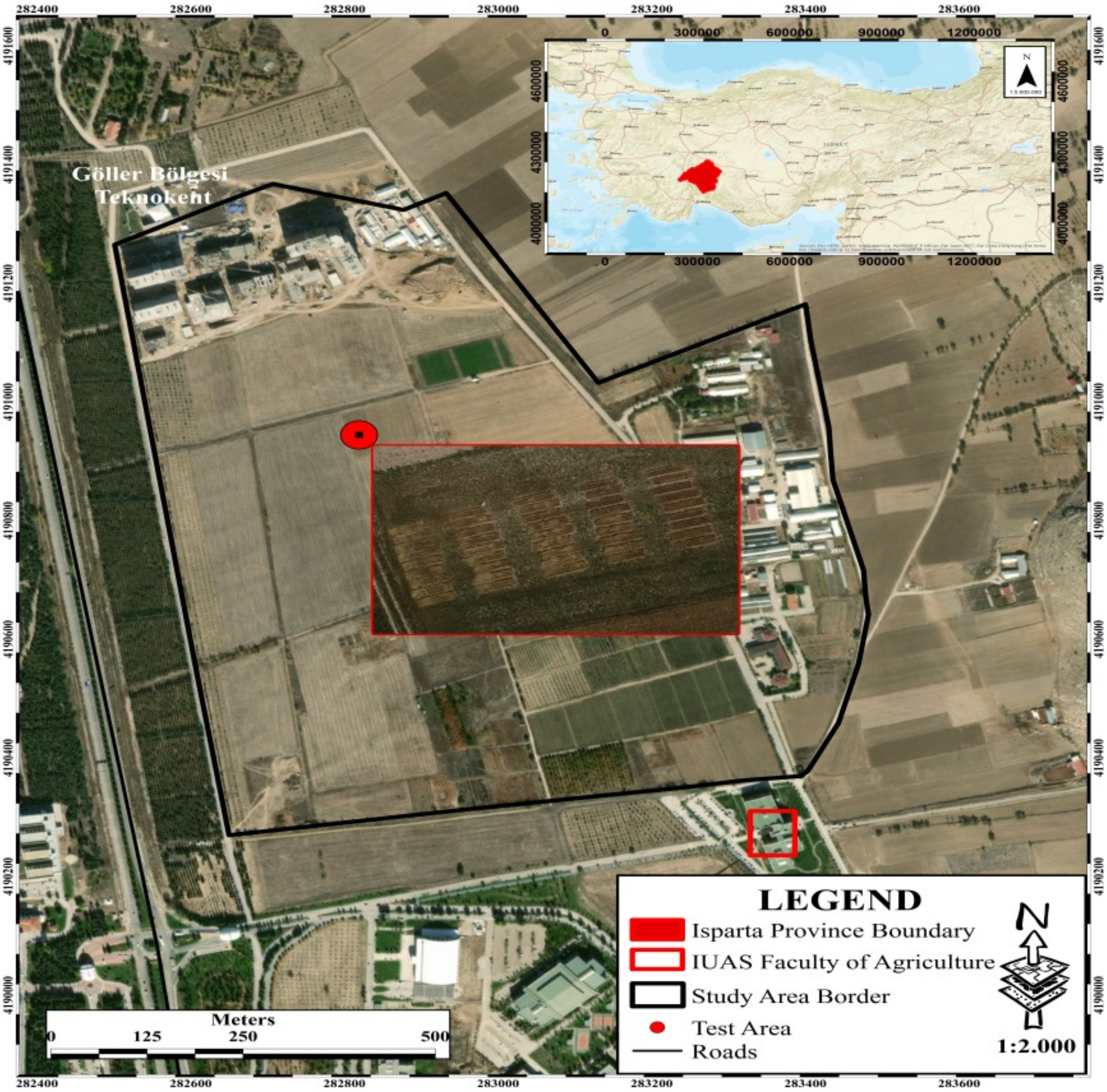

Figure 1. Study area

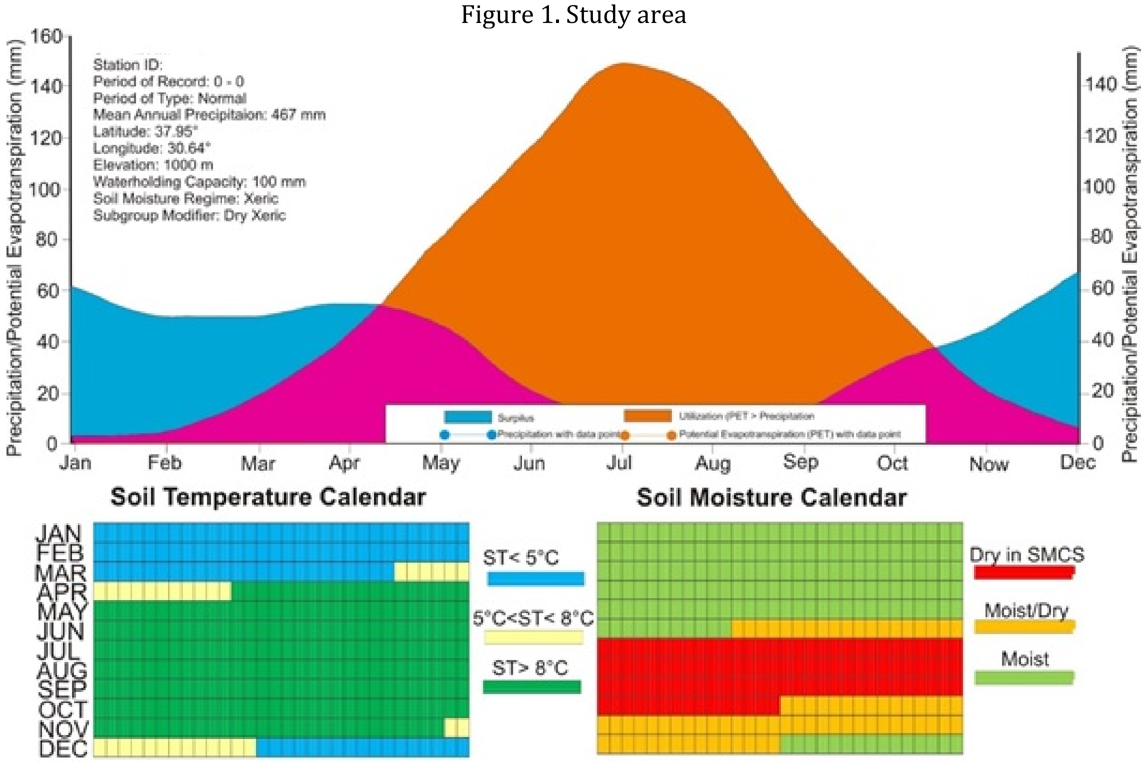

Figure 2. Diagram of the soil moisture and temperature regimes

Method

The texture analysis of the soils (sand, silt and clay %) was determined with the Bouyoucos hydrometer method (Bouyoucos, 1962). Bulk density (P_b) was determined using sampling cylinders (100 cm^3). The electrical conductivity (EC) and pH values of the soils and biogas waste were measured using 1:1 soil-water and 1:5 organic material-water suspensions. The $CaCO_3$ % content was determined using volumetric calcimeter and organic matter content was determined using the Walkley-Black and dry combustion methods (Soil Survey Staff, 1993). The nitrogen content was determined by following the Kjeldahl method (Kacar, 2009) and the moisture characteristic curve was determined in volumes using a pF set with ceramic plate (U.S.A, Soil Moisture Equipment Corp.) (Soil Survey Field and Laboratory Methods Manual, 2014). The 0.001(θ_S)-, 0.1-, 0.33(θ_{TK})-, 1.0-, 5-, 10- and 15(θ_{SN})-bar moisture contents were used to form the pF curves. The air-dry moisture contents of the soils were evaluated as water kept at 1000-atm pressure. The total pore volume was obtained from the water volumes at saturation and micro pore volume was obtained from the water volumes kept at 0.33 bar (field capacity). The macro pore volume was obtained by subtracting the micro pore volume from the total pore volume (Danielson and Sutherland, 1986). The penetration resistance (PR) measurements were made with a cone penetrologger (Eijkelkamp) using the conical edge with 60º (NEN 5140, 1996) and base surface of 1 cm^2. The moisture corrections in the penetration resistance value was made using the correction equation proposed by Alaboz (2019).

Van Genuchten model

The van Genuchten model (van Genuchten, 1980) (Equation 1) was used in the prediction of the soil moisture characteristic curve. Retention Curve (RETC) program-Rosetta neural network was used in the evaluation of the moisture characteristic parameters. For the determination of the coefficients of the shape parameters, (1) texture class, (2) sand, clay and silt contents, (3) sand, clay and silt contents, bulk density, (4) sand, clay and silt contents, bulk density, water content at 33kPa and (5) sand, clay and silt contents, bulk density, water contents at 33kPa and 1500 kPa properties and their predictions were used.

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1+|ah|^n)^m} \quad \text{(Eq. 1)}$$

θ(h): volumetric water content in soil water potential (cm^3 cm^{-3}) h: soil water potential (cm), θr: residual water content (cm^3 cm^{-3}), θs: saturated water content (cm^3 cm^{-3}), α (cm^{-1}), n ve m: are shape parameters. n>1, ve m : 1−1/ n (Mualem, 1976), 0<m<1.

Assessment of the predictions

The coefficient of determination (R^2) and root mean square error (RMSE) values were used to evaluate the relationship between the real data obtained from the soil moisture characteristic curve and predicted values obtained using the Van Genuchten model (Equation 2, 3).

$$\text{RMSE} = \sqrt{\frac{\sum (Zi-Z)^2}{n}} \quad \text{(Eq. 2)}$$

$$R^2 = \left[\frac{\sum ZiZ - \frac{\sum Zi \sum Z}{n}}{\left[\sum Zi^2 - \frac{(\sum Zi)^2}{n}\right]\left[\sum Z^2 - \frac{(\sum Z^2)}{n}\right]}\right]^2 \quad \text{(Eq. 3)}$$

Zi: predictive value, Z: actual value, n: number of observations.

The effects of the application on certain soil properties were examined using the Tukey test among the multiple comparison tests and Minitab 16 package program.

Results and Discussion

Table 1 shows the properties of the soil and biogas waste. According to Kacar (2009) and Hazelton and Murphy (2016), soils from the loamy clay texture class contain high levels of lime and low levels of organic material and have a slight alkaline reaction and do not have a salinity problem. The organic material content of the biogas waste was 46.7%. The biogas waste had a pH value of 7.70 and its C/N ratio was 12.1.

Table 1. Some properties of soil and Biogas waste

	Texture	$CaCO_3$, %	OM, %	pH	EC, dS m^{-1}	C/N
Soil	CL	25.43	1.69	7.89	0.38	10.9
Biogas waste			46.70	7.70	1.44	12.1

Table 2 shows the effects of biogas waste applications at different ratios on some soil properties and Figure 3 shows their effects on soil moisture characteristic curve.

Table 2. The effect of biogas waste applications on soil properties

	P_b , g cm^3	PR, MPa	Macro pore volume	Micro pore volume	θ_S , cm^3 cm^3	θ_{FC}, cm^3 cm^3	θ_{WP}, cm^3 cm^3	θ_{AWC}, cm^3 cm^3	OM, %
B0	1.46a	1.56a	0.26	0.28c	0.54b	0.28c	0.18b	0.10c	1.69e
B1	1.35b	1.37b	0.25	0.29bc	0.54b	0.29bc	0.18b	0.11c	2.03d
B2	1.29c	1.30c	0.24	0.33 b	0.57ab	0.33b	0.19b	0.14bc	2.47c
B3	1.22d	1.28c	0.24	0.38a	0.62a	0.39a	0.19b	0.20a	2.86b
B4	1.20d	1.22d	0.22	0.39a	0.61a	0.38a	0.23a	0.15b	2.97a
P	*	*	NS	**	**	**	*	*	*

P_b : bulk density, PR: penetration resistance, θ_S: saturated water content, $\theta_{FC:}$ field capacity, θ_{WP}: wilting point θ_{AWC}: available water content, OM: organic matter, P: significance level, * : P<0.01, ** : P<0.05, NS : not significant

The changes in the effects of different levels of biogas waste applications on the investigated properties were statistically significant, except for macro pore volume. The organic material contents of the soils significantly increased due to the biogas waste applications (P<0.01) and these increases caused expected decreases in bulk density and penetration resistance. The bulk density in the control application was 1.46 g cm^{-3}, while the bulk density in the B4 application was 1.20 g cm^{-3}. Compared with the control application, penetration resistance decreased by about 16% in the B4 application. The increase in porosity due to the application of organic materials with a porous structure decreases penetration resistance and bulk density. The negative relationship between penetration resistance and porosity is in compliance with the literature (Gülser and Candemir, 2012; Mujdeci et al., 2017). The biogas waste applications did not have a significant effect on the macro pore volume of the soils, but the micro pore volume significantly changed depending on the applications (P<0.05). The 0.28-cm cm^{-3} micro pore volume in the control sample increased by 39% in the B4 application. The B3 and B4 and the B0 and B1 applications were statistically similar. Micro pores retain higher levels of water than macro pores (air-filled pores) (Calonego and Rosolem, 2011). Organic material particles enter the large pores in soils and create smaller-diameter pores. Thus, the B3 application was considered effective on water retention. The statistically-not-significant decrease in the macro pores is due to the increase in micro pores. The inverse proportionality of the air-filled pores to water-holding pores has also been reported in the literature (Birol, 2010).

Increasing doses of biogas waste application caused statistically significant changes in the soil moisture constants (θ_S, θ_{FC}, θ_{WP}, θ_{AWC}) (P<0.05; 0.01). The moisture content at saturation (θ_S) was at the same level in the B0 and B1 applications (0.54 cm cm^{-3}), while an application-caused increase, albeit unstable, was observed in other applications. The highest θ_S was obtained in the B3 application. The low saturation values are attributable to the number of large drainage pores and decreases in the total pore volume due to increasing bulk density with compaction. The θ_{FC} level in the control application was 0.28 cm cm^{-3}, while the other applications had θ_{FC} levels of 0.29, 0.33, 0.38 and 0.39 cm cm^{-3}, respectively. The θ_{WP} levels were 0.18, 0.18, 0.19, 0.19 and 0.23 cm cm^{-3}, respectively. The wilting point was stable until the B4 application and resulted in an increase in θ_{AWC}, while the increase in θ_{WP} in the B4 application caused a decrease in θ_{AWC}. The biogas waste application increased the number of water-holding pores in the soils. Until the B4 application, more water was held by plants by lowering the water-holding energy. Abdulwahhab (2020) reported that, with the application of cattle manure, the values at wilting point decreased leading to decreased water-holding energy and, thus, increased available water amount. The B4 application caused an increase in the wilting point by about 21%, which led to a decrease of about 25% in the plant-available water content.

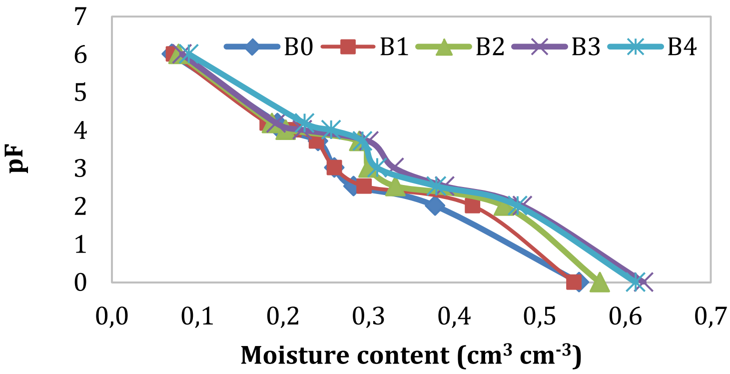

Figure 3. Soil moisture characteristic curve

Air-dry soil moisture (pF: 6) were 0.07, 0.072, 0.078, 0.082 and 0.09 cm cm^{-3}, respectively, depending on the application. The addition of organic material increases surface area and water-holding capacity increases at higher tensions (Gliński et al., 2011). The remaining water in soil approaches to zero as soil water potential increases and water retention curve begins to bend after a point and remains stable. The inflection point corresponds to the residual water content. Some studies refer to the residual water content either as the remaining moisture content below 1500 kPa or air-dry soil moisture content (Abdulwahhab, 2020). Within this framework, considering the air-dry moisture as the residual water content, residual water content with the increases in the applications. The soil moisture characteristic curve (Figure 3) revealed that the differences between the applications did not cause significant changes in the dry region. Especially after pF 4.2, the changes in the B0 and B1 applications were close to each other in water contents kept at lower pressures, while differences in the curves emerged as other applications differed when compared with the control application.

Prediction of the moisture characteristic curve using the Van Genuchten model

Table 3 shows the parameters that were obtained by assessing the combinations of five different soil properties using the Rosetta neural network for the prediction of the parameters of the van Genuchten model. For the prediction of the parameters, the closest results to the real θ_r and θ_S values were obtained by using the sand, silt, clay, bulk density, θ_{FC} and θ_{WP} properties. The air-dry moisture was taken into consideration for the comparison of the θ_r values. Unguraşu et al. (2012) reported that the Rosetta program successfully predicted the water-holding parameters and hydraulic conductivity at saturated and unsaturated conditions.

Table 3.Van Genuchten model parameters

	θ_S, cm^3 cm^3	θ_r, cm^3 cm^3	α, cm^{-1}	1/ α, cm	n	m
B_0	0.565	0.089	0.024	41.667	1.383	0.277
B_1	0.473	0.098	0.023	43.478	3.634	0.725
B_2	0.560	0.128	0.023	43.478	1.395	0.283
B_3	0.487	0.096	0.019	52.632	4.374	0.771
B_4	0.566	0.122	0.018	55.556	4.327	0.769

θr: residual water content (cm^3 cm^{-3}), θs: saturated water content (cm^3 cm^{-3}), α (cm^{-1}), n and m: are shape parameters.

The parameters that were predicted using the Rect-Rosetta program varied depending on the application. In the applications, θ_S levels were around the levels of 0.473-0.566 cm cm^{-3}, while θ_r ranged from 0.089 to 0.128 cm cm^{-3} and α ranged from 0.018 to 0.024 cm^{-1}. The inverse of the parameter α (1/α, cm) is known to be the air entry value. The beginning of the entry of air to the large pores in soils is described as the matric potential of water, which is the beginning of drainage. The decreases in the air entry values with the increase in macro porosity (Wang et al., 2015) and increases due to compaction (Abdulwahhab, 2020) have been reported in the literature. n and m are shape parameters and are based on the minimization of the difference between the predicted volumetric water content at a certain soil water pressure and measured water content value. n is a dimensionless parameter related to the shape of the curve. The equation m=1-1/n proposed by Mualem (1976) was used for the constant m. The constant m determines the shape of the pF curve and is affected by various soil properties such as texture, organic material content, structural conditions, compaction, etc. (Van Genuchten et al., 1991). The constant n ranged from 1.383 to 4.374 and generally increased as the application dose increased, except for the B2 application. The constant m ranged from 0.277 to 0.771 and exhibited a similar change to that in the constant n. Figure 4 shows the changes in the pF curves that were predicted using the van Genuchten model (VG) and real pF values. Table 4 shows the R^2 and RMSE values that were used in the assessment of the predicted and real data.

The pF curves revealed that the predictions of the van Genuchten model was more realistic for the B0 and B2 applications both in the dry and wet regions. However, in other applications, although the θ_S and θ_r were similar, the real and predicted values of the moisture constants were significantly different. Abdulwahhab (2020) reported that θ_r can be predicted with a high accuracy in the dry region and stated that there were significant differences in the measured and calculated values depending on the increase in the application dose. This study was in compliance with the literature. In their study in which some algorithms and the Retc – Rosetta programs are compared in terms of their effectiveness in the determination of the van Genuchten model, Yang and You (2013) reported that Rect well-reflected the moisture content but failed to determine the θ_r values used in the model.

The highest R^2 value between the real and predicted values was obtained in the B0 application with a value of 0.901 and the other R^2 values were 0.601, 0.833, 0.544 and 0.582. The lowest RMSE value was obtained in the B0 application with a value of 0.061 cm^3 cm^{-3}, followed by 0.078 (B2), 0.155 (B1), 0.177 (B4) and 0.207(B3) cm^3 cm^{-3}, respectively. A high R^2 and low RMSE improve the reliability of the models in the assessment of the accuracy of the models. Thus, the highest reliability with the van Genuchten model was obtained in the control (B0) application. The lowest accuracy was obtained in the moisture characteristic curves obtained in the B3 and B4 applications. The lack of regular increases in the moisture constants resulting from the application of organic material led to differences in the shapes of the curves. Therefore, the values predicted by the van Genuchten model differed due to the differences in the shape parameters.

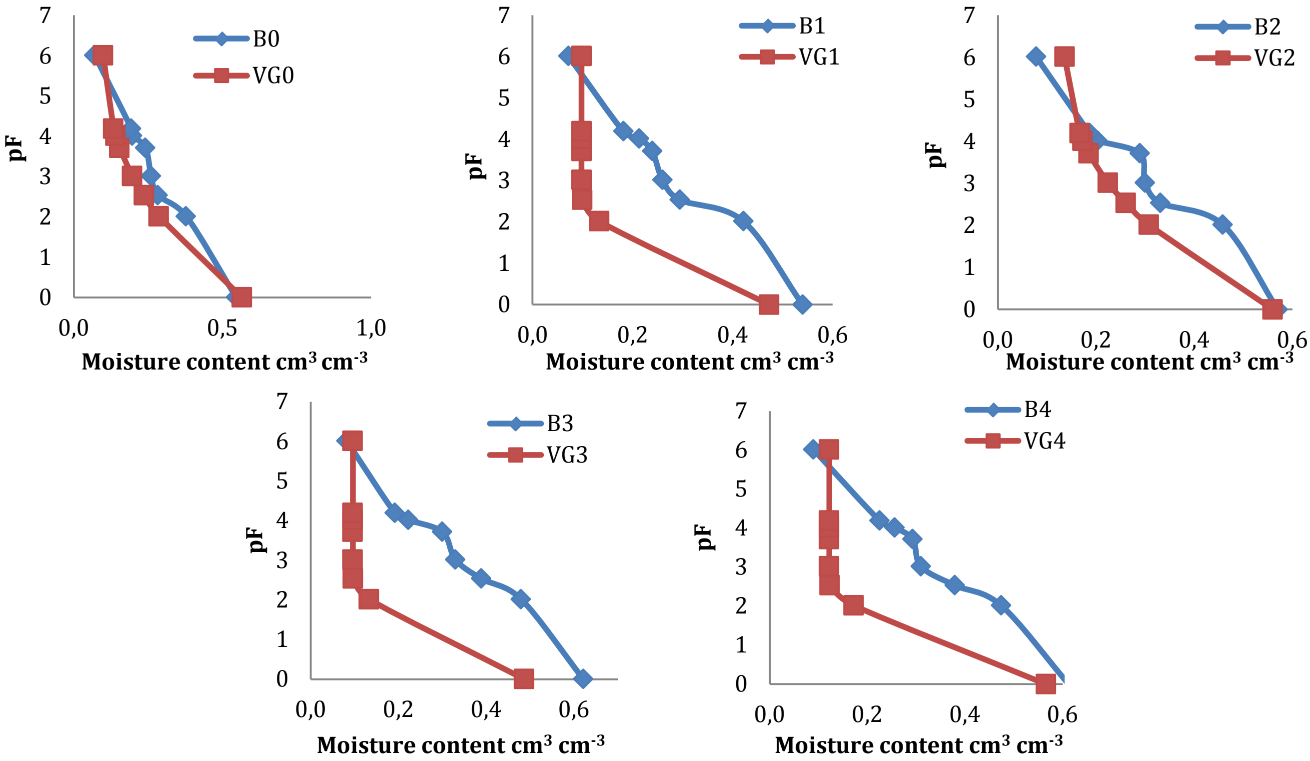

Figure 4. Variation of pF curves estimated by Van Genuchten model and determined in reality

Table 4. Model evaluation for soil moisture curve

Applications	Equation	R^2	RMSE
B0	Y= 1.0089X-0.0471	0.901	0.061
B1	Y=0.7018X-0.0455	0.601	0.155
B2	Y=0.7981X+0.0104	0.833	0.078
B3	Y=0.5926X-0.0443	0.544	0.207
B4	Y=0.7421X-0.061	0.582	0.177

R^2:coefficient of determination, RMSE: root mean square error; Y: actually determined water content, X: predicted water content

Conclusion

The study investigates the effects of the applications of different ratios of biogas waste on some soil properties and soil moisture characteristic curve (pF). The predictive accuracy of the van Genuchten model for hydraulic properties was also examined. The biogas waste applications were determined to be more effective on the increase in moisture in the wet region of the moisture characteristic curve than in the dry region. The effects of the B3 and B4 applications on the soil properties were either generally similar or the B3 application can be considered more effective. Therefore, we recommend the B3 application as the effective dose considering the economic aspects of its use and improvements in the soil physical properties.

Using the van Genuchten model, the most realistic predictions were obtained in the control (B0) application and the model had high predictive accuracy. The lack of a regular change in the moisture constants with the biogas waste applications led to changing shape parameters that were determined on the pF curve and, thus, the predictive accuracy of the applications was lower. The van Genuchten model achieved an accuracy of about 70% in the examined region. We recommend testing the model for larger areas and different soils. Conventional agriculture is carried out in the study area. Therefore, organic materials of different forms are applied to the soils. The results of this study revealed the need to investigate the relationship between the diversity of the organic materials added to soils and soil moisture characteristics. Moreover, expanding the study area will greatly contribute to the irrigation and soil management in the area in terms of labor and economy by improving the predictive power.

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