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A review on the rheological behavior of organic waste for CFD modeling of flows in anaerobic reactors

Hélène Caillet^{1,*}, Laetitia Adelard¹

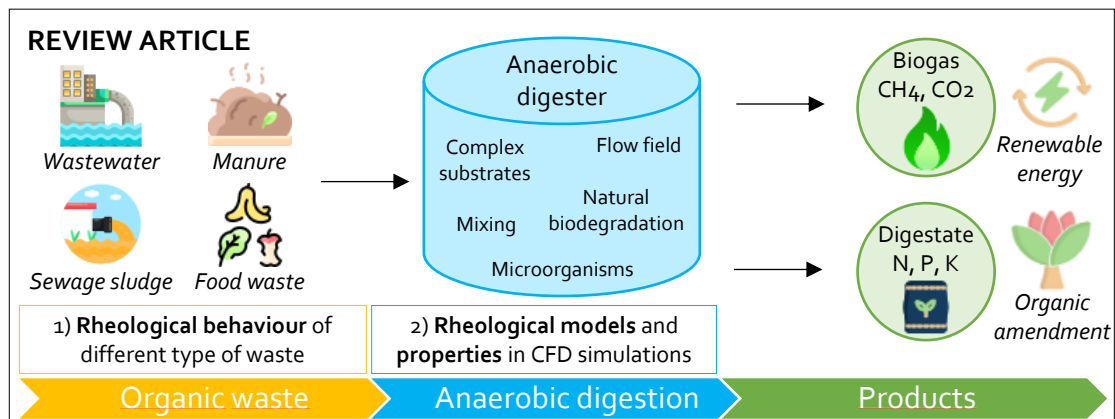
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Abstract

Anaerobic digestion is a widely used process for organic waste treatment and renewable energy production. This is a complex natural biodegradation of organic matter involving four main biochemical reactions through the action of four microbial groups. The performances of anaerobic digestion (biodegradation and biogas production) depend on the contact between the biodegradable materials and the micro-organisms. Consequently, hydrodynamics phenomena have a significant impact on the anaerobic digestion. Computational Fluid Dynamics (CFD) simulations allow to simulate the flow field within anaerobic digesters. In these models, the waste are characterized by their physical properties, specifically their rheological properties. Rheology consists in the study of the flow of liquids or viscous materials. In this respect, it involves the properties related to the flow behavior of liquids and the temporary and/or permanent deformation of materials. The knowledge on the rheological properties of the biowaste is crucial in order to describe the flows using CFD models. The aim of this review is to present the physical properties of different type of waste, as well as the rheological models. In conclusion, the rheological behaviors of wastewater, manure, and sludge are described in literature. However the rheological behaviors of a mix of biowaste and solid food waste are poorly known. Research should focus on the experimental measurements of these biowaste. These data are necessary for CFD modeling of flows in anaerobic reactors treating this type of waste.

Graphical abstract



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Statement of Novelty

Rheological characterization of organic waste is mandatory in order to carry out CFD simulations of anaerobic digesters. However, no review on the rheological properties of the different types of waste has ever been conducted. In this paper, the whole data on the rheological behavior of the waste (models and parameters) are summarized and discussed. We also present the data used in CFD simulations, indeed, when the rheological properties of a waste are unknown, the properties of another type of waste can be used. The interest is to make it easy to find data that can be used in CFD simulations. In addition, this study identifies missing data, such as the rheological properties of food waste and mix of waste.

Highlights

- Literature review of rheological properties of biowaste.
- The rheological behaviors of wastewater, sludge, and manure are well-known.
- The rheological behavior of solid biowaste is poorly known.
- The parameters impacting the rheological properties are reviewed.

Keywords: anaerobic digestion; CFD; rheological behavior; waste valorization; rheological models; literature review

Word Count: 8,062

Abbreviations:

ASM	Activated Sludge Model
CFD	Computational Fluid Dynamics
COD	Chemical Oxygen Demand
FIW	Food Industry Waste
OFMSW	Organic fraction of municipal solid waste
SHW	Slaughterhouse waste
T	Temperature (°C)
Thix	Thixotropy (Pa.s ⁻¹)
TDS	Total Dissolved Solid
TS	Total Solid (% or g.L ⁻¹)
TSS	Total Suspended Solid (%)
VFA	Volatile Fatty Acids
WV	Working volume (m ³)
R ²	Coefficient of determination
k	Consistency index (Pa.s ⁿ)
$\dot{\gamma}_c$	Critical shear rate (s ⁻¹)
ρ	Density (kg.m ⁻³)
η	Dynamic viscosity (Pa.s ⁿ)
FC	Flow consistency of the Sisko model (s)
α_0	High shear rate viscosity or Bingham viscosity (Pa.s ⁿ)
η_{IR}	Infinite-rate viscosity (Pa.s ⁿ)
η_{lim}	Limit viscosity (mPa.s)
η_{max}	Maximum viscosity (Pa.s ⁿ)
η_{min}	Minimum viscosity (Pa.s ⁿ)
n	Flow index (dimensionless)
$\dot{\gamma}$	Shear rate (s ⁻¹)
τ	Shear stress (Pa)
C_p	Specific heat (J.kg ⁻¹ .K ⁻¹)
λ	Thermal conductivity (W.m ⁻¹ .K ⁻¹)
τ_0	Yield stress (Pa)
τ_{0dyn}	Yield stress obtained by dynamic measurements (Pa)
τ_{0flow}	Yield stress obtained by flow measurements (Pa)

1. Introduction

Nowadays, the organic waste treatment is in high stakes insofar as sustainable development is at the center of the concerns [1]. On the one hand, the world's population is continuously growing, resulting in an increase in energy and water demand, but also in the production of organic waste [1]. On the other hand, organic waste disposal in landfills, which is the commonly used, led to major environmental issues due to the greenhouse gas emissions and soil pollution (leachate) [2]. Hence, there is an urgent need to develop environmentally friendly methods of waste treatment and renewable energy production. Anaerobic digestion is a natural process whereby the organic matter is converted into biogas and digestate through the action of a set of microorganisms [3]. This process is widely used in order to reduce the organic fraction of waste with material and energy valorization [4]. Indeed, the biogas produced is mainly composed of methane and carbon dioxide and the digestate is the residual matter that can be used as nutrient sources or soil amendment [1]. At industrial scale, anaerobic digestion is conducted in an industrial unit commonly called anaerobic digester (or reactor).

All organic waste is potentially methanizable. There are the lignocellulosic biomass such as agriculture residues. This type of waste is hardly biodegradable through anaerobic digestion due to the presence of lignin, cellulose and hemicellulose [5, 6]. Therefore, this literature review does not include this category of waste. However, anaerobic digestion of animal manures (cattle, dairy, poultry manure), is well-studied [7–11]. Indeed, in contrast to lignocellulosic materials, these waste present a high buffer capacity and low carbon to nitrate ratios [1]. Animal manure is of major interest as a substrate for anaerobic digestion. Sewage sludge (byproduct from municipal wastewater treatment plants) and wastewaters can also be treated by anaerobic digestion [4, 12–16]. Finally, there is food waste. This category comprises many types of waste of industrial (vegetal and animal sources) or household origin. The anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) is increasingly studied despite the heterogeneity of this deposit [17–25]. The OFMSW are composed of cardboard, paper, putrescible matters, and fine elements [26]. The physical characterization of the OFMSW is complex because of the heterogeneity of the mix and the differences of the deposits according to the territories. The performances of anaerobic digestion (reduction of the pollutant content and biogas production) depend on the efficient contact between the biodegradable materials and the micro-organisms [27]. It is therefore essential to describe the flows within anaerobic reactors. The rheological behavior has a significant impact on the flow field within the anaerobic digester [28]. The rheology, which is the study of the flow of liquids or viscous materials, allows to model the flow field using Computational fluid dynamics (CFD) [29, 30]. In CFD models, the rheological behavior must be described [31, 32]. It involves the properties related to the flow behavior of liquids and the temporary and/or permanent deformation of materials. Rheological models describe the fluid flow as a function of the shear stresses applied to the fluid [33]. The knowledge on the rheological properties of the biowaste is crucial in order to choose the adequate rheological model in CFD modeling [34]. The rheological properties are obtained from experimentations (the slump test, the consistometer, the shear-box, *etc.*) [35–37]. As an example, Hernandez-Shek *et al.* (2021) developed devices based in order to determine the rheological properties of coarse biomass treated by dry anaerobic digestion [38]. The slump test provided the yield stress and the delayed period, the consistometer the flow profile, and the cohesion and friction angle were evaluated using the shear-box [38]. The yield stress, which represents the transition from elastic to plastic behavior, is the minimum stress at which a solid undergoes permanent deformation or plastic flow without significant increase in external load or force. Fluids can exhibit Newtonian or non-Newtonian behavior. The shear stress in linearly proportional to the shear rate for the Newtonian fluid. The behavior of Newtonian fluids is well understood. Non-Newtonian fluids present specific flow characteristics such as variable viscosity [39], high apparent viscosity, complex variations of rheology during mixing, and the necessity to exceed the elastic limit of the fluid to enable flow [40]. In the case of anaerobic reactors, we mainly deal with non-Newtonian fluids due to the high biomass concentration [39] and for reducing water consumption [40]. These fluids are grouped into three classifications [33]:

- Time-independent non-Newtonian fluids, where the shear rate is unique but is a nonlinear function of the shear stress.

- Time-dependent non-Newtonian fluids, where the relationship between shear stress and strain rate is more complex. The shear rate is not a single value. The shear rate depends on the duration of shear or previous shear rates experienced by the fluid.

- In the case of viscoelastic fluids, the shear strain as well as the strain rate are related to the shear stress. As opposed to a viscous fluid in which all of the strain energy is dissipated, some of the strain energy of a viscoelastic fluid can be recovered as during the deformation of an elastic solid.

In literature, the physical properties used in order to carry out CFD simulations are chosen according to the type of waste studied [30, 41], the viscosity of the material [34, 42], the physical and chemical characteristics (particle size, solid content) [40] and the operational conditions such as the temperature [36, 37, 43, 44]. However, no review article provide a global vision on the available experimental data and limitations. In addition, no overview exist on the rheological parameters and models used for CFD simulations.

In this paper, a critical review on the rheological behavior of several waste is presented. A literature data dealing with the waste (vinasse, sewage sludges, manures, and food waste) rheological models is presented. The rheological properties are detailed and analyzed according to the rheological models, the type of waste and other parameters such as the total solids (TS) content or the temperature. Finally, a discussion is provided on the current state of knowledge and challenges concerning the rheological properties of biowaste.

2. Rheological behavior of wastewater

Wastewater includes all water contaminated by human activities, whether domestic, agricultural or industrial. These are characterized by a high content of pollutants and must be treated before their discharge into the natural environment [4, 45]. Anaerobic digestion of wastewater allows to reduce its organic content [15]. We present in this section the rheological properties of this waste, as well as the rheological model and parameters.

The vinasse, which is a liquid effluent generated during alcohol production, can be considered as a Newtonian fluid [30, 33, 35, 46–49]. However, this assumption is valid when the TS content is less than 1 % in the liquid phase because the rheological behavior of the wastewater depends on the TS content [49]. We show in the Table 1 the dynamic viscosity of the vinasse. The Newtonian fluids obeys to the following linear relation [50, 51]:

$$\tau = \eta \dot{\gamma} = \eta \frac{\partial u}{\partial y} \quad (1)$$

Where τ is the shear stress, η is the dynamic viscosity, and $\dot{\gamma}$ is the shear rate.

Table 1. Dynamic viscosity of vinasse

Source	Substrate	ρ (kg.m ⁻³)	η (Pa.s)
[46]	Vinasse	1044.69	1.0097x10 ⁻³
[52]	Sludge	999.66	6.5x10 ⁻²

The vinasse can also be characterized by the Herschel-Bulkley model, which is a non-Newtonian model [35]. The Herschel-Bulkley model allows to model the behavior of pseudoplastic fluids. These fluids do not have elasticity stress, and are characterized by a progressive decrease of the slope of the shear stress as a function of the shear rate [50]. This slope is defined as the apparent viscosity.

$$\eta_a = \frac{\tau}{\dot{\gamma}} \quad (2)$$

At high shear rates, the apparent viscosity becomes constant and equal to η_∞ and the shear stress versus shear rate becomes linear.

The governing equation of a Herschel-Bulkley fluid is [50, 51]:

$$\tau = \tau_0 + k \dot{\gamma}^n \quad (3)$$

Where τ_0 is the yield stress, k is the consistency index, $\dot{\gamma}$ is the shear rate, and n is the flow index.

The Table 2 presents the yield stress, and the parameters of the models at different temperature. Indeed, the rheological properties are temperature dependent [35–37]. The yield stress decreases with the increase of the temperature from 20 to 35°C. This parameter traduces the maximum stress that can be developed in a material without causing plastic deformation. The consistency index decreases with the increase of the temperature. This parameter provides information on the viscosity of the fluid. From these results, we can conclude that the temperature has an impact on the flow behavior: the increase of the viscosity. Anaerobic digestion process commonly occurs in mesophilic conditions with a temperature of 37°C. In this case, the Herschel-Bulkley model can be utilized in order to characterize the flow behavior of the vinasse. However, the flow behavior index approaches the Newtonian behavior because the index n is close to 1 [35]. It is therefore preferable to use a Newtonian model for this waste.

Table 2. Herschel-Bulkley model parameters of vinasse [35]

T (°C)	τ_0 (Pa)	k (Pa.s ⁿ)	n
20	0.11177	1.774x10 ³	1.1
25	0.10537	1.68x10 ³	1.08
30	0.0998	1.479x10 ³	1.05

35	0.08950	1.392x10 ³	1.01
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The power-law (Ostwald) model also enables to describe the pseudoplastic fluids behavior [50, 51]. Ostwald's power law is stated as follows:

$$\tau = k\dot{\gamma}^n \quad (4)$$

Where τ is the shear stress, k is the consistency index ($k = \eta$ for a Newtonian fluid), $\dot{\gamma}$ is the shear rate, and n is the power-law index.

In a study conducted by Chacua et al. (2016), it has been shown that vinasse has a pseudoplastic behavior for temperatures between 10 and 20 °C [53]. Indeed, when the temperature is superior to 30 °C, the power-law index is close to 1, indicating an approach to the Newtonian model [53]. The power-law model parameters (consistency index and power-law index) are presented in the Table 3. In contrast to the previous study [35], the consistency index and the power-law index increase with the increase of temperature [53]. At 40°C, the temperature closest to the mesophilic regime, the power-law index is 1.01, characterizing Newtonian behavior. This result meets the conclusions of the previous works [35, 46, 47]. In conclusion, the vinasse behavior in the mesophilic regime should be modeled by as a Newtonian fluid.

Table 3. Power-law model parameters (sugarcane vinasse) [53]

Soluble solids content (°Brix)	T (°C)	k (Pa.s ⁿ)	n
44	20	0.04	0.89
60		0.40	0.74
44	30	0.03	1.09
60		0.18	1.02
44	40	0.02	1.12
60		0.11	1.01

3. Rheological behavior of sludges

Sewage sludge is the residue of the biological activity of the micro-organisms present in sewage treatment plants, which transforms aerobically the materials carried by the wastewater so that they can be extracted. Sludges constitute the main waste of wastewater treatment plants and are mainly composed of organic matter (dead bacteria), animal, vegetable and wet mineral organic matter. This waste is therefore a potential substrate for anaerobic digestion. The rheological data used in CFD modeling are also outlined. Since experimental data are not necessarily generated by numerical scientists, the strategy is usually to select rheological properties from the literature that most closely approximate the fluid being studied.

Experimental studies were performed to determine the pseudoplastic viscosity and the power-law index of sludge in function of the sludge concentration inside the digester [54]. These parameters are related in the Table 4. It was shown that the rheological parameters depend on the sludge concentration. The pseudoplastic viscosity increases with the increase of the sludge concentration whereas the flow index decreases. This result is logical because the non-Newtonian behavior of this fluid results from the viscous character of the sludge. The more the mixture is concentrated in sludge, the more it will present a resistance to flow. These experimental results show the impact of the sludge concentration on the viscosity characterizing this flow resistance. Within the framework of anaerobic digestion and the optimization of industrial units, it will be necessary to question the interest of diluting the sludge to facilitate the agitation or not diluting it to save the water resource but to consume more energy for the agitation. Another alternative is to co-digest the sludge with another liquid waste to provide additional water and thus reduce the viscosity of the mixture. The authors proposed the following equations to describe the relationships between the viscosity coefficients and the solid concentration [54]. The two equations describing the relationships were [54]:

$$\eta = 0.018e^{0.071X} \quad (5)$$

$$n = 0.68e^{-0.0069X} \quad (6)$$

Table 4. AD sludge rheological properties in Pseudoplastic model (non-Newtonian)

Source	Sludge Concentration (kg.m ⁻³)	η (Pa.s ⁿ)	n
[54]	19	0.085	0.58
	63	1.80	0.43
	72	3.0	0.41

A review on the data collection and modeling of activated sludge was carried out by Ratkovich *et al.* (2013) [55]. In particular, the measurements and experimental protocols, used to study the rheology of sludge [55]. As the authors pointed out, the quality and validity of the models obtained from rheological measurements depended on the accuracy of the experimental measurements and protocols [55]. A critical analysis of the protocols and models found in literature was done [55]. In conclusion, precautions should be taken before using an existing model, by verifying that the model was properly developed [55].

3.1. Impact of temperature on the sludge rheology

The rheological behavior of the sludge is impacted by the temperature [36]. Rheological measurements of anaerobic digested sludge at different temperatures (10, 25, 40 and 60 °C) were carried out [36]. The viscosity and the yield stress decreased with the temperature increasing [36]. This means that the flow of sludge will be favored by an increase in temperature. Anaerobic digestion can take place at different temperature ranges: psychrophilic digestion (6 - 15°C), mesophilic digestion (30 - 35°C) and thermophilic digestion (> 45°C). The temperature regime of the process therefore has an impact on the agitation of the digester and therefore on the energy consumption. A compromise must be found between the energy expenditure to guarantee the optimal temperature (variable according to the temperature regime) and the agitation of the medium. In general, the most widespread regime is the mesophilic regime because it allows to drastically reduce the energy consumptions. As for the CFD simulations, it is necessary to use the rheological properties of the fluid at the studied temperature to guarantee the quality of the results. In addition, the rheological behavior of the sludge is irreversibly modified by the thermal history [36]. Farno *et al.* (2014) assessed the impact of the temperature, and the thermal history (20 to 80 °C, then to 20 °C) on the sludge rheology [43]. The authors concluded that the changes in temperature, previously cited, affected irreversibly the rheology and the yield stress [43]. Moreover, a proportionality was found between the soluble chemical oxygen demand (COD), and the yield stress, and infinite viscosity [43]. The variation of the yield stress, and the apparent viscosity of the digested sludge (in the case of thermal treatment) can be estimated by the soluble COD measurement [44]. Farno *et al.* (2015) studied the impact of the temperature, and the duration of thermal treatment on anaerobic digested sludge [44]. The modified Hershel-Bulkley model was used by coupling the Herschel–Bulkley and Bingham model, developed by [36, 44]:

$$\tau = \tau_0 + \alpha_0 \dot{\gamma} + k \dot{\gamma}^n \quad (7)$$

Where τ_0 is the Herschel-Bulkley yield stress, τ / τ_0 is dimensionless shear stress, α_0 is the high shear rate viscosity, $\dot{\gamma}$ is the shear rate, and n is the power-law index. A new model for the prediction of yield stress and apparent viscosity at various temperatures, and thermal histories is proposed [44].

Baroutian *et al.* (2013) carried out rheological measurements on a mixture of primary and secondary sewage sludge [37]. During wastewater treatment, the sludge undergoes various stages of treatment. The primary sludge comes from the primary treatment by decantation. Biological sludge (also called secondary sludge) is the sludge resulting from biological treatment through oxygenation of the medium by aerators, and is largely composed of dead aerobic microorganisms. The aim was to study the impact of solid concentration and temperature on the rheological behavior [37]. The Hershel-Bulkley model was used because it allowed to study the rheogram on the complete range of shear rate, while the Ostwald model only allows rheogram to be studied in the case of the modeling of the shear-thinning zone [37]. The authors concluded that the Hershel-Bulkley model fitted well with the experimental data [37]. Moreover, the solid concentration and the temperature had a significant impact on the yield stress and the model parameters [37]. Lotito and Lotito (2014) carried out rheological measurements on sewage sludge in the aim to design pump [56]. The Bingham model was used and the Ostwald model provided good correlation coefficients [56]. The Bingham plastic model is suitable for viscoplastic fluids that behave like a perfect fluid at low stresses and then like a viscous fluid above a threshold stress. Bingham plastic fluids exhibit a yield stress at zero shear rate, followed by a linear relationship between shear stress and shear rate. The governing equations of a Bingham plastic fluid is [50, 51, 57]:

$$\tau = \tau_0 + \eta \dot{\gamma} \quad (8)$$

Where τ is the shear stress, τ_0 is the yields stress, and η is the plastic viscosity or Bingham viscosity.

3.2. Impact of the sludge age on the rheological behavior

Craig *et al.* (2013) performed CFD simulations of anaerobic digester with variable sewage sludge rheology and age (0 and 40 days) [31]. This study is of major interest because the hydraulic retention time (also called residence time) of the waste in an industrial digester is about 30 days. This parameter depends on the operational parameters defined by a compromise between the rate of degradation of the organic matter and the volume of the

reactor. The Table 5 shows the rheological properties used in different models. The consistency index is significantly lower for the sludge of 40 days (0.0017 Pa.sⁿ) than for the sludge of 0 day (0.5 and 0.75 Pa.sⁿ). In contrary, the flow index is larger for the sludge of 40 days (1.15) and lower for the sludge of 0 day (0.5 and 0.66). In both cases, the sludge exhibits a non-Newtonian behavior. The critical shear rate does not vary (0 or 0.01 s⁻¹). The yield stress decreases from 0.9 and 0.7 Pa (0 day sludge) to 0.3 Pa (40 day sludge). This means that the flow is favored with the age of the mud. The agitation could therefore be adapted according to the hydraulic retention time with a greater agitation at the time of filling. In the CFD model developed by López-Jiménez *et al.* (2015), different TDS contents sludge were used in simulations (2.5, 5.4 and 9.1 TDS), according to the sludge treated in a Wastewater treatment plant anaerobic digester. At the beginning, the fluid was considered Newtonian. The physical parameters are given in the Table 1 [52]. This hypothesis was supported by viscosity measurements from a rotating viscometer [52]. The physical parameters are shown in the Table 5. As a second assumption, the sludge was considered as non-Newtonian, the rheological properties used in the CFD model are those of liquid manure [52].

Table 5. Sludge rheological properties used in Hershel-Bulkley model

Model using data	T (°C)	TS (%)	Sludge age (days)	k (Pa.s ⁿ)	n	$\dot{\gamma}_c$ (s ⁻¹)	τ_0 (Pa)
[31]		3-4	0	0.5	0.5	0	0.9
		3-4	0	0.75	0.66	0.01	0.7
		3-4	40	0.0017	1.15	0.01	0.3
[36, 58]		1.85	-	0.169	0.308	0.01-30	0.092
		2.55	-	0.436	0.308	0.01-30	0.293
[36]	25	3.25	-	0.905	0.308	0.01-30	0.711
		4.90	-	2.769	0.308	0.01-30	2.300

According to Hong *et al.* (2015), the solid concentration, the temperature, and the sludge age affected the viscosity, the yield stress, the flow index, and the flow consistency [59]. The sludge rheology was affected by a low temperature storage (4 °C), and thus by the sludge age [59]. The sludge age should be taken into account during CFD simulations in order to provide accurate results. Indeed, the hydraulic retention time of anaerobic digesters is approximately thirty days, therefore the sludge age varies between 0 and 30 days inside the bioreactor [4]. The Table 6 presents the rheological parameters of the Bingham and Sisko models of sludge for different sludge age (1, 15 and 32 days). The Sisko model is [59]:

$$\eta = \eta_{\infty} + k\dot{\gamma}^{n-1} \quad (9)$$

The TS and volatile solids (VS) contents decrease in function of the time. Concerning the Bingham model, the yield stress and the viscosity decrease with the increase of the sludge age. Regarding the Sisko model, the infinite-rate viscosity is near-constant and the flow consistency index and flow index decreased with the increase of sludge age. The impact of the age and the mixing of sludge was also a decrease of the viscosity and the yield stress with an increase of the adhesive effect [60].

Table 6. Yield stress and viscosity (Bingham model), and the infinite-rate viscosity, flow consistency index and flow index (Sisko model) for different sludge age [59]

Days	TS (g.L ⁻¹)	VS (g.L ⁻¹)	Bingham model		Sisko model		
			τ_0 (Pa)	η (Pa.s)	η_{IR} (Pa.s)	FC (s)	n
1	29	25.4	5.8	0.020	0.02	3.9	0.3
15	28	24.9	6.1	0.019	0.01	1.9	0.1
32	25	21.65	4.9	0.016	0.01	2.2	0.2

In addition, various rheological models were tested by Hong *et al.*: Bingham, power law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau, and Cross models [59]. In conclusion, the Bingham plastic and the Sisko models best fitted with experimental data [59]. The yield stress and the viscosity (Bingham model), the infinite-rate viscosity, the flow consistency index, and the flow index (Sisko model) for different temperature are shown in the Table 7. The yield stress (Bingham model) and the flow consistency (FC) (Sisko model) decrease with the augmentation of the temperature. The maximum yield stress (Bingham model) and FC (Sisko model) are obtained at 35 °C and the minimum yield stress and FC at 55 °C.

Table 7. Yield stress and viscosity (Bingham model), and the infinite-rate viscosity, flow consistency and flow index (Sisko model) for different temperature [59]

T (°C)	Bingham model	Sisko model
--------	---------------	-------------

	τ_0 (Pa)	η (Pa.s)	η_{IR} (Pa.s)	FC (s)	n
25	6.8	0.02	0.02	3	0.2
30	7.9	0.02	0.02	5	0.1
35	8	0.02	0.01	3	0.2
40	5.8	0.02	0.02	4	0.1
55	4.5	0.01	0.01	2	0.2

3.3. Impact of TS content on the rheological behavior of sludge

Rheological measurements were done at different solid concentrations (1.69 to 9.35 % for anaerobically digested sludge, 3.37 to 12.16 % for raw mixed sludge and 1.30 to 7.55 % for return activated sludge) and different temperatures (10 to 30 °C) [56]. The Bingham coefficients of the three sludge studied at 30 °C are shown in the Table 8 [56]. The yield stress and consistency coefficient increase with TS concentration and decreased with temperature [56]. In function of the TS content, the yield stress ranges from 0.518 to 85.30 Pa for the anaerobically digested sludge, from 0.920 to 62.10 Pa for the raw mixed sludge, and from 1.195 to 120.5 Pa for the return activated sludge. The consistency index of the three fluids increases with the augmentation of the TS content from 0.0065 to 0.1123 Pa.sⁿ for the anaerobically digested sludge, from 0.0084 to 0.0663 Pa.sⁿ for the raw mixed sludge, and from 0.0092 to 0.1524 Pa.sⁿ for the return activated sludge. These results allow to consider the impact of the anaerobic digestion process on the rheological behavior of the sludge. In fact, in order to perfectly model the flow field within anaerobic digesters, we should take into account the evolution of the rheological behavior in function of the digestion as well as the variation of the TS content.

Table 8. Bingham coefficients and thixotropy at 30 °C [56]

Sludge	TS (%)	τ_0 (Pa)	k (Pa.s ⁿ)	Thix (Pa.s ⁻¹)
Anaerobically digested sludge	1.69	0.518	0.0065	22.18
	3.48	4.365	0.0185	95.67
	5.07	11.04	0.0500	153.3
	6.39	28.87	0.0841	315.3
	7.96	44.92	0.1165	1197
	9.35	85.30	0.1129	2260
Raw mixed sludge	3.37	0.920	0.0084	6.416
	5.07	4.103	0.0189	51.06
	7.43	9.140	0.0253	147.6
	9.02	24.46	0.0362	506.4
	9.66	36.92	0.0619	864.8
	12.16	62.10	0.0663	2311
Return activated sludge	1.30	1.195	0.0092	5.446
	3.50	13.97	0.0547	308.0
	4.88	34.88	0.0913	633.8
	5.88	48.56	0.1193	1620
	7.55	120.5	0.1524	3990

The study of the characteristics of highly concentrated anaerobic digested sludge with TS upper to 8 % was investigated [61]. The impact of TS (8 to 16 %) and temperature (35, 55 and 70 °C) were evaluated [61]. The Hershel-Bulkley model was used to model the sludge rheology [61]. The sludge rheology was more impacted by the TS content than by the temperature [61]. The Table 9 presents the yield stress obtained by flow and dynamic measurements [61].

Table 9. Yield stress obtained by flow and dynamic measurements [61]

TS (%)	τ_{0flow} (Pa)	τ_{0dyn} (Pa)
8	25.3	35
10	81	91
13	171	300
16	319.2	420

Dai *et al.* (2014) investigated the rheology evolution of sludge through high-solid anaerobic digestion [16]. The anaerobic digestion is considered as high-solid digestion when the TS content is higher than 10 % [62]. The use

of solid digestion reduces the volume of the reactor. There is therefore an economic interest. In the study carried out by Dai *et al.*, the Herschel-Bulkley model was also used [16]. The shear stress, the viscosity, the yield stress, and the consistency index were lower and the flow index was higher with longer solid retention time [16]. Furthermore, the TS of the thermophilic digester was higher than the TS of the mesophilic digester, but had a better flowability [16]. This work showed that the sludge rheology could be a controlling parameter of the anaerobic digestion process [16]. The rheological behaviour of slaughterhouse waste, Biosludge paper mill industry, wheat stillage and cereal residues was evaluated [63]. These waste demonstrated viscoplastic or thixotropic viscosity behavior as shown in Table 10 [63]. In addition, the rheological parameters are presented in Table 11 for the three mathematical models: Herschel-Bulkley, Ostwald and Bingham [63].

Table 10. Rheological properties and models [63]

Digested substrate	TS (%)	Viscosity curve behavior	η (mPa.s)	η_{lim} (mPa.s)
Slaughterhouse waste	3.9	Viscoplastic	18	6
Biosludge paper mill industry1	3.8	Thixotropic	436	8
Biosludge paper mill industry2	3.7	Viscoplastic	267	29
Wheat stillage	3.0	Pseudoplastic or viscoplastic	33	6
Cereal residues	7.7	Viscoplastic	443	36

Table 11. Obtained results from mathematical modeling of rheogram data [63]

Digested substrate	Herschel-Bulkley				Ostwald			Bingham	
	τ_o (Pa)	n	k (Pa.s ⁿ)	R ²	n	k (Pa.s ⁿ)	R ²	τ_o (Pa)	R ²
Slaughterhouse waste	0.24	1.06	0.003	0.93	0.69	0.35	0.8	0.21	0.92
Biosludge paper mill industry1	2.57	3.40	5.x10 ⁻¹⁰	0.45	0.08	2.28	0.002	1.88	0.12
Biosludge paper mill industry2	2.89	0.59	0.42	0.99	0.44	1.23	0.99	6.36	0.95
Wheat stillage	0	0.65	0.04	0.88	0.64	0.04	0.87	0.33	0.95
Cereal residues	2.38	0.49	0.98	0.96	0.39	1.98	0.96	8.31	0.91

Liang *et al.* (2017) proposed a protocol of uniaxial compression test for studying the transition between solid and fluid behavior of sludge (TS around 20 %) [60]. Several samples were studied: raw sludge, six days aging sludge, 5 min mixing sludge, and 20 min mixing sludge [60]. As a result, the viscosity and yield stress were the most sensitive rheological factors to operational conditions [60]. The Table 12 presents the yields and the viscosity for varying TS [59]. Three rheological models were studied: Casson, Bingham and Power models. The yield stress (Casson and Bingham) increases with the TS content increase. The viscosity (Bingham, Casson and Power) varies in function of the TS content with a maximum viscosity obtained at 25 °C for the Casson and Bingham models and at 30 °C for the power model. The power-law index is lower than 1 for the three temperatures and increases with the decrease of the temperature. Cao *et al.* (2016) studied the rheology of municipal sewage sludge (with and without AD) [64]. Rheological measurements at 20, 35 and 55 °C, and at TS concentration from 4 to 10 % were performed [64]. Three rheological models (Ostwald de Waele, Herschel-Bulkley and Bingham) were compared [64]. The Ostwald model best fitted with experimental data [64]. In addition, the TS concentration and temperature impacted sludge rheology critically [64].

Table 12. Yield stress and viscosity for different TS [59]

TS (g.L ⁻¹)	Rheological model	τ_o (Pa)	η (Pa.s)	n	R ²
30	Casson	4.6	0.010	-	0.99
	Bingham	7.4	0.021	-	0.98
	Power	-	1.100	0.46	0.94
25	Casson	0.8	0.017	-	0.99
	Bingham	2.1	0.024	-	0.97
	Power	-	0.154	0.73	0.99
20	Casson	0.3	0.015	-	0.98
	Bingham	1.1	0.018	-	0.98
	Power	-	0.061	0.83	0.99

Hong *et al.* (2017) demonstrated that the yield stress and the viscosity of digested sludge increased with the increase of TS and VS concentration [65]. Moreover, Hii *et al.* (2017) highlighted that the treated sludge viscosity and the yield stress decreased linearly with temperature [66]. Furthermore, the soluble COD presented a linear correlation with yield stress and apparent viscosity [66]. The Hershel-Bulkley model was used and the calculated parameters were provided [66]. Seyssieq *et al.* (2015) carried out in situ rheological characterization of wastewater sludge in order to compare stirred bioreactor (helical ribbon impeller equipped with a rheometer) and the pipe flow configurations [67]. As a result, the Hershel-Bulkley model best fitted with the experimental data obtained with the helical ribbon impeller [67]. Nonetheless, the measurements on suspensions were not consistent, and thus required an adjustment due to the wall slip effect [67]. The model parameters were provided in function of total suspended solids (TSS) concentration [67]. The principal interest of in situ characterization was to overcome the effects of the study of a sample, especially since it will not necessarily be representative of the medium in the case of heterogeneous fluid. Moreover, this method facilitated the study of the medium during digestion process in real-time. Bobade *et al.* (2017) studied the impact of gas injection on the apparent viscosity and viscoelastic property of waste activated sewage sludge [68]. A linear relationship between the variation of viscoelastic properties, and the variation of other physicochemical properties were proposed [69]. Cao *et al.* (2018) studied the effect of TSS content and heat and anaerobic digestion treatments on the rheological properties of municipal sludge [70]. The sludge exhibited shear-thinning behavior [70]. The viscosity of the anaerobically digested sludge was the lowest, then it was fresh mixed sludge, and the thermal hydrolyzed sludge was the most viscous [70]. The Hershel-Bulkley model fitted well with the experimental results [70]. Feng *et al.* (2016) evaluated the rheological behavior of the sludge in an anaerobic digester (105 days) [39]. The Herschel-Bulkley model, the Bingham Law equation, and the Power-Law equation were compared [39]. The Herschel-Bulkley model best fitted [39]. The authors observed that the TSS concentration influenced the viscosity [39]. Cheng and Li (2015) studied the rheological behavior of sewage sludge with TS content ranging from 2 to 15 % (cf. Table 13) [71]. The influence of organic content was non-significant at low TS (inferior to 6 %) [71]. The consistency increases whereas the flow index decreases with the increase of TS content from 2 to 15 %. Therefore, the TS content has a significant impact on the rheological behavior of the sludge. A new model was developed, combining the exponential model and power model, in order to describe the relation between the TS, the shear rate, and the viscosity of the high solids sludge [71]. Al-Dawery (2016) investigated the effects of suspended solid and polyelectrolyte on the settling, and the rheological properties of municipal activated sludge [72]. The Bingham model was used [72]. In conclusion, the yield stress and the limit viscosity increased with the increase of TS, and the limit viscosity was strongly dependent on TS [72]. The variation of the rheological characteristics of high-solid (15-20 % TS) municipal sludge during the anaerobic digestion process was studied [73]. The two-part Hershel-Bulkley model was used to characterize the rheological behavior of the sludge [73]. The authors observed that the yield stress, the viscosity, and the critical shear rate decreased with the digestion [73].

Table 13. Ostwald model parameters in function of the sludge TS content [71]

TS (%)	k (mPa.s ⁿ)	n	R^2
2	182.56	0.536	0.9435
4	3,367.6	0.256	0.9988
6	1,773.2	0.264	0.9926
7	3,235.8	0.222	0.9859
10	18,185	0.160	0.9828
13	44,511	0.078	0.9959
15	117,648	-0.100	0.9989

Eshtiaghi *et al.* (2016) carried out a study on the prediction of apparent viscosity and yield stress of digested, and secondary sludge mixtures [74]. The sludge studied (1.4 to 7 % TS) could be treated in anaerobic digester [74]. A master curve was developed in order to predict the sludge flow behavior independently of the TS concentration [74]. The apparent viscosity and yield stress of mixtures of primary, secondary and anaerobically digested sewage sludge were predicted by Markis *et al.* (2016) [75]. They established an equation to predict the viscosity in function of the pH [75]. The equation developed was [75]:

$$\eta = -0.0135 pH^2 + 0.1965 pH - 0.667 \quad (10)$$

A dimensionless Hershel-Bulkley form, previously developed [76], was used by Markis *et al.* [75]. The impact of TS content on the viscosity of the sludge was studied [76]. The study showed that the apparent viscosity, the yield stress and the fluid consistency increased with the TS concentration increase [76]. Abbà *et al.* (2017) evaluated the rheology and microbiology of sludge from a thermophilic aerobic membrane reactor [77]. The Hershel-Bulkley model fitted with experimental data [77]. In this work, the influence of pH, aeration,

temperature, and suspended solid concentration (biomass concentration) on rheological behavior of sludge were studied [77]. Björn *et al.* (2018) studied the rheology of sewage sludge [78]. The Bingham model, the Ostwald model and the Hershel-Bulkley model fitted with experimental data, depending on the sample [78]. The rheological models and parameters are shown in the Table 14.

Table 14. Rheological models and parameters of primary and biological sewage sludge [78]

TS (%)	TVS (%)	T (°C)	WV (m ³)	Rheological model	τ_0 (Pa)	k (Pa.s ⁿ)	n	R ²
2.4	1.6	51-53	1.70	Ostwald	-	0.1900	0.4627	0.48
				Bingham	0.6404	0.0047	-	0.90
3.0	1.8	36-38	2.00	Ostwald	-	0.3377	0.4448	0.98
				Hershel-Bulkley	0.9130	0.0372	0.7479	0.96
3.9	2.4	36-38	2.00	Ostwald	1.8640	0.1559	0.6128	0.97
				Hershel-Bulkley	1.5385	0.0913	0.6862	0.98

Björn *et al.* (2018) studied the relationship between the rheological properties of 12 full-scale continuous stirred-tank biogas reactors and operational conditions [78]. Both mono-digestion and co-digestion under mesophilic and thermophilic conditions were studied [78]. Several feedstocks were evaluated: sewage sludge, primary and biological sewage sludge, FIW, whey, fodder residues, manure, starch, fat, OFMSW, and SHW [78]. Correlations were found between TVS content and the apparent viscosity (shear rate of 20 s⁻¹) and limit viscosity of reactor with sewage sludge substrate [78]. Moreover, they also found correlation between TS content and limit viscosity, in the case of thermophilic co-digestion reactors [78]. No correlation was found in the case of mesophilic mono-digestion [78]. Thereby, it is necessary to consider the operating conditions of continuously stirred digesters in the study of the rheology of digestion media [78]. The data presented are valid for specific cases and additional studies must be carried out if the conditions change. Gienau *et al.* (2018) carried out study on the rheological characterization of 16 anaerobic sludge from agricultural and bio-waste biogas plants [79]. The power-law equation was used to describe the rheological behavior, and the Arrhenius law was used for the temperature dependency [79]. The authors highlighted that the temperature-dependent rheology was essential for engineering utilizations such as pressure drops, agitators and pumps design [79].

4. Rheological behavior of manure

In this section, we focus on the rheological properties of animal manure. Achkari-Begdouri and Goodrich (1992) carried out rheological measurements on Moroccan dairy cattle manure at different TS content and temperature [80]. This waste was studied for TS content between 2.5 and 12.1 % and temperature from 20 to 60 °C [80]. We present in the Table 18 the rheological parameters k and n for different TS content at 35 °C [80]. The consistency coefficient k and the power-law index n of liquid manure were expressed as [80–82]:

$$k = \left[8.722e^{(4830/T+0.58319 \times TS)} \right] \times 10^{-10} \quad (11)$$

$$n = 0.6894 + 0.0046831 \times (T - 273) - 0.042813 \times TS \quad (12)$$

The density, the specific heat and thermal conductivity were expressed as [80, 81, 83, 84]:

$$C_p = 4187.5 - 28.9 \times TS \quad (13)$$

$$\lambda = 0.6173 - 0.0069 \times TS \quad (14)$$

$$\rho = 0.0367 \times TS^3 - 2.38 \times TS^2 + 14.6 \times TS + 1000 \quad (15)$$

Rheological properties of liquid manure depend on the TS content [84]. Moreover, the viscosity and the shear stress increase exponentially with the increase of the TS content [84]. Non-linear regression technique was used in order to provide the following relations [84]:

$$\eta = 0.001e^{0.462TS} \quad (16)$$

$$\tau = 0.157e^{0.462TS} \quad (17)$$

The rheological properties used in this study are shown in the Table 18. Bakker *et al.*, (2009) carried out numerical modeling of non-Newtonian slurry, using Hershel-Bulkley and Bingham models (cf. Table 15) [40].

The rheological properties are given in function of the solid concentration (40 and 50 wt%) and the density. The consistency and the yield stress increase with the increase of the solid concentration. In addition, the consistency and the yield stress are greater when the slurry density is higher.

Table 15. Bindura nickel ore slurry rheological properties used in Hershel-Bulkley and Bingham models [40]

Model	Solid concentration (wt%)	k (Pa.s ⁿ)	n	ρ (kg.m ⁻³)	τ_0 (Pa)
Hershel-Bulkley	40	0.439	0.34	1364	0.456
	50	2.130	0.323	1500	2.130
	50	3.774	0.565	1667	3.774
Bingham	40	6.79x10 ⁻³	-	1364	1.945
	50	1.47x10 ⁻²	-	1500	8.189
	50	7.42x10 ⁻²	-	1667	52.180

Thota Radhakrishnan *et al.* (2018) studied the rheology of two types of slurries using a narrow gap couette rheometer: black water (consisting of human fecal waste, urine, and flushed water from vacuum toilets) (sample 1) and black water with ground kitchen waste (sample 2) [85]. Depending on the percentage of TSS, the slurry rheological behavior was described by the Hershel-Bulkley model, the Bingham model or the linear model [85]. The viscosity increased with the increase in TSS concentration, and decreased with the increase of temperature [85]. The authors concluded that the Hershel-Bulkley model best suited. The physical properties (at 30 °C) are related in the Table 16 and the Table 17. In their model, Wu (2010) considered that the manure slurry exhibited non-Newtonian pseudo-plastic fluid behavior when TS was superior to 2.5 % [86]. The rheological properties of liquid manure are presented in the Table 18.

Table 16. Slurry rheological properties at 30 °C (sample 1) [85]

Model	TSS (%)	k (Pa.s ⁿ)	n	τ_0 (Pa)
Hershel-Bulkley	11.2	0.9462	0.45	1.07
	10	0.28666	0.56	0.803
	7.2	0.08741	0.65	0.325
	5	0.02123	0.78	0.135
	3.9	0.01187	0.82	0.073
	3.2	0.00764	0.87	0.053
Bingham	2.6	0.00293	1	0.052
	1.8	0.00223	1	0.011
Linear	1.4	0.00204	1	0
	0.7	0.00152	1	0
	0.4	0.00125	1	0

Table 17. Slurry rheological properties at 30 °C (sample 2) [85]

Model	TSS (%)	k (Pa.s ⁿ)	n	τ_0 (Pa)
Hershel-Bulkley	3	0.01021	0.85	0.054
	2.6	0.00343	1	0.074
	2.1	0.00303	1	0.061
Bingham	1.8	0.00278	1	0.044
	1.2	0.00244	1	0.035
	1	0.00227	1	0.023
Linear	0.8	0.00159	1	0

Table 18. Liquid manure rheological parameters used in Pseudoplastic model [10, 52, 80, 81, 83, 84, 86–88]

TS (%)	Manure type	T (°C)	k (Pa.s ⁿ)	n	$\dot{\gamma}$ (s ⁻¹)	ρ (kg.m ⁻³)	η_{\min} (Pa.s)	η_{\max} (Pa.s)	C_p (J/kg.K)	λ (W/(m.K))
2.5	DC	35	0.042	0.710	226-702	1000.36	0.006	0.008	4186.78	0.6171
5.4		35	0.192	0.562	50-702	1000.78	0.01	0.03	4185.94	0.6169
7.5		35	0.525	0.533	11-399	1001.00	0.03	0.17	4185.33	0.6168

8.9		17-24	2.6	0.42	-	-	-	-	-	-	
9.1		35	1.052	0.467	11-156	1001.31	0.07	0.29	4184.87	0.6167	
12.1			5.885	0.367	3-149	1001.73	0.25	2.93	4184.00	0.6165	
10	DC		5.3	0.11	0.90-23.90	999.6	-	-	-	-	
	S	17-24	2.7	0.33	0.90-23.90	1008.3	-	-	-	-	
	P		8.9	0.29	0.96-24.14	1036.5	-	-	-	-	
	Pi		2.2	0.21	0.90-23.90	1025.7	-	-	-	-	
			35	16.1	0.348	-	-	-	-	-	-
	DC		40	16.7	0.325	-	-	-	-	-	-
		50	13.0	0.332	-	-	-	-	-	-	
14.2	DC	17-24	22.9	0.41	-	-	-	-	-	-	
15	DC		31.3	0.3	0.61-24.37	973	3.35	44.24	4183.17	0.6163	
	S		19.4	0.29	0.70-23.90	965.1	2.04	24.99	4183.17	0.6163	
	P	17-24	2.4	0.38	0.80-23.90	1063.6	0.34	2.76	4183.17	0.6163	
	Pi		2.4	0.38	0.96-23.90	967.7	0.34	2.46	4183.17	0.6163	
20	P		35.4	0.29	0.64-24.14	1091.8	3.69	48.6	4181.72	0.6159	
	Pi		56.8	0.35	0.24-23.90	1090	7.22	143.62	4181.72	0.6159	
	-	35	56.8	0.35	0.24-23.90	1090	34.47	172.5	-	-	

(DC=dairy cattle, S=sheep, P=poultry, Pi=pig).

5. Rheological behavior of food waste

Few researches were carried out on the rheology of solid waste such as food waste. However, anaerobic digestion of food waste is worthwhile and growing interest [1, 89–91]. In addition, the impact of hydrodynamics on the performances of anaerobic digestion of high-solid waste is significant [62, 92]. Solely, a review was carried out on the rheological properties of fruits and vegetables [93]. The Table 19 shows the rheological models able to describe the behavior of different types of biowaste, mostly fruits, purees, pastes and juices. It can be observed that the Newtonian model can only describe the rheological behavior of juices (cherry, carrot, apple and pear). It can be explained by the high water content of juices, which is consider as a key controlling factor of the rheology [94]. However, we notice that the behavior of other type of juices is described by non-Newtonian models:

- Tamarind and tomato juices are described by the Hershel-Bulkley model.
- Kiwifruit juice is modeled by the Power-Law model.
- Sloe and pineapple juices are described by the Bingham model.

Therefore, the water content is not the unique parameter able to deduce the appropriate rheological model of fruit juices.

All the fruits and vegetables products, purees, or pastes, are characterizes by a non-Newtonian rheological model: Hershel-Bulkley and Power-Law models. Baroutian et al. (2017) obtained similar results: the Hershel-Bulkley was used in order to characterize the flow behavior of fruits and vegetables [94]. The aim of their study was to characterize treated and non-treated putrescible food waste [94]. Rheological measurements were performed at different temperature (25, 35, and 45 °C) using a model ARG2 stress-controlled rotational rheometer (TA Instrument Ltd, US) [94]. Food waste exhibited shear-thinning flow behavior; viscosity was a

function of temperature and composition; the flow properties were affected by the waste composition; at a given temperature, the viscosity decreased as the carbohydrate proportion increased [94].

Table 19. Rheological models of fruits and vegetables

Model	Waste	Sources
Hershel-Bulkley	Berry fruits products	[95–99]
	Stone fruits	[99–106]
	Coriander puree	[107]
	Mint puree	[107]
	Tamarind juice	[108]
	Tomato juice	[109, 110]
Power-Law	Citrus fruit juice	[111, 112]
	Kiwifruit juice	[111]
	Guava products	[113, 114]
	Fenugreek paste	[115]
	Tomato ketchup	[116]
Bingham	Sloe juice	[105]
	Pineapple juice	[117]
Newtonian	Cherry juice	[101]
	Carrot juice	[118]
	Apple juice	[100, 119]
	Pear juice	[112, 119]

Björn *et al.* (2018) studied the rheology of full-scale digester feedstocks, in mesophilic and thermophilic conditions (cf. Table 20) [78]:

- Feedstock 1: OFMSW (62 %), SHW (9 %), fodder residues (13 %), other waste (16 %).
- Feedstock 2: SHW (45 %), Manure (29 %), whey (14 %), fat (12 %).
- Feedstock 3: OFMSW (23 %), SHW (45 %), Manure (32 %).
- Feedstock 4: OFMSW/SHW (32 %), Manure (68 %).
- Feedstock 5: OFMSW (57 %), SHW (12 %), starch (21 %), other waste (10 %).
- Feedstock 6: OFMSW (95 %), fat (5 %).
- Feedstock 7: SHW (in majority), FIW.

The different types of feedstock are constituted of different proportions of OFMSW ranging from 23 to 95 %. The TS and TVS contents are presented in the Table 20 as well as the rheological models and model parameters. The TS and TVS contents are comprised between 2.7 and 5.3%, and 1.6 and 3.8% respectively. All the feedstocks are characterized by a non-Newtonian rheological model. No correlation between the feedstock composition, TS and TVS contents and the appropriate rheological model can be deduced from these experimental results. However, it can be seen that the rheological properties depend on the TS content, TVS content and the temperature.

The Table 20 presents the rheological models and parameters proposed by Björn *et al.* (2018) for different mix of feedstocks: OFMSW, SHW, manure, whey, fat, starch and FIW [78]. The TS content is comprised between 2.1 and 5.3 % and the TVS between 1.5 and 3.8 %. In addition, the rheological models and parameters are given for different temperatures: around 37 °C and 50 °C. Three non-Newtonian rheological models fitted in function of the feedstock and process temperature: Ostwald, Bingham and Hershel-Bulkley models. Despite the low TS content, the fluids present a non-Newtonian behavior. The feedstock1 is modelled by the Ostwald model

Table 20. Rheological models and parameters [78]

Feedstock	WV (m ³)	TS (%)	TVS (%)	T (°C)	Rheological model	τ_o (Pa)	k (Pa.s ⁿ)	n	R ²
OFMSW (62 %), SHW (9 %), fodder residues (13 %), na* (16 %)	3.20	2.7	1.6	52-55	Ostwald	-	0.0000	2.0831	0.97
					Ostwald	-	0.0000	2.2345	0.89
		3.6	1.8		Ostwald	-	0.0000	1.8681	0.99
					Ostwald	-	0.0000	2.0276	0.94
SHW (45 %), Manure (29 %), whey (14 %), fat (12 %)	1.70	5.0	3.8	51-53	Ostwald	-	0.0001	1.5865	0.92
					Ostwald	-	0.0003	1.4265	0.93

OFMSW (23 %), SHW (45 %), Manure (32 %)	6.50	3.9	2.8	37	Bingham	0.1394	0.0074	-	0.96
					Bingham	0.4527	0.0102	-	0.95
OFMSW/SHW (32 %), Manure (68 %)	2.25	4.0	2.9	38	Hershel-Bulkley	0.3322	0.0001	1.5581	0.69
					Ostwald	-	0.0001	1.6643	0.98
					Ostwald	-	0.0007	1.2796	0.70
OFMSW (57 %), SHW (12 %), starch (21 %), na* (10 %)	2.90	4.2	2.5	37	Hershel-Bulkley	1.2207	0.0370	0.7618	0.71
					Hershel-Bulkley	0.5489	0.0193	0.8754	0.99
					Bingham	3.4542	0.0068	-	0.52
					Hershel-Bulkley	1.0244	0.0227	0.8519	0.91
OFMSW (95 %), fat (5 %)	1.10	2.1	1.5	53	Ostwald	-	0.0000	1.9554	0.90
SHW (in majority), FIW	na	5.3	3.8	37	Bingham	0.8060	0.0119	-	0.95

* Information not available.

6. Discussions

Many studies have been carried out on the rheological characterization of different type of organic waste. The authors agreed on the appropriate rheological models in order to characterize each type of waste. The choice of the rheological model depended on different parameters such as the type of waste, the temperature, the age of the waste, and the total solid content.

The choice of the rheological model is crucial for CFD simulations. Literature data if the rheological behavior of the studied fluid is known can be used. Otherwise, it is possible to use the data of a similar fluid or rheological measurements must be carried out.

The vinasse was mostly characterized by a Newtonian model at temperatures above 30 °C, even if the Hershel-Bulkley model or the power-law model were also suitable. The rheological behavior of sludge has been well studied. For this purpose, the Hershel-Bulkley model, the modified Hershel-Bulkley model, the Bingham model, and the Sisko model were evaluated. The rheological behavior of the manure was modeled by the Hershel-Bulkley model or the Bingham model, depending on the study. Moreover, some authors highlighted the relation between soluble COD, pH, and the viscosity of the sludge. These relations allowed to estimate the viscosity from these parameters. The relationships are valid for the studied waste.

Concerning the food waste, rheological measurements have been carried out only on fruits and vegetables, showing both the Newtonian and non-Newtonian behavior depending on the biowaste type. Most of the studies were done on one fruit or vegetable, but not on a mixture. A lack of experimental data of the rheological behavior of this category of waste was noted. Hershel-Bulkley model, power-law model and Bingham models were used in order to model the rheological behavior of fruits and vegetables. However, because of the diversity of biowaste, there were only specific studies of biowaste rheological behavior, and few literature data of a mix of biowaste were reported. It is important to note that the rheological properties depended on the mix of biowaste, the total solid and volatile solid contents. Thus, the data available in the literature allowed to obtain a general idea of the rheological behavior of some biowaste: manure, vinasse, sludge, fruits, vegetables, mix of OFMSW, SHW, starch, fat, whey, fodder residues. However, in the case of anaerobic digestion of specific biowaste or biowaste mixture, rheological measurements on the specific waste mixture should be performed.

7. Conclusion

In conclusion, the knowledge on the waste rheology is required in order to model and describe the flows using CFD. The rheological behavior of manure and sludge are well described, however the rheological behavior of a mix of biowaste is poorly known and requires further investigations. The rheological characterization of solid waste is still barely studied and requires further work to be able to model the flows of this type of medium using CFD. The main difficulty is related to the existing measurement equipment, which is not well adapted to rheological measurements of heterogeneous materials.

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