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Estimation of rheological properties of cow manure slurry using simulation method

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Abstract
Rheological parameters are the properties which show the behavior of fluid in different condition. In this study simulation model was developed based on different function of total solids, viscosity, temperature, shear rate and consistency coefficient. Simulation range was decided based on most probable conditions. Optimum values of consistency coefficient and viscosity as a function of shear rate, total solids and temperature have been determined in the research paper. Different shear rate was investigated on different total solid of manure in the simulation programme. The viscosity values for different shear rates was in the range of 0.683 to 18.69 Pa.s for activation energy (Ea) 225 J/mol. The simulation method was found suitable for estimation of rheological properties for wide range of input functions. The output data can be used for design of anaerobic bioreactors, slurry mixing and handling systems.

Keywords: activation energy, cattle manure slurry, rheological properties, viscosity, simulation, temperature

1. Introduction

Rheological behavior of digestate from agricultural biogas plants exhibit a non-Newtonian shear-thinning flow behavior. The most common identified influencing factors include feedstock, temperature, total solids, particle size and extent of anaerobic digestion. Viscosity in the rheological behaviour of the digestate in a biogas plant is a crucial parameter impacting system. Increasing slurry viscosity reduces flow velocities for a given rotational speed, resulting in poorer mixing, but lowered viscosity reduces the biogas plant's energy consumption (Schneider & Gerber, 2020) [1].

Rheological properties are required in the design of anaerobic treatment plants, pipe systems, pumping, material handling, storage and treatment of slurries. These properties are important in selection of material handling equipment, power requirements, heat and mass transfer, and related applications of manure slurries (Kariyama *et al*., 2018) [2].

The rheological characterization of raw and anaerobically digested slurries has received little attention. These fluids contain big 'particles,' such as stem and straw fragments, which make rheological measurements difficult (Hreiz. *et al*., 2017) [3]. The lack of rheological characterization of coarse biomass limits the design as well as operation of Anaerobic Digestion processes and systems (Hernandez-Shek *et al*., 2021) [4]. Temperature consider as the highest environmental related factor which change the rheological properties. The increase in storage temperature from 15 to 20 ^{0}C and from 20 to 25 ^{0}C raised CH_4 generation rate by 81 percent and 77 percent, respectively, in cattle and pig slurry (Elsgaard *et al*., 2016) [5]. Viscosities can not be measured so perfectly by using single viscometer for a wide range of rheological properties. The viscosity of anaerobic sludge cannot be measured with a particular viscometer due to the significant amount of fibrous particles (Gienau. *et al*., 2018) [6].

In this study simulation model was prepared based on different function of total solids, viscosity, temperature, shear rate and consistency constant. Simulation range was decided based on most probable conditions.

2. Materials and Methods

2.1 Simulation platform

The simulation computing system was based on 64 bit Intel i7 3.5 GHz processor with 4GB DDR4 memory (Lenovo, India). The programming for simulation and visualization was done in Python 3.8 software. Python is a general-purpose, versatile and popular programming language. The simulation program was developed to automatically calculate the rheological properties of cattle manure slurry at different temperature and total solids.

2.2. Estimation of rheological properties

All fluids can be generally classified into three categories: (1) Newtonian fluid whose viscosity is dependent only on temperature, (2) non-Newtonian fluid whose viscosity is dependent on temperature and shear rate, and (3) non-Newtonian fluid whose viscosity is dependent on temperature and shear rate as well as time. Fig. 1 shows five fluid types based on shear stress with respect to shear rate. Under most circumstances, the organic wastes such as wastewater sludge and manure slurry may exhibit non-Newtonian behavior the rheological behaviors for time-independent non-Newtonian power-law fluids are expressed as:

$$\eta = k\gamma^{n-1}H(T) \quad (1)$$

where η is the apparent viscosity, k is the consistency coefficient, γ is the shear rate, n is the power-law index, and H(T) is the function of temperature described by;

$$H(T) = \exp[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_a-T_0}\right)] \quad (2)$$

Where,
α is the ratio of the activation energy to the thermodynamic constant,
T_a is the reference temperature for which H(T) = 1, T_0 is the temperature shift which can be the theoretical digestion temperature. (T_0 = 35 ^{0}C).
For liquid manure the consistency coefficient and the shear rate (Achkari-Begdouri and Goodrich, 1992) [7]. Three shear rates were considered for simulation SR1: 85.7 s^{-1}, SR2: 142.8 s^{-1}, SR3: 238 s^{-1} as per the range suggested by El-Mashad *et al*., (2005)[8].
For the simulation of viscosity, consistency coefficient and shear rate following formula is expressed-

$$k = \left[8.722e^{\left(\frac{4830}{T}+0.58319TS\right)}\right] \times 10^{-10} \quad (3)$$

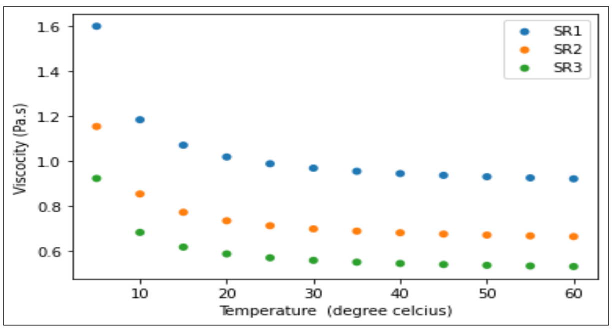
$$n = 0.6894 + 0.0046831(T-273) - 0.0442813TS$$

Where T is temperature in Kelvin, and TS is the percentage of total solids by weight in liquid manure (Wu *et al*., 2006) [9].

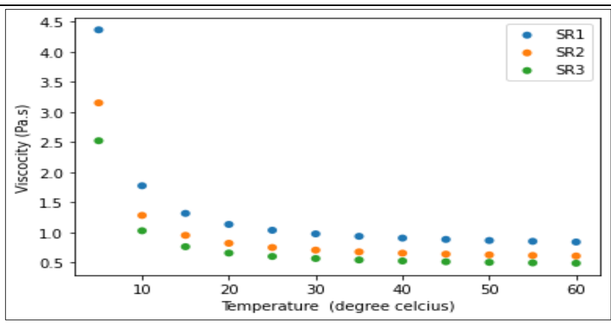
3. Results and Discussion

3.1 Effect of temperature and shear rate on viscosity

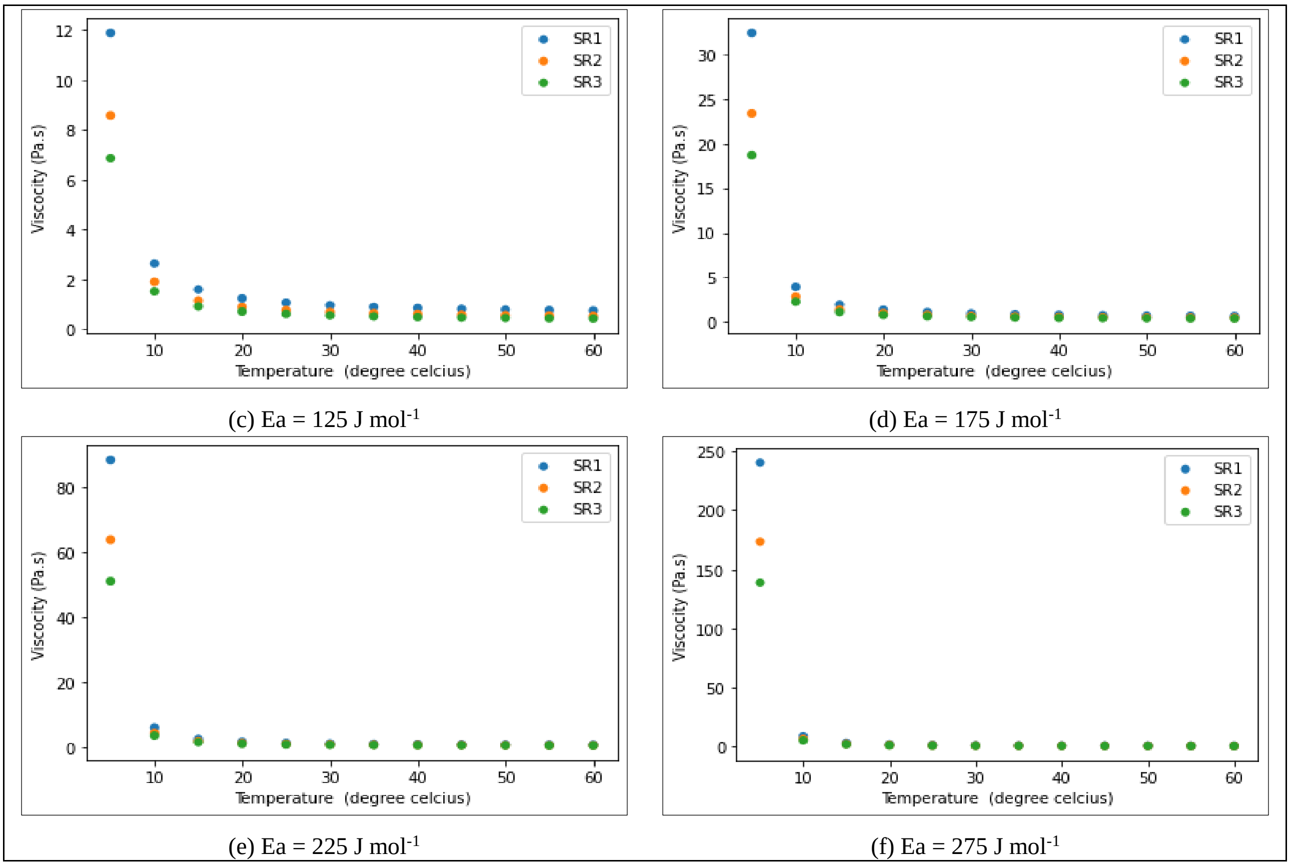
At activation energy (Ea) 25 J/mol, values of viscosities were in the range of 0.923 to 1.601, 0.666 to 1.155 and 0.533 to 0.924 Pa.s for SR1, SR2 and SR3, respectively. The difference of viscosity value at same temperature and different shear rate can be explained by the non-Newtonian behaviour of the manure slurry. There was a sudden drop in viscosity when temperature increased above 5 °C for all three shear rates.
The viscosity - temperature plot was used to understand the relationship between viscosity, temperature and shear rate (Fig.1). For activation energy of 75 J/mol, viscosity values for SR1, SR2, and SR3 ranged from 0.835 to 4.362, 0.602 to 3.148, and 0.482 to 2.518 Pa.s, respectively. When the temperature was above 5 °C, all three shear rates saw a rapid reduction in viscosity.
At a constant activation energy of 125 J/mol, SR1, SR2, and SR3 viscosity values varied from 0.755 to 2.643, 0.545 to 8.576, and 0.436 to 6.861 Pa.s, respectively. The changes in viscosity followed a negative exponential relationship with temperature which is inherent characteristic of an Arrhenius equation. When the temperature exceeded 5 °C, all three shear rates saw a rapid decrease in viscosity. Anaerobic digestion results in reduction in the slurry viscosity and its non-Newtonian behavior. Another factor that may significantly reduce viscosity is sieving of slurry to remove course particles. Slurry exhibit highly shear-thinning properties and has negligible yield stress value ((Hreiz. *et al*., 2017) [3].
For activation energy 175 J/mol, SR1, SR2, and SR3 viscosity values varied from 0.683 to 32.38, 0.493 to 23.37, and 0.394 to 18.69 Pa.s, respectively. Overlap of viscosity curve and values for different shear rates was observed in the temperature range of 25 to 60 °C.
The viscosity values for different shear rates SR1, SR2, and SR3 ranged from 0.683 to 32.38, 0.493 to 23.37, and 0.394 to 18.69 Pa.s, respectively for activation energy of 225 J/mol. Viscosity values coincided for different shear rates in the temperature range of 15 to 60 °C.
The viscosity for SR1, SR2, and SR3 varied from 0.559 to 240.33, 0.403 to 173.44, and 0.323 to 138.75 Pa.s respectively for activation energy of 275 J/mol. Viscosity curve followed similar trend at different shear rates in the temperature range of 10 to 60 °C. At the point when the temperature surpassed 5 °C., each of the three shear rates saw a rapid reduction in viscosity of manure slurry.
The measurements revealed that when the temperature dropped, the viscosity increased. If shear rate increased at the same temperature, viscosity would decrease. The curve demonstrated that when activation energies grew from 25 to 275 J/mol, the effects of shear rates on viscosity were negated. At higher temperatures, viscosities collided at different shear rates. At lower temperatures, the curve begins to exhibit nonlinear behavior or acts as a non Newtonian fluid. The scattering was excessively high if the shear rate was low, and the last viscosity point scattered (at 5 ^{0}C) differed much from the other points. When the activation energies were raised at the same temperature and same shear rate, the viscosity values increased.



(a) Ea = 25 J mol^{-1}



(b) Ea = 75 J mol^{-1}



(c) Ea = 125 J mol^{-1} (d) Ea = 175 J mol^{-1}

(e) Ea = 225 J mol^{-1} (f) Ea = 275 J mol^{-1}

Fig 1: Variation in viscosity of manure slurry as a function of temperature (5 to 60 °C) and shear rates for different activation energy (Ea)

3.2 Effect of temperature and total solids on consistency co-efficient

The consistency coefficient values were in the range of 0.0056 to 0.0983, 0.0179 to 0.3156, 0.0575 to 1.0133, 0.0179 to 0.3156, and 0.0575 to 1.0133 for TS 2, 4, 6, 8, and 10%, respectively. Consistency coefficient curves overlapped for 2, 4, and 6% TS in the temperature range of 20-60 °C (Fig.2). It can be seen that the flow consistency index k increases with decreasing temperature and with increasing TS content for all samples (Fig. 3). As the temperature increased from 5 to 60 °C, consistency coefficient values decreased linearly for TS 2 to 8%. Exponential decrease in consistency coefficient was observed with increase in temperature for TS = 12%.

As temperature increased from 5 to 60 °C, consistency coefficient decreased for TS 12 to 20% (Fig.4.32). Wide variation in consistency coefficient was observed in the range of 1.902 to 33.528 (12% TS), 6.105 to 107.636 (14% TS), 19.60 to 345.55 (16% TS), 62.93 to 1109.34 (18% TS), and 202.01 to 3561.36 (20% TS). Consistency coefficient 12, 14 and 16% curves overlapped in the temperature range of 20-60 °C.

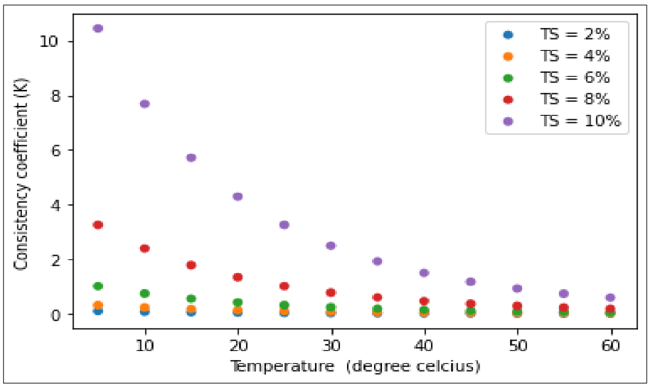


Fig 2: Variation in consistency co-efficient with temperature (5 to 60 °C) and total solids (2-10% TS)

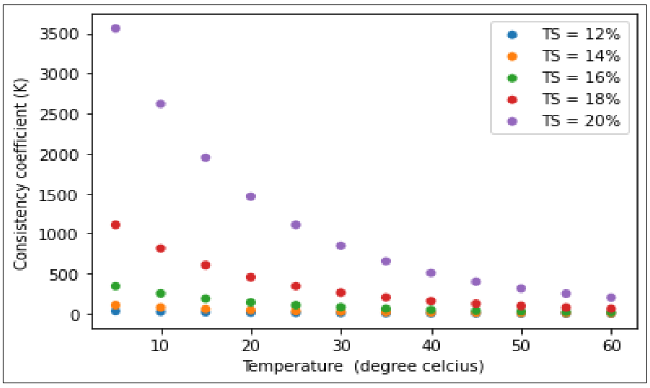


Fig 3: Variation in consistency co-efficient with temperature (5 to 60 °C) and total solids (12-20% TS)

4. Conclusions

The simulation result was found suitable for wide range of different input functions. The viscosity and consistency coefficient were estimated as a function of temperature and total solids. The present study has been carried on cattle manure slurry but the same simulation algorithms and program can be applied to predict rheological properties of straw or biomass based cattle manure slurry.

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