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Effects of temperature and total solid on rheology properties and rheology modelling of cow manure

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Abstract

Since, rheological properties have a major role in the simulation, design and construction of the many types of biogas digesters. Therefore, in this research for determining the rheology properties such as consistency coefficient, behaviour index and viscosity of cow manure were investigated. A rotational viscometer with temperature control bath was used to study effects of temperature and solids concentrations on rheological properties of dairy manure slurry having total solids concentrations (TS) ranging from 3 to 18.5%, shear speed ranging from 0.5 to 160 rpm and temperature ranging from 15 to 55°C. The results showed that manure behaves as a non-Newtonian fluid since the viscosity highly depend on the applied shear rate, also demonstrated that manure's behaviour is similar to a pseudo-plastic fluid. Three equations were established to relate the power-law model of the shear stress and the rate of shear which reveals that in power law, the value for consistency coefficient "K" increases with higher temperature and decrease with reducing total solid. In addition, power index "n" increases for higher temperatures. Moreover, R^2 of the model shows that the Arrhenius model provides a suitable description of the effect of temperature on viscosity. The model that provided in this research can show relation between K and n with T and TS.

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Introduction

In recent decades, anaerobic digestion has been developed as one of the most appealing techniques for producing energy from renewable resources (*Khalid et al, 2011*). Anaerobic digestion is one of the biological activities that help to manage and control animal and cattle, agricultural and food-related wastes. The process produces biogas including methane (CH_4), carbon dioxide (CO_2) and some other gases. Biogas has many advantages such as renewable energy, waste management, and carbon reduction (*Perrigault et al., 2012*). According to the fact that biogas production is related to many issues such as biological, microbiological, physical and chemical changes, in order to produce biogas, there should be a balance among these variables. Anaerobic digestion is a widely applied technique for disposal of manure. It is used under various ranges of temperature including psychrophilic (<25 C), mesophilic (25–40 C) and thermophilic (>45 C) *(Hooshyar, 2011)*. In arid and semi-arid regions, the mesophilic and thermophilic digestion are used. One of the key factors contributing to the performance of an anaerobic digester is the rheological properties of the substrate which play an important role (Abbassi-Guendouz *et al.*, 2012; Liotta *et al.*, 2014).

The viscosity changes could have very important effects on the above-mentioned variables, especially physical and chemical conditions. Moreover, they should be taken closely into consideration in order to be stabilized (Brambilla *et al.*, 2013). For higher fluid viscosity, the more we need shear tension in order to create identical changes. As mentioned above, viscosity affects temperature, mixing and material transfer inside the digester. Viscosity is the flow resilience properties against imposed forces on it and creating cutting tension. Viscosity is the main factor for transferring momentum in flow layers. It appears when there is a relative movement between the layers. It is clear that the level of viscosity in fluids is higher than that of gases. Viscosity is defined as a fluid resilience against shear tension. In a fluid during movement in which its different layers are moved relatively to each other, the resilience of fluid layers against vibration on each other is called viscosity. Based on Newton's law, when a liquid is located between two solid surfaces, a force tangentially applied to a surface, which is in contact with the liquid underneath, leads to a flow in the liquid layer. The flow's velocity that can be maintained by given force is controlled by the internal resistance of the liquid (viscosity) (Goodwin and Hughes, 2008).

In many anaerobic digesters, heating and mixing systems are used in order to increase the biogas production and yield. According to the research (Hooshyar, 2011), using mixing for homogenizing the substrate inside and creating steady thermal condition requires a fast transfer of heat (Mbaye *et al.*, 2014). In order to simulate heat transfer and anaerobic digester dynamic fluid in CFD software, some information about physical, chemical and rheological aspects of the materials are required (Landmark *et al.*, 2014; Craig *et al.*, 2013).

Rheological properties of the material are important for heat transfer, mixing power and simulation conditions. By knowing the type of material in terms of Newton and non-Newton, it is possible to have a great insight about inside digester processes while trying to save consuming power for mixing and consuming energy for heat transfer in order to have more production. Viscosity data are also important in measuring size, type, and power of the pump. Viscosity is an important parameter in controlling the process (Moeller and Torres, 1997).

The obtained rheological data are required in a wide area of temperature and density in any branch of industry for different research and engineering applications. Fluid viscosity is a significant property which has different applications in technologies related to processing equipment, production control, filters, and mixers and understanding building materials (Qanbarzadeh, 2009). Knowing rheological properties, affects how to determine the type of operation, feed or heat transfer speed.

Therefore, the knowledge of the rheological properties of raw and anaerobically digested slurries is of undeniable. In fact, the efficiency and the power requirements of these unit-operations are closely linked to the rheological behavior of them. Moreover, reliable data on the rheology of the raw and anaerobically digested slurry are necessary for determining the type, capacity and optimal design of the process equipment such as the mixing, heat exchanger(s), pump(s), dewatering material and piping systems (Hreiz *et al.*, 2016).

In many studies, manure and its power law are obtained by $\tau= K(dV/dY)^n$ which could give a better description of material rheology (Smith *et al.*,1980; Chen, 1986). If we draw the shear tension graph "τ" based on (dV/dY) and measured in logarithmic basis, the line slope will be equal to power "n" and "K" factor will be measured from Y intercept.

Generally, liquid animal wastes demonstrate non-Newtonian behavior in which the relationship between shear stresses and shear rates is nonlinear (Kumar *et al.*, 1972). Anaerobically digested sludge rheology can be described using the Herschel-Bulkley model, for which the rheological characteristics decreased with the degree of fermentation (Baudez *et al* 2013).

Chen showed that Viscosity of cattle manure is affected by temperature (Chen, 1982; El-Mashad *et al.*, 2005). In the conducted study ranged from 2.5 to 12 total solid (TS) percent it was shown that viscosity it under the influence of TS (El-mashad *et al.*, 2005). Viscosity is influenced by temperature. Arinious model explains an equation in which the temperature could be considered in material shear rate change (Marcotte *et al.*, 2001).

Chen and Shelter (1983) examined the effect of temperature on viscosity of cattle manure with the density of 2.5-19.5 in the temperature ranged from 14-64 degrees. The results showed that softening fluid is obtained by shear and efficiency of the power law model for describing fluid behavior in shear speed range.

Viscos waste in transferring the non-Newton normal fluid heat is a power model which is stable in sinus wave surface. In rheology, the Arrhenius equation as given in Eqn (1) is generally applied for showing temperature dependency. In this research, the temperature dependency of the consistency coefficient (K) was utilized for specifying activation energy for viscous flow (Baudez *et al*,. 2013).

$k=k_\infty \exp(Ea/RT)$ ....(1)

Where k = consistency coefficient, k_∞ = consistency coefficient at the reference temperature, the Ea= activation energy for k, T is absolute temperature and R gas constant. The viscosity and consistency coefficient of fresh manure slurry was found to decrease with an increase of temperature (Chen, 1986). Chen (1982) concluded that by increasing TS, density will rise and also for cattle manure with 1-14 percent solid material, there are non-Newton behavior and deviation of Newton behavior increases with TS% increase.

The total solids effect on viscosity has been investigated by a little research. (Bashford *et al.*, 1977; Barker & Driggers, 1980). Kumar *et al* (1972) found, using a coaxial cylindrical viscometer, that the viscosity of fresh cow manure slurry decreased with an increase in water and that the substrate was Newtonian below 5% total solids and pseudo plastic above 6%.

It is well known that temperature generally influences the viscosity of materials. An Arenius-type model generally expresses the effect of temperature on the apparent viscosity at a specific shear rate (Bhandari *et al.*, 1999; Marcotte *et al.*, 2001). The literature indicates that some studies on thermal properties and bulk density of beef and dairy cattle manure (Chen, 1982; Achkari-Begdouri and Goodrich, 1992), but the data reported on the rheological properties of manure and the temperature effect on its viscosity are limited: Chen and Hashimoto (1976), studied the rheological properties of fresh and digested livestock waste slurries.

The main purpose of this project is to estimate consistency coefficient, behavior index and apparent viscosity with respect to dilution and temperature of Tabriz dairy cattle manure. These rheological properties are needed in determining heat transfer coefficient (heating and heat loss), mixing power, pump type and its required and simulation process. Estimating of these coefficients is necessary to explain for anaerobic reactor and energy balance.

Material and methods

In this study dairy manure with total solids ranging between (3 to 18.5%) (Wet basis) and temperature ranging between 15 to 55 was used as material. Manure used in this study was transferred from Tabriz dairy cattle in a raw and fresh form to biochemical and digestion laboratory at Tabriz University. The Viscosity experiments were done in digestion laboratory, at Tabriz University.

Preparing the sample

In order to measure total solid percentage, 50ml of the samples were weighed and put into the oven at 103 degrees for 24 hours. Then the total solid weighed and determined by the following equation (APHA, 2005).

$$TS\% = \frac{w_{103}-w_B}{w_1-w_B} \quad \text{.........(2)}$$

W_{103}: mass after 103 temperature (gr)

W_1: mass (gr)

W_B: crucible mass (gr).

Viscosity was measured using Brook field in shear speed of 0.5, 1, 5, 10, 20, 40, 80 and 160 round per minute in which the values of shear stress, shear rate and viscosity were obtained from the flowing relations (Fig.l 1).

$$\text{Viscosity (CP)} = \frac{100}{RPM} \times TK \times SMC \times Torqul \quad \text{.........(3)}$$

$$\text{Shear rate} \left(\frac{1}{s}\right) = RPM \times SRC \quad \text{.........(4)}$$

$$\text{Shear stress} \left(\frac{\text{Dynes}}{\text{cm}^2}\right) = \tau = \frac{2T}{\pi D^2 L} \quad \text{.........(5)}$$

TK: Torque constant

SMC: Spindle constant

SRC: Spindle constant for shear rate

T, Torque: Torque between 0-100 (percent)

RPM: spindle rotational speed (round per minute)

D: diameter of spindle (cm).

L: length of spindle (cm).

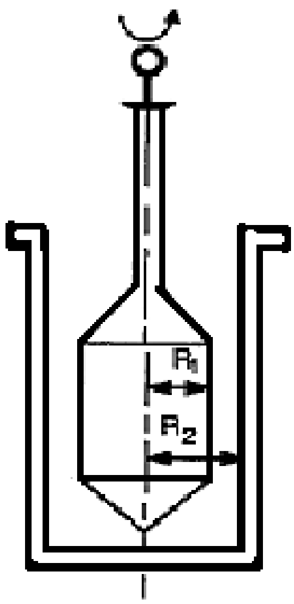


Fig. 1. Viscometer schematic.

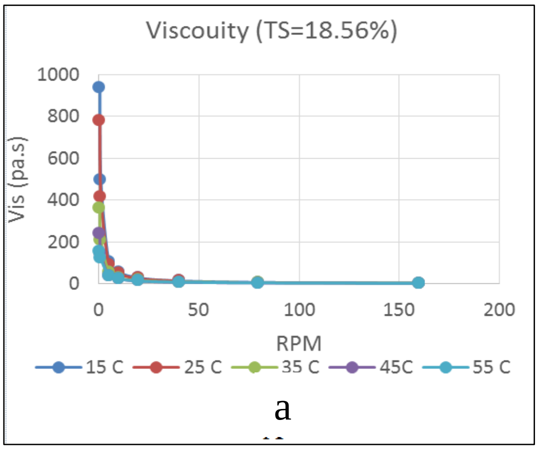
Digestion happens in different temperatures so the effect of temperature on viscosity have been studied. Apparent viscosity was determined for each TS% at 15, 25, 35, 45 and 55 C from mesophilic to thermophilic ranges. The rheology model was obtained from diagram fitness of shear stress - shear rate and gaining dependency of rheology parameters done by Excel 2013 and SPSS software.

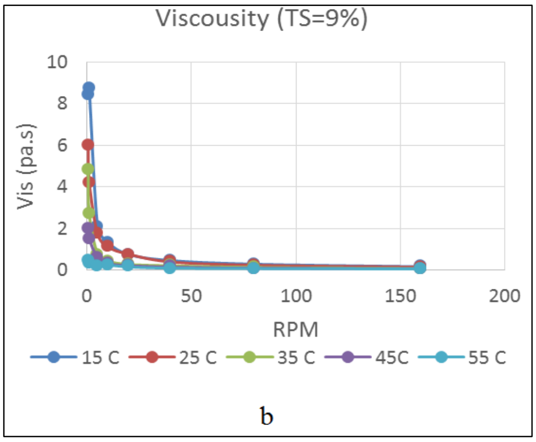
Results and discussion

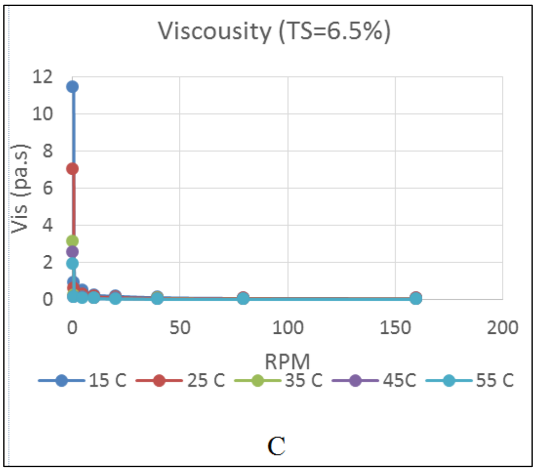
Studying of manure behavior

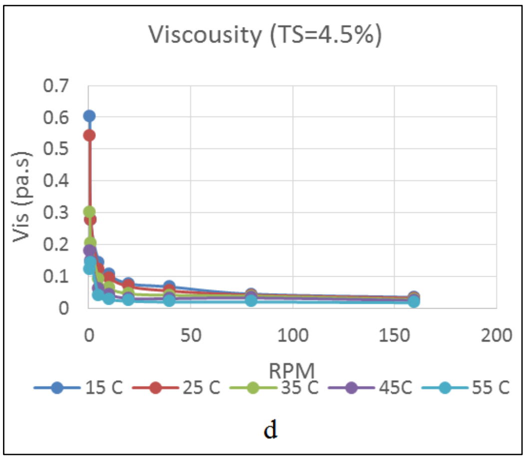
The percentage of solid material was the most important property of manure for transportation (Schofield, 1984). The value for %TS has a significant effect on viscosity of the manure. The density of raw manure in the primary humidity in the 25 C temperature was equal to 1100 Kg/m^3.

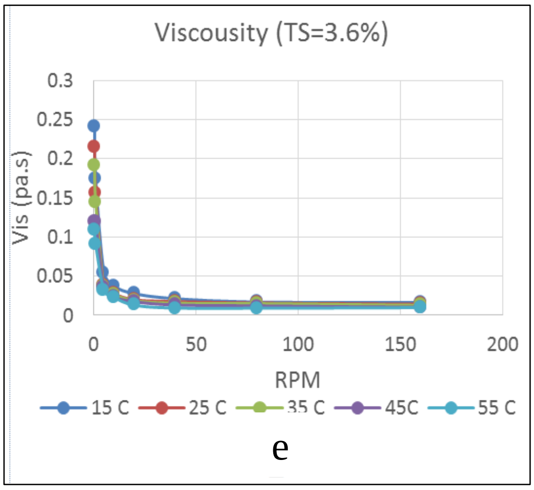
According to Fig. l 2, by increasing shear stress, the viscosity declines. Moreover, by increasing temperature, viscosity will also decrease. By increasing % TS, viscosity increases. The highest level of viscosity is related to TS=18.5% and 15 C temperature and shear speed of 0.5rpm. The graphs and data related to viscosity could be used in measuring mixing power, heat transfer calculations and simulating fluids that require the maximum and minimum values based on speed and temperature.











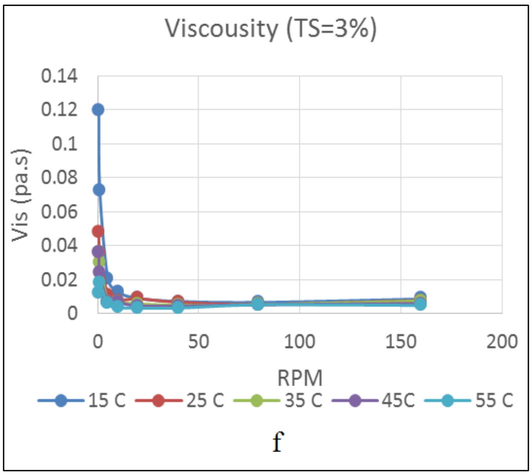


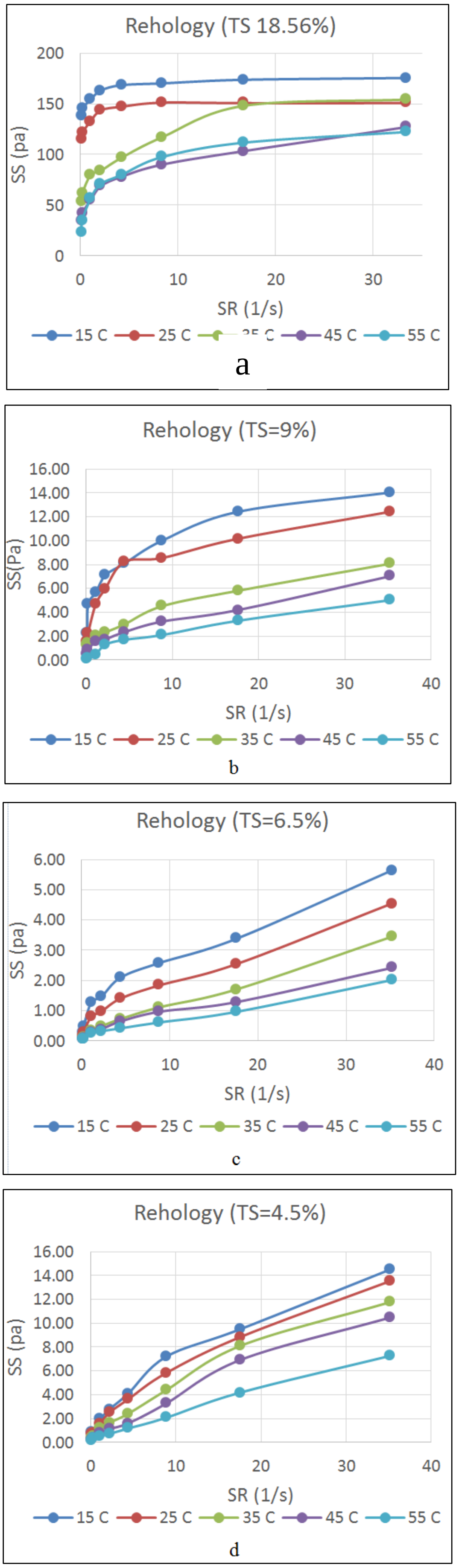
Fig. 2. The relationship between viscosity and shear rate in different temperatures.

Fig. 3. Shows the relation between shear stress (SS) and shear rate (SR). As graphs show, it can be observed that cattle manure has non-Newton behavior but when mixed with different amount of water, it can be considered as Newton fluid for some parts. In a sense.

The manure shows non-Newton behavior or Pseudo plastic behavior which increases following the power law for this fluid.

Fresh cattle manure is shown graph 3 which has non-Newton behavior accord pseudo-plastic behavior and Empirical data were perfectly fitted by power law model.

The values of consistency coefficient (K) and behavior index (n) in power law for different temperatures were gathered.



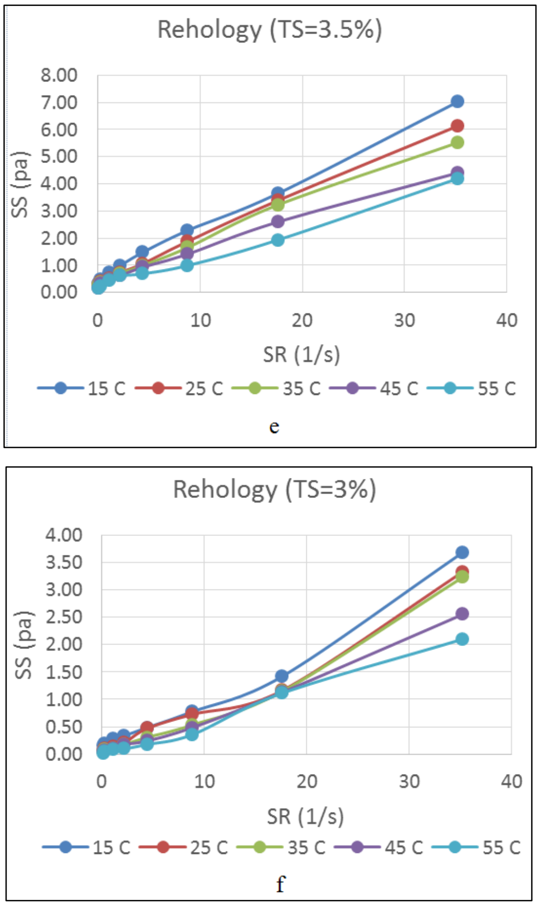


Fig. 3. The graph for manure rheological behavior in different temperatures.

Table 1 along with R^2 factors (Graph 4 and Table 1). Chen and Hashimito (1976) used power law for cattle manure rheological behavior describing its efficiency. Moreover, it was observed that by increasing temperature, the shear stress will decline which is in agreement with the findings of El-Mashad *et al.*, 2005 and Chen and Shelter (1983). In addition, viscosity declines as TS value decreases. As the graphs show, by decreasing TS value, it is possible to consider the material in fewer rounds in Newton way but in high TS values, only frequent rounds could account for Newtonian picture of material.

Studying the power law of manure

Fig. 4 shows the relation between logarithmic shear stress and shear rate. Empirical data were perfectly fitted by the power law model. The calculated values for K and n along with R^2 factors were obtained. Power law could be used for cattle manure rheological behavior while explaining its efficiency. Moreover, it is observed that in constant shear rate, the values for shear stress were higher at lower temperatures.

As can be deduced from Table 1, manure is a non-Newtonian fluid as the ratio of shear stress to shear rate is not constant but depends on the shear rate. This ratio is called apparent viscosity (Coulson and Richardson, 1964). The reason of this non-Newtonian behavior may be due to the presence of large molecules, like cellulosic materials which have not degraded in the animal digestion system. It can also be observed that shear stress is higher at lower temperatures for the same shear rate. Moreover, it can be observed that the relation between shear stress and shear rate becomes linear only at higher rates of shear. This kind of material is intermediate in behavior between Bingham plastic and pseudo plastic.

Consistency coefficient (K) value in power law decreases when the temperature rises and declines when total solid decreases. As the total solid increase the volume increase (Chen and Hashimto, 1976) which increase K because of increase in cohesive forces between manure particles. About the effect of temperature on K, viscosity decrease with increase temperature because of influence the suspending medium (water).

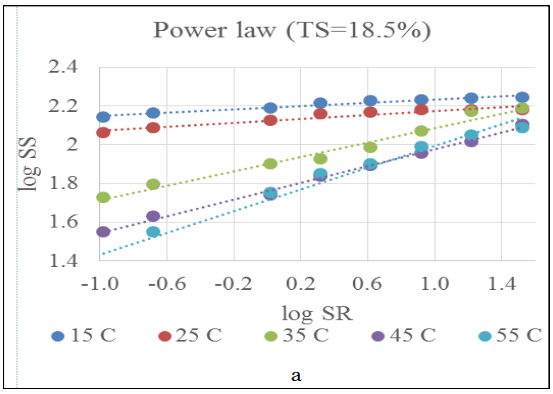
This result is in agreement with Kaya and Belibagˇli (2002), who used a comparable biological material: organic solid in water, highly viscous, non-Newtonian fluid. The power-model describes the flow behavior of manure adequately, as the R^2 values are at least 0.85. The power law is also applied for pseudo plastics fluids (Coulson and Richardson, 1964). Similar results were also obtained by Moeller and Torres (1997) for anaerobically digested sludge.

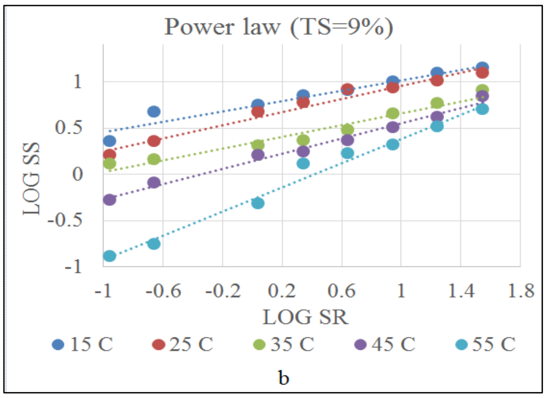
The results of this study, showed that behavior index (n) increases with temperature and its behavior becomes Newtonian. This is in agreement with report of Chen (1986). It's because of the forces between molecules decrease with temperature rise and the sample consistency coefficient decreases. As this force decrease the molecules initially tangle up, start to fall into lines and to slide easily on each other.

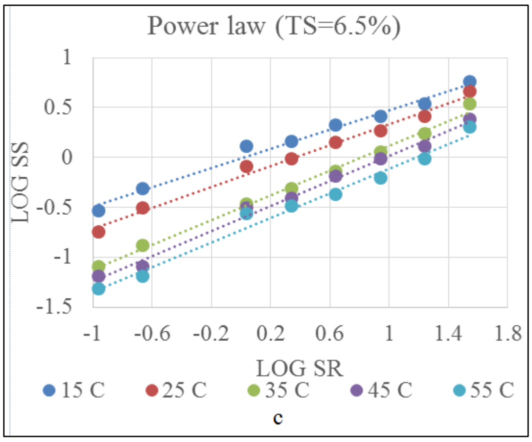
Table 1. Table for values of viscosity power law in different temperatures.

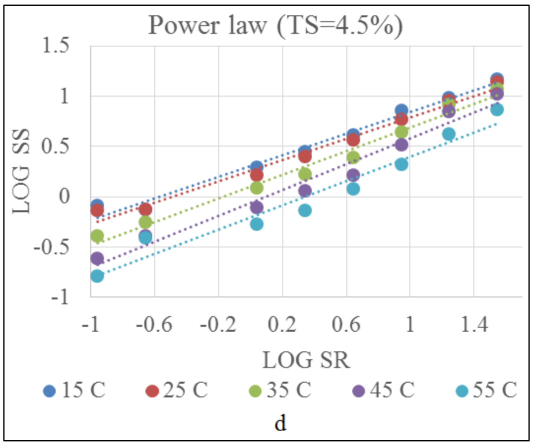
% TS	18.5			9			6.5		
Temp (C)	n	k	R^2	N	k	R^2	n	k	R^2
15	0.0423	154.81	0.9645	0.2814	5.446	0.9395	0.4809	0.9776	0.9844
25	0.0501	132.617	0.9146	0.3528	4.0327	0.9709	0.5247	0.64	0.9897
35	0.1866	79.469	0.9772	0.3152	2.212	0.9535	0.6211	0.312	0.9945
45	0.2151	57.57	0.9951	0.4126	1.383	0.9859	0.6279	0.2443	0.993
55	0.2811	51.689	0.9701	0.6531	1.846	0.9825	0.6166	0.1884	0.9815

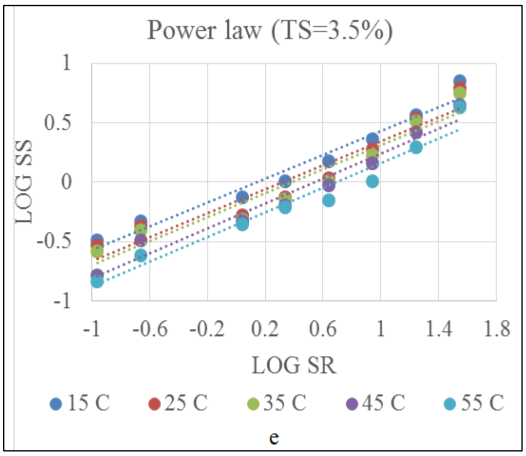
% TS	4.5			3.5			3		
Temp (C)	n	k	R^2	N	k	R^2	n	k	R^2
15	0.5359	2.0146	0.9828	0.5021	0.843	0.9628	0.4898	0.3361	0.8781
25	0.5298	1.817	0.9834	0.5015	0.689	0.9207	0.6715	0.153	0.9133
35	0.588	1.26	0.9833	0.503	0.635	9279	0.639	0.198	0.9368
45	0.6406	0.8647	0.9702	0.5266	0.517	0.9627	0.6587	0.14	0.9239
55	0.6064	0.6208	0.9512	0.5184	0.432	0.951	0.7694	0.0873	0.9361











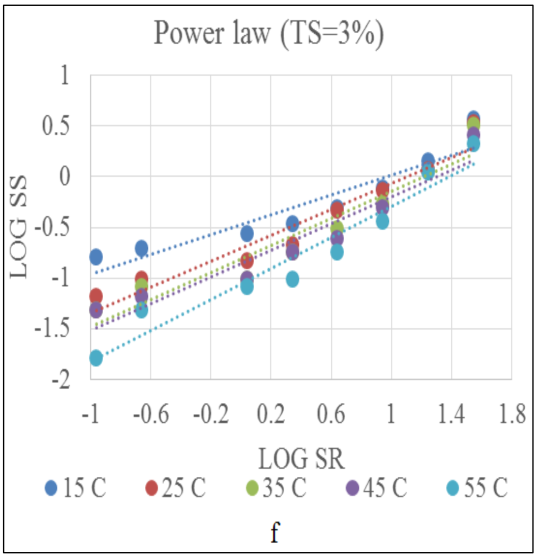


Fig. 4. The viscosity power law diagram in different temperatures.

The effect of temperature in apparent viscosity

The properties of cattle manure affect the processes for transfer and pump of mixed manure and separation. Most of the processes are done in a disturbed status, Hence, in all shear rates, temperature was used in order to explain dependency of fluid viscosity. Fig. 1 5 shows Arrhenius model diagram in different shear rates for different percentages of TS. In table 2 Ea, k_∞ are included.

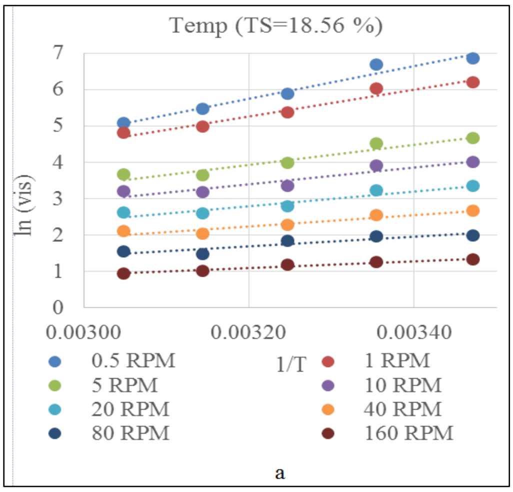
The effect of temperature: In diagram 5 and Table 2 Arrhenius model values are given. R^2 values show that the model is effectively able to describe the effect of temperature on viscosity. The results showed that disturbance could lead to decrease in the effect of temperature on viscosity.

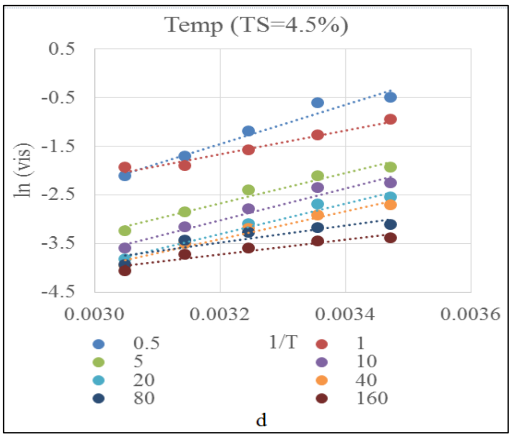
Table 2. Arrhenius data values in different shear rates.

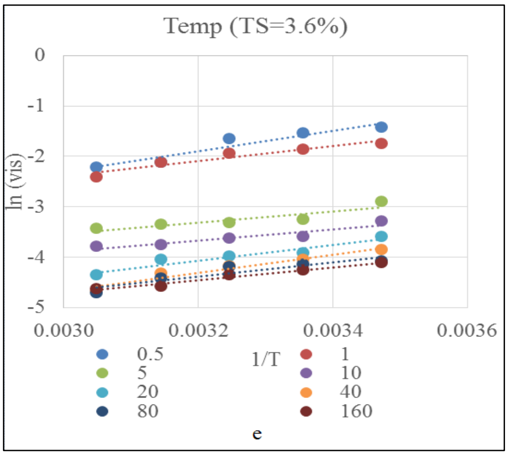
% TS	18.5			9			6.5		
SR (RPM)	μ_∞ (Pa.s)	Ea (J/mol^{-1})	R^2	μ_∞ (Pa.s)	Ea (J/mol^{-1})	R^2	μ_∞ (Pa.s)	Ea (J/mol^{-1})	R^2
0.5	37.33069	1.79E-11	0.9711	59.00446	2.03776E-10	0.9262	36.30474	2.7941E-08	0.9643
1	30.44088	1.583E-11	0.9616	52.90614	3.02305E-09	0.8577	32.31161	1.8959E-08	0.9719
5	22.75376	8.034E-10	0.9233	46.54593	9.65297E-09	0.914	32.27495	6.0201E-07	0.899
10	19.00747	1.9738E-10	0.89	37.33069	1.65383E-07	0.9371	31.02619	6.0563E-07	0.957
20	16.83585	2.5213E-09	0.9136	36.51259	3.4079E-07	0.9459	31.50507	3.7214E-07	0.9723
40	12.90499	6.5848E-08	0.8972	32.09786	7.86243E-07	0.9717	27.63241	1.1753E-06	0.9817
80	10.75748	8.6657E-07	0.8305	27.8253	2.74426E-06	0.9783	25.0293	2.3292E-06	0.9969

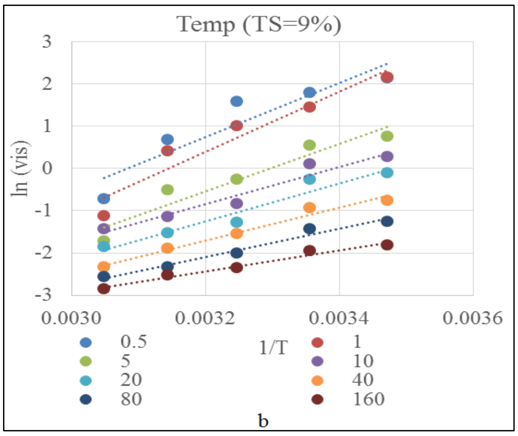
160	7.871363	1.45148E-07	0.9337	20.59045	3.1897E-05	0.9677	21.10758	1.009E-05	0.9891

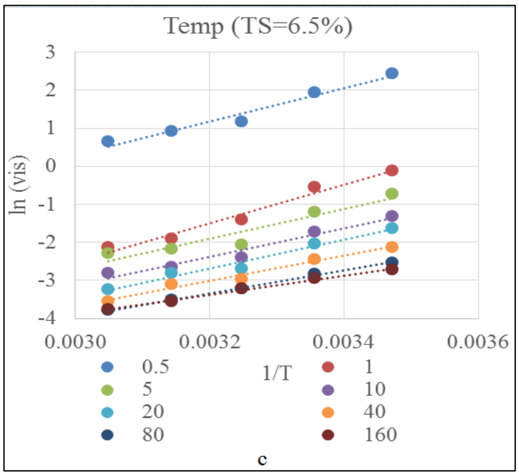
% TS	4.5			3.5			3		
SR (RPM)	μ∞ (Pa.s)	Ea (J/mol⁻¹)	R^2	μ∞ (Pa.s)	Ea (J/mol⁻¹)	R^2	μ∞ (Pa.s)	Ea (J/mol⁻¹)	R^2
0.5	33.74071	5.36607E-07	0.9604	17.05118	2.11E-07	0.913	38.39239	1.2E-08	0.8825
1	20.32191	7.58388E-06	0.9681	15.15559	3.93E-06	0.9492	25.1407	1.7E-06	0.9408
5	25.87317	3.26255E-06	0.9626	12.28975	1.087E-06	0.9172	22.72715	1.3E-06	0.8703
10	14.54368	1.13603E-06	0.8008	12.9715	1.17E-05	0.9159	20.96292	1.9E-06	0.8852
20	26.08268	1.60241E-06	0.9718	11.86574	1.29E-05	0.8671	20.83073	1.7E-06	0.9499
40	24.00584	3.20115E-06	0.9697	10.68432	1.9E-04	0.9734	15.35513	1.262E-04	0.948
80	27.25495	1.36276E-06	0.9557	9.294221	1.017E-04	0.8039	4.135217	1.3E-04	0.6867
160	12.71211	1.79992E-05	0.8835	9.099673	7.68E-04	0.8791	10.79905	1.1E-04	0.9092











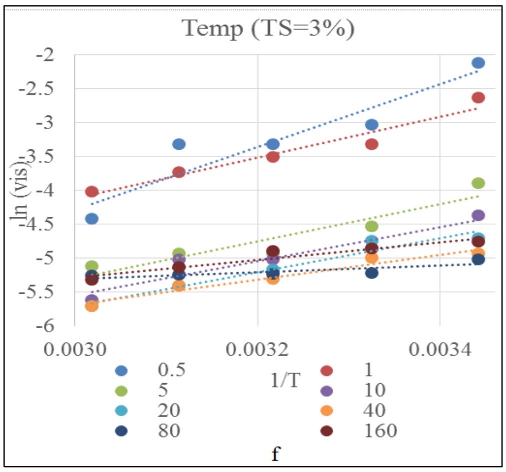


Fig. 5. Viscosity Arrhenius diagram in different shear rates.

Temperature and total solid combined effect

For describe viscosity related to temperature and % TS using multiple regression analysis in SPSS. This equation can be used to estimate viscosity in different % TS and temperature between 3-18.5% and 15 to 55C, respectively.

K = - 0.497(T) + 6.161(TS) (6)

Where

R^2 = 0.88,

K in pa.s,

T in Celsius and

TS in percent.

Equation (6) shows that "K" can be expressed as linear function of total solid and temperature of manure.

n = - 0.005(T) - 0.29(TS) + 0.539 (7)

Where:

R^2 = 0.92.

Equation (7) relates the flow behavior index "n" and both temperature and total solid that was also implemented in the linear model. The above mentioned equations can be used to estimate the consistency coefficient and behavior indexes of any TS% and temperature within the range of data in this study.

Conclusion

The rheological behavior of cattle manure was studied for ranges of 3–18.5% TS and temperature between 15 to 55 C. The results showed that manure is a non-Newtonian fluid and it behaves like a pseudo-plastic fluid but with decrease of the %TS and increase of temperature could considered as Newtonian fluid. The relation between shear stress and rate of shear is linear at higher shear rates for all temperatures. The higher solid content causes higher apparent viscosity. The results also showed that the temperature effect on "n" and "K" increases and decreases respectively with increasing temperature. Also, the value of K increases with total solid amount. The apparent viscosity of manure can be described very well by an Arrhenius-type model with good and acceptable R^2 values. Finally, for the activation energy a value was obtained, which is comparable to that of beef-cattle manure.

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