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Food Rheology: An Introduction and Fundamentals Concepts

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Abstract: Food rheology is the study of the flow and deformation of food materials. It involves understanding the physical and mechanical properties of food, such as how it behaves when subjected to external forces or changes in temperature. Understanding food rheology is essential in various food processing and manufacturing industries as it helps in product development, quality control, and optimization of processing parameters. Some fundamental concepts in food rheology include as follows. Viscosity refers to a material's resistance to flow. In food rheology, it is a measure of how easily a food material flows under an applied force. Food materials can exhibit different types of viscosity, such as Newtonian, pseudoplastic, dilatant, and viscoelastic behavior. Shear stress is the force per unit area applied to a food material, while the shear rate is the rate at which the food material deforms. In food rheology, these two variables are used to describe the flow behavior of food materials. Different food materials have different flow behaviors. Some foods, like water, exhibit Newtonian flow behavior, where the viscosity remains constant regardless of the applied shear rate. Other foods, like ketchup or mayonnaise, exhibit non-Newtonian flow behavior, where the viscosity changes with the shear rate. Elasticity refers to a material's ability to regain its original shape after deformation. In food rheology, elasticity is important in determining the texture and shelf life of food products. Viscoelasticity refers to the combined properties of both viscosity and elasticity, where a material exhibits both liquid-like (viscous) and solid-like (elastic) behavior. Yield stress is the minimum amount of shear stress required to initiate flow in a material. Many food materials, such as gels or semisolid foods, exhibit yield stress where they behave like a solid until a certain stress threshold is reached. By understanding these fundamental concepts, food scientists and engineers can manipulate and control the rheological properties of food materials to achieve the desired texture, mouthfeel, and sensory attributes, as well as optimize processing conditions to improve the overall quality of food products.

Keywords: Food rheology; Newtonian fluids; non-Newtonian fluids; Rheology measurement

1. Introduction

In the manufacturing of foods and food products, rheology is the study of the flow and deformation of materials, particularly liquids and semi-solids or soft solids such as gels, pastes, and slurries. It's important in food manufacturing because it helps to understand how food products will behave during processing and storage, and how they will feel and taste in the mouth. In addition to that the rheological properties of feedstock and food intermediates also control the quality of the food. Food is comprised of various and also numerous biological compounds controlling their rheological properties. It is necessary to understand the rheological behavior of food products and their feedstock for efficient manufacturing of desired food products of interest. The theme of understanding the behaviors of food helps to understand various key questions in food processing and engineering such as whether the food product of interest deforms easily, can flow in pipes or tubes, and flows through pipes and various joints. The process engineering of food manufacturing plants requires a good understanding of the flow properties of the food materials including feedstocks and food intermediates in the food processing. This is why scientists and engineers need to understand the rheological characterization of foods for the development, optimization, and processing of food of interest [1–2].

The rheological characterization of food products does control their food texture. Fluid mechanics is the foundation for food rheology. Food rheologist develops the correlation between stress and strain for various food materials and fixes the rheological characterization of food materials in different models. These models are used for scaling up the process and process development. Food is an extremely intricately constructed substance. It is made up of water, proteins, carbohydrates, lipids, and fibers either free form or bound with other constituents. Food's structural behavior and flow are determined by its constituent parts, and structured fluids' stability is influenced by several variables. Consider the flow property, it relies on how viscous the liquid phase is in a dispersion of a food ingredient. The emulsion or suspension properties, or dispersion characteristics, of a food product, can be used to predict its rheological flow behavior. Food dispersion, for instance, is crucial in some frequently consumed meals including mayonnaise, tomato paste, sauces, and infant food. The rheological behavior of the dispersion-based food product was controlled by particle size distribution, particle characterization, and interactions between the particles. According to research, suspensions are made up of solid particles dispersed in a liquid medium. Emulsions, in contrast, are made up of deformable particles in a liquid media. The temperature and length of the measurement have a major impact on the rheological characteristics of food as well. Food behavior is greatly influenced by gel formation. Most foods containing proteins, carbohydrates, and polysaccharides become gels when exposed to heat or pressure. A gel's microstructure can be altered to create a variety of products with different physical properties, such as soft hydrogels and hard rubbery polymers. Given this correspondence, the flow behavior of food materials was controlled by various parameters such as constituents of the materials and gelation phenomena when exposed to the surroundings.

Food rheology deals with the flow behavior of food materials either liquids or semi-solids such as gels and paste. Normally rheology means the study of non-Newtonian behavior of food materials, food liquids, food gels, or emulsions. The microstructure of liquid food has a significant influence on both the quantitative and qualitative characteristics of the food product. The inter/intramolecular connections and different physicochemical associations between the intricate dietary constituents produce the microstructure of foods. Usually, the material's microstructure has a considerable effect on how it flows under shear stress and deforms under shear force. In thermal processing such as heating and fluid flow operations such as pumping and combining ingredients, the viscosity and elasticity, which are comparable to the liquid-like and solid-like components of the meal, help with the heat and mass transfer in various operations of food processing. It results that the liquid components in the food materials were efficiently processed. The rheological properties of food materials were mainly influenced by the mass transfer of the food processing and other unit operations such as drying, fermentation, and separation. In addition to that, the rheological performance of the food materials indirectly influences the diffusion coefficient of the food materials and also the heat transfer coefficient of the food substances involved in the food processing.

The rheology of food indirectly controls the food texture of the material and also their microstructure. Food texture helps to consume the food via the mouth. Various food processing operations such as over-process or under-processes with the involvement of shear or heat affect the food texture and microstructure of the food products. In the case of liquid products, the flow behavior of the liquid foods depends on the shear stress and shear strain. For instance, spreads made up of fat, molten chocolate, mashed potatoes, and some salad dressings behave like liquids under high shear forces and like solids under low shear stress. By minimizing textural flaws in processed meals, a thorough understanding of food rheology and microstructure raises consumer satisfaction and the quality of food.

Several researchers have determined that food rheology is the subject of the deformation and flow of food materials in various food processing under optimized conditions. This is why an in-depth study of food rheology is required to understand food processing and develop an efficient process for product development as well. The following applications in the food process show the importance of food rheology.

Create a concrete process for new food materials; Determination of fluid characteristics of liquid foods and semi-solids; Understanding the microstructure of food materials and its relationship with rheological performance and developing models for fluid flow; Assess the quality of the foods and their relationship with the rheological performance of the foods (For example, Winterization of oils and fats causes gelling and increases the viscosity of the oils and fats); Evaluate the shelf life properties of the foods; Rheological data is used to scale up the process of food manufacturing; Rheological data is used to assist in the coating process, extruding, mixing, and homogenization.

The microstructure and food texture of the food materials were characterized by advanced instruments that help to understand the rheology of the foods. Food is a complex material consisting of water, proteins, carbohydrates and fats, and a significant amount of fibers. These constituents normally influence the flow behavior and structural properties of these foods. Therefore, the rheological characteristics of food are significantly different from those of conventional polymeric materials. various factors influence the stability of structured fluids, with the viscosity of the liquid phase in dispersions being the major contributor to the material's flow properties. Nowadays, food rheology does not only measure apparent viscosity, it provides more detailed information on the microstructure and fluidity of food with the development of technology. The transitions from rotational viscometry to either controlled stress or strain rheometry or more advanced optimal Fourier transformation rheometry have increased the accuracy and complexity of the measurements [3–7].

This chapter deals with an overview of food rheology with a coverage of the following information, including fundamental concepts involved in food rheology; the correlation and models involved in food rheology; characterization of food rheology; and factors controlling the food rheology.

2. Fundamental concepts

Food rheology is an important concept to be understood for the development of food processing. It was highly linked with various fluid flow phenomena such as stirring, mixing, agitation, pumping, dosing, dispersion on the solid food, and spraying. Food rheology is one of the controlling parameters linked with the structure of the foods and in context with their dynamic properties. The relationship between rheology and structure of the foods controls flow processing and behavior and also determines the flow conditions under which food material flows [8]. Notably, food rheology can play an important role in flow properties controlled by the structure of the food substance and its constituents during the processing of food products of interest. Dynamic properties of the food are fundamental in cooking and kitchen operations such as physiologically flowable in the gastrointestinal system where food structure is perceived and digested well for metabolic functions. Rheology mainly impacts on perception and digestion of food in the gastrointestinal system where the food structure of the product controls flow properties.

Food rheology is one of the important practices playing in various categories of food product development as shown in **Figure 1**. Food product developers develop food products of interest where the structure and rheology performance are interlinked. The typical properties of the interest linked with food rheologies include sensory or perception characteristics such as texture; stability; convenience aspects such as portioning, scoping, dosing, and filling; and nutritive characteristics such as release kinetics and safety of food products. In the case of the second category food process engineers, they are interested in developing rheology–process relationships of the foods and their products and use rheological data for process or product optimization and scaling up the process of interest as well. In addition to that, the measurement of the rheological properties of foods can help in developing analytical solutions and formulating/correlating semi-empirical modeling and also the simulation of flow behavior with computational fluid dynamics software. Various flow processes include mixing, stirring, dispersing, extrusion, spinning, coating, injection molding, and spraying. Finally, material scientist focuses on the structure and rheological relationship of the food materials for process development. These people focus on the empirical model development for modeling and simulation in food process development [9].

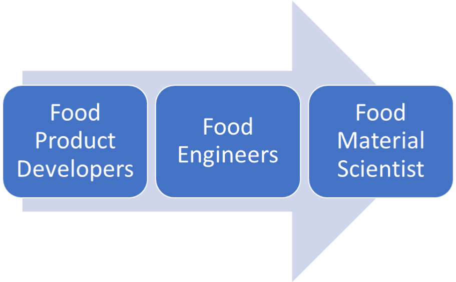

Figure 1. Role of food rheology in different categories

Although rheology is a complex topic and most food systems include properties that are not ideal, it has recently seen a larger application in the food sector. Nevertheless, a variety of methods and tools can be used to ascertain the rheological behavior of meals. According to Bourne, rheology is the study of the deformation and flow of materials. Rheology is being used in food processing, food acceptance, and food handling. Numerous studies have been done to understand the rheology of different types of food, including pastes, emulsions, gels, liquid food, and food in powder form, liquid food, and gels. Large food materials exhibit a rheological behavior that places them between the liquid and solid states, which means that both viscous and elastic behaviors can be found in these materials. The tangling of these molecules, called viscoelasticity, is what causes this behavior. For example, this rheological behavior has been observed in egg white, nanocellulose suspension, tomato products, and so on.

The study of matter flow and deformation, or rheology, explains how time, force, and deformation interact. The word has Greek roots and means “to flow” (*rheos*). All materials, from gases to solids, may use rheology. Rheology as a science is just a few decades old. Two scientists who met in the late 1920s realized there was a need for characterizing fluid flow parameters, which led to the creation of the field. Professors Marcus Reiner and Eugene Bingham were the scientists. Heraclitus, a Greek philosopher, defined rheology as panta rei, or “everything flows.” According to Marcus Reiner’s rheological interpretation, this suggests that everything will flow if you simply wait long enough.

The consistency of various goods is described by fluid rheology, often using the two components viscosity and elasticity. Viscosity often refers to flow resistance or thickness, whereas elasticity typically refers to stickiness or structure. Rheological connections aid in the comprehension of the fluids dealt with, enabling scientists to control their behavior or determine how they should act. Rheological data may then be utilized to forecast performance and behavior if a link between rheological data and product behavior has been established.

The first thing anyone learning to think “rheologically” must do is ask themselves, “Why should I make a rheological measurement?” The answer may be found in the experiences of countless individuals who have performed such measures, which demonstrate that it is possible to gather a wealth of behavioral and predictive information for a variety of goods, as well as an understanding of the impacts of processing, formulation changes, aging phenomena, and so on. The need for constant raw materials from batch to batch in quality control is a common justification for the assessment of rheological parameters. Flow behavior serves as a proxy for product consistency and quality in this context. Making flow behavior studies is also advantageous since it allows for the direct evaluation of processability. For instance, rheological measurements are also useful in following the course of a chemical reaction. Such measurements can be employed as a quality check during production or to monitor and/or control a process. Rheological measurements allow the study of chemical, mechanical, and thermal treatments, the effects of additives, or the course of a curing reaction

Think about the following query first: “Can some rheological parameter be employed to correlate with an aspect of the product or process?” It is necessary to acquire an instinct for the types of chemical and physical processes that influence the rheological reaction to determine this. Suppose for the time being that this information is known and that numerous options have been determined, preliminary rheological data must then be gathered to ascertain the kind of flow behavior that is typical of the system under study. The simplest form of this entails taking measurements with whatever viscometer is available and forming inferences based on the descriptions of various sorts of flow behavior. After determining the kind of flow behavior, more may be learned about how system components interact [10–15].

3. Rheological parameters

3.1. Viscosity

Viscosity may be defined as the resistance to flow and deformation. It is a measurement of a fluid’s internal friction. When a fluid layer is forced to move to another layer, this friction becomes visible. Under the same shear force, various fluids deform at varying speeds. Syrup, which has a high viscosity, deforms more slowly than water, which has a low viscosity. The quantity of “shear” necessary to produce this movement increases as friction increases. Every time the fluid is physically moved or dispersed, such as when pouring, spreading, spraying, mixing, and so on, shearing happens. Therefore, it takes more force to move highly viscous fluids than it does to move less viscous materials.

Using these simplified terms, the viscosity may be defined mathematically by the formula shown in **Figure 2**.

$$\eta = \text{viscosity} = \frac{F'}{S} = \frac{\text{shear stress}}{\text{shear rate}}$$

Figure 2. Formula of viscosity

3.2. Newtonian fluids

Newton’s theory of universal fluid flow behavior is referred to as “Newtonian.” However, it is just one of several flow behavior patterns that may occur in fluid flow. **Figure 2** shows a visual representation of a

Newtonian fluid. The connection between shear stress (F’) and shear rate (S) is depicted as a straight line. The viscosity of the fluid does not change when the shear rate changes. Water and thin motor oils are examples of typical Newtonian fluids. In food processing, examples of Newtonian fluids are dilute solutions, oil, milk, clarified juices, and the juice serum.

In real life, this implies that regardless of the viscometer type, spindle size, or measurement speed, the viscosity of a Newtonian fluid will stay constant at a given temperature. The simplest fluids to test are Newtonian fluids; all you need to do is take readings using a viscometer. They are less frequent than the non-Newtonians, a category of fluids that are far more complicated as shown in **Figure 3**.

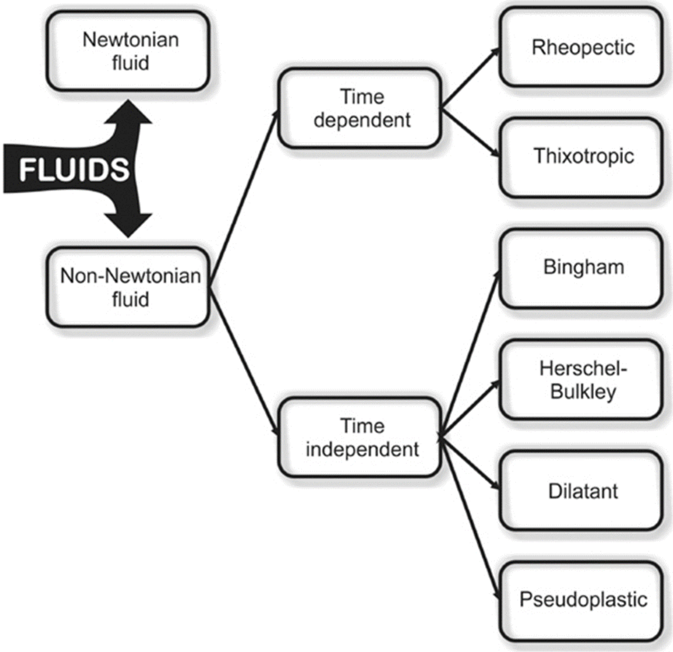

Figure 3. Classification of fluids according to the flow performance or behavior

Newton’s law does not apply to most liquid meals, though, since flow causes structural changes. Although they are referred to as non-Newtonian fluids, they exhibit a variety of behaviors. These fluids can alternatively be categorized as non-Newtonian fluids that are time-dependent or time-independent. Time-dependent fluids change their structure as flow time extends. For instance, when the fluid moves, some of the fluid’s particles may combine to form larger particles or they may break apart to generate smaller particles, modifying the rheological behavior.

3.3. Non-Newtonian fluids

In general, a non-Newtonian fluid is one for which the relationship between shear stress and shear rate is not constant. In other words, the shear stress does not change proportionally or even necessarily in the same direction as the shear rate changes. Since the shear rate may be changed, so can the fluids’ viscosity. Therefore, the observed viscosity of a non-Newtonian fluid is affected by the experimental parameters of the viscometer type, spindle, and speed. This observed viscosity is known as the fluid’s “apparent viscosity” and is only precise when precise experimental criteria are provided and followed. Imagine any fluid as a combination of molecules of various sizes and shapes to see non-Newtonian flow. The most common types of non-Newtonian fluids encountered in food process engineering include the following.

3.3.1. Pseudoplastic

As illustrated in **Figure 3**, this kind of fluid will exhibit a decreasing viscosity with a rising shear rate. Pseudoplastics, which are among the non-Newtonian fluids most often used, include starch paste, paints, emulsions, and many kinds of dispersions. Sometimes this flow behavior is referred to as "shear-thinning."

3.3.2. Dilatant

The dilatant fluid is characterized by increasing viscosity as the shear rate increases. Dilatancy is commonly seen in fluids with large concentrations of deflocculated particles, such as candy compounds, corn starch in water, and sand-water mixtures, but it is less common than pseudoplasticity. Another name for dilatancy is "shear-thickening" flow behavior.

3.3.3. Plastic

Under static conditions, this kind of fluid will act like a solid. The yield value is the amount of force that must be applied to the fluid before any flow may be produced. A notable example of this kind of liquid is tomato ketchup; due to its high yield value, it frequently will not pour from the container unless it is shaken or struck, at which point it will flood out freely. Plastic fluids may exhibit Newtonian, pseudoplastic, or dilatant flow properties once the yield value has been exceeded and flow has started.

3.4. Thixotropy and rheopexy

Under constant shear rate circumstances, some fluids will show a change in viscosity over time. Two types exist. First is thixotropy, a thixotropic fluid gradually loses viscosity over time while being continuously sheared. Second is rheopexy, which is the exact reverse of thixotropic behavior in that the viscosity of the fluid rises with time as it is sheared at a constant pace

Any of the above-mentioned flow behaviors may be present in conjunction with thixotropy or rheopexy, or just at specific shear rates. Under conditions of steady shear, some fluids will achieve their full viscosity value in a matter of seconds, while others will take much longer.

The term laminar flow refers to the passage of one fluid layer through another without any transfer of stuff between them, which is implied by the basic concept of viscosity. There is a limit speed beyond which an actual transfer of mass happens from one layer of fluid to another, depending on a variety of variables. This is referred to as "turbulence." Larger particles or molecules leap from one layer to another, losing a lot of energy in the process. Overall, a turbulent flow requires more energy to sustain than a laminar flow does at the same velocity. The apparent rise in shear stress results from the increased energy intake.

When compared to what would be seen under laminar flow circumstances at the same shear rate, the extra energy input appears to result in a higher shear stress. As a result, the reading for viscosity is very high. In addition to the velocity at which the layers move, other factors also affect when laminar flow turns into turbulent flow. The point at which this transition takes place is affected by the viscosity and specific gravity of the substance, as well as by the shape of the spindle and sample container in the viscometer. Dilatant flow behavior should be distinguished from turbulent flow situations with care. Turbulent flow is characterized by a very abrupt and significant increase in viscosity over a certain shear rate; while dilatant materials typically display a continuously increasing viscosity with increasing shear rate.

4. Factors affecting rheological parameters

Data on viscosity frequently serve as a "window" through which other properties of a substance can be seen.

Viscosity is a useful tool for the characterization of materials since it is easier to quantify than some of the factors that influence it. This section focuses on a few of the variables that impact viscosity.

4.1. Temperature

Temperature is one of the most evident variables that might affect a material's rheological behavior. Depending on the temperature, certain substances can alter significantly in viscosity with only a minor shift, while others are comparatively unchanged. When assessing products like starch paste, vegetable oils, and so on, that may experience temperature fluctuations during usage or processing, consideration of the impact of temperature on viscosity is crucial.

4.2. Shear rate

Anyone involved in the practical use of rheological data must have an understanding of the impacts of shear rate since non-Newtonian fluids are more frequently the norm than the exception in the actual world. For instance, it would be devastating to try to pump a fluid through a system only to have it solidify inside the pump, stopping the operation completely. Even though this is an extreme case, shear rate effects should not be undervalued. Knowing a material's viscosity at the anticipated shear rates is crucial when it is going to be processed or used at a variety of shear rates. If they are unknown, a best-guess calculation should be done. Viscosity measurements should then be made at shear rates as close as possible to the estimated values.

Due to those values being beyond the viscometer's shear rate range, it is usually hard to approximate anticipated shear rate values during measurement. Measurements must be taken in this situation at various shear rates, and the results must then be extrapolated to the predicted values. Even while this is not the most precise way to get this data, it is sometimes the only option, especially when the expected shear rates are quite high. In fact, it is always a good idea to test viscosity at a variety of shear rates to look for rheological behavior that might affect how something is processed or used. A straightforward plot of viscosity vs viscometer speeds (rpm) will frequently be usable in situations when shear rate data are either unknown or not significant. Examples of materials that are subjected to, and are affected by, wide variations in shear rate during processing and use are certain food products, paints, cosmetics, liquid latex, coatings, and blood in the human circulatory system.

4.3. Measuring conditions

The state of a substance at the time of its viscosity measurement can significantly affect the findings of that measurement. Thus, it is critical to be aware of and to as much as possible manage the environment in which any sample is being evaluated. The viscosity of the substance being measured is also impacted by factors like the viscometer model, spindle/speed combination, sample container size, guard leg presence or absence, sample temperature, sample preparation method, and others. All of these factors have an impact on the accuracy of viscometer measurements.

The homogeneity of the sample is another element that could have an impact on viscosity measurements. A homogenous sample is often preferred since it allows for more reliable results to be produced. However, there are occasions when a material's propensity to divide into non-homogeneous layers is the feature of greatest importance. In these situations, it is important to take care not to mix or shake the sample in a way that disturbs the subject intended to research.

4.4. Time

Shear-related time definitely has an impact on thixotropic and rheopectic (time-dependent) materials. But even when a material is not being sheared, changes in viscosity can take place over time in many different materials. When choosing and preparing samples for viscosity measurement, aging phenomena must be taken into account. Additionally, keep in mind that many materials may experience variations in viscosity throughout a chemical reaction, which means that a measurement of viscosity taken at one point in the reaction may differ dramatically from one taken at a later point.

4.5. Pressure

Changes in pressure can result in dissolved gases forming bubbles, entrained gases changing size and distribution, and occasionally even turbulence. Compared to other characteristics, pressure is not felt as frequently. Fluids are compressed under pressure, which raises intermolecular resistance. Under the influence of very high pressures, liquids are compressible, but to a considerably smaller amount than gases. The viscosity tends to increase as pressure rises. As an illustration, a three-phase mixture such as solids, liquids, and typically air, is produced by the flow characteristics of highly concentrated slurries (over 70–80% by volume of particles), when there is insufficient liquid to fill all the spaces between the particles. The combination is compressible since air is present, thus the more it is compressed, the higher the intermolecular resistance is.

Particularly in fluids susceptible to heat or aging, what has happened to a sample before a viscosity test might considerably alter the outcome. Therefore, sample preparation procedures and storage conditions must be created to have the least possible impact on later viscosity tests. Since their viscosity will be impacted by stirring, mixing, pouring, or any other action that causes shear in the sample, thixotropic materials in particular are highly sensitive to this.

4.6. Composition and additives

A substance’s viscosity is influenced by its makeup. A change in viscosity is highly probable when this composition is altered, whether by changing the quantities of the component elements or by the addition of other materials [16–18].

5. Rheological instruments for fluids

In general, rotating-type and tube-type instruments are both capable of measuring the basic rheological characteristics of fluid and semi-solid meals. The majority are offered commercially. From a cheap glass capillary viscometer to an extremely costly rotatable device that can measure dynamic characteristics and normal stress variations, prices vary greatly. In compression between parallel plates, tension, or torsion tests, solid meals are frequently subjected. Rheometers are devices that measure rheological characteristics. The word “viscometer” is more restrictive and refers to instruments that exclusively measure viscosity. Rotational instruments can be used in oscillatory dynamic or stable shear fixed angular velocity modes.

Some rotating devices work in the controlled stress mode, making it easier to examine yield stresses and analyze materials at extremely low shear rates. To grasp the interior structure of materials, one must have this knowledge. The regulated rate option is best for gathering the data needed for computations in process engineering. Because tube systems only let one pass of the material through the instrument, rotational systems are typically utilized to explore time-dependent behavior. Both benefits and drawbacks are related to each instrument. For instance, because the shear rate changes during discharge, gravity-operated glass capillaries are only suited for Newtonian fluids. Cone and plate systems are restricted to mild shear rates, although computations are straightforward for tiny cone angles. Contrary to cone and plate, or parallel plate, instruments, pipe, and mixer viscometers can handle significantly bigger particles. With mixer viscometers, issues with slides and deterioration in materials with high structural sensitivity are reduced. High shear rates are possible with high-pressure capillaries, although they often require a sizable end pressure adjustment.

5.1. The correlation and models involved in food rheology

Depending on how they react to the applied shear stress, fluids may be divided into the following groups. Different scientists construct viscoelastic models for Newtonian and non-Newtonian fluids while taking into account various components like dashpots and springs in series, parallel, and combination. The Burgers Model, the Maxwell Model, and the Kelvin Model are three commonly used rheological models that are discussed here. Newtonian fluids are those in which the shear stress increases linearly with the rate of shearing. The connection between the shear stress and the rate of shear in these fluids is linear.

5.2. Model for Newtonian fluids

The equation for Newtonian fluid is described as the following correlation (**Equation 1**).

$$\tau = \mu \frac{-dv}{dx} \tag{1}$$

Where τ is shear stress; -dv/dx is shear strain/velocity gradient, the viscosity of the fluids that are called proportionality constant; and μ is the dynamic viscosity of the fluids.

In general, a non-Newtonian fluid is one for which the correlation between shear stress and shear rate is not linear. The shear stress does not change proportionally with a change in shear rate. Some of these fluids show a yield stress, whereas others display shear thickening or thinning behavior.

The two most commonly used equations for characterizing non-Newtonian fluids are the power law model (**Equation 2**) and the Herschel-Bulkley model (**Equation 3**) for fluids.

$$T = K\,(\gamma)^n \tag{2}$$

$$T = T_0 + K\,(\gamma)^n \tag{3}$$

Where T is shear stress, K is consistency constant, γ is shear rate, n is flow behavior index, and T_0 is yield stress.

5.3. Rheological models

To describe the viscoelastic behavior of materials, many models have been devised. There are two fundamental viscoelastic models: Maxwell and Kelvin. Combinations of these fundamental models are used to describe further complicated viscoelastic behaviors.

5.3.1. Kelvin models

The spring (an elastic component) and dashpot (a viscous component) are used concurrently in the Kelvin model. This stress is the result of the addition of two factors, one of which is related to strain and the other to the rate of shearing. Because the components are parallel, they must travel at a constant speed. When a continuous load is given to the Kelvin model, an initial delayed deformation and a final steady-state deformation are both achieved. The Kelvin model recovers fully but not immediately once the load is removed. The model is written as follows in mathematics (**Equation 4**).

$$\varepsilon_t = \sigma_0 \,/\, E[1 - \mathrm{e}^{-(-\frac{t}{Tret})}] \tag{4}$$

where ε_t is the strain at time t, σ_0 is applied stress, E is elastic modulus and Tret is retardation time.

5.3.2. Maxwell model

A series-connected spring and dashpot are used in the Maxwell model. The deformation in this model is divided into two sections, one of which is entirely viscous and the other entirely elastic. The Maxwell body will experience immediate elastic deformation when a constant load is applied, followed by ongoing viscous flow. Because the viscous flow is not constrained by the spring component, it will never stop. The Maxwell body recovers swiftly and fully when the stress is removed. While the Kelvin body does not exhibit stress relaxation, the Maxwell body does. The Maxwell model's stress-strain-time connection may be expressed as follows.

$$\varepsilon_t = \sigma_0 / E_d [1 - e^{-(-\frac{t}{Tret})}] + E_0 \ldots\ldots \qquad (5)$$

where ε_t t is stress at time t, σ_0 is fixed strain, E_d is elastic decay modulus, Tred is relaxation time, and E_0 is equilibrium modulus.

5.4. Characterization of food rheology

Food products were normally liquids and semi-solids subjected to stress and strain for flowing. These materials are composed of micro and nanostructure of the components with a range of considerable hierarchy. Normally, suspension, emulsion, interfaces and foams, gels of biopolymer, and mixtures are encountered in the characterization of rheology. The rheology of complex food products was governed by their main constituents and interactions based on length and time scales. For example, in a normal food emulsion or food suspension, such as a salad dressing or chocolate, droplets and particles largely interact on the molecular level. Proteins, surfactants, cell walls, lipids, and polysaccharides that stabilize the dispersed system interact on the colloidal length scale as opposed to the non-colloidal level. Moreover, length scales in the order of meters are important in industrial-scale food processing. The associated time scales may range from milliseconds to years during the long-term shelf life of canned food items or the sub-millisecond regime during the aggregation of the components.

To quantify the functional connections between deformation, stresses, and the resulting rheological characteristics, such as viscosity, elasticity, or viscoelasticity, is the goal of rheological characterization. The existence of rheometric flow conditions, or a well-defined laminar deformation field, is a need for accurate rheological data. Many food items will be affected by non-homogeneous flow fields, whether the substance is strawberry yogurt or any other heterogeneously structured material. The measurements are driven by quick and reliable evaluation during food processing or by the fact that, literally speaking, an apple does not fit into a Couette geometry and even if it did, the resulting flow profile would most likely not be rheometrical in the strictest sense. As a result, somewhat odd measuring devices for food characterization have been developed in the past. For practical reasons, the second case may be avoided by tackling the hierarchical structure of food systems including fruits, cheese, dough, and meat in addition to others utilizing various mechanical analysis approaches. In contrast, rheological tests on individual ingredients in aqueous or lipid-based solvents ignore the complexity of the actual food matrix while illuminating the colloidal level self-assembly of food components. When taking into account the aforementioned methods, it is evident that food rheology is characterized by its application rather than by a simple physical classification of materials.

Food rheology refers to the study of how food materials flow and deform under applied forces. It involves characterizing the texture, consistency, and flow properties of food products. There are several parameters used to characterize food rheology as listed below.

5.4.1. Viscosity

Viscosity is a measure of a food's resistance to flow. It indicates how easily a food material can be poured or spread. Low-viscosity foods flow easily, while high-viscosity foods resist flow. Viscosity is influenced by factors such as the concentration of solid particles, moisture content, and temperature.

5.4.2. Elasticity

Elasticity refers to a food material's ability to regain its original shape after deformation. Elastic foods, like gels or certain batters, can recover their original structure when stress is removed. This property is important for determining the texture and mouthfeel of food products.

5.4.3. Plasticity

Plasticity is the ability of a food material to change shape and deform without breaking. It is associated with the flow and spreadability of materials, such as dough or chocolate. Plasticity helps determine how easily a food can be shaped or molded.

5.4.4. Yield stress

Yield stress represents the minimum amount of force needed to initiate flow in a food material. It is commonly used to measure the flow properties of semi-solid foods like sauces or creams. Yield stress affects the ease of pumping or dispensing of such products.

5.4.5. Thixotropy

Thixotropy refers to the property of some foods to become less viscous over time when they are subjected to continuous shearing or shaking. This property is observed in materials like ketchup or mayonnaise. Thixotropy affects the ability of a food to maintain its structure and stability during processing or storage.

5.4.6. Firmness

Firmness is a measure of how resistant a food material is to being compressed or deformed. It is often used to assess the texture of solid foods like fruits or vegetables. Firmness helps determine the perceived quality of a food product.

5.4.7. Flow behavior

Flow behavior describes how a food material responds to different applied forces or shear rates. Different foods exhibit different flow behaviors, ranging from Newtonian (constant viscosity regardless of shear rate) to non-Newtonian (viscosity changes with shear rate). Understanding flow behavior is crucial in processes like pumping, mixing, or coating.

Overall, the characterization of food rheology parameters plays an essential role in designing and optimizing food formulations, processing methods, and sensory attributes.

5.5. Factors controlling the food rheology

Various factors controlling the rheology of the foods have been documented. Food rheology is not only the measurement of apparent viscosity, as it now offers more detailed information on the microstructure and fluidity of a meal as a result of advancements in instruments and time. Rotational viscometry measurement to either a controlled stress/strain rheometer or more sophisticated ideal rheological data now have precision, sophistication, and dependability thanks to Fourier transformation rheometry. Understanding food microstructure and its relationship to the textural and rheological qualities of food is becoming increasingly important for the creation of food products in both academics and the food industry. This understanding of food rheology and microstructure aids in reducing textural flaws in processed foods and raising customer satisfaction.

Temperature and measurement time have a considerable impact on the rheological characteristics of food and biopolymers. Time-temperature superposition (TTS) is a good technique to enlarge the frequency regime considerably at a reference temperature. To create a single “master curve” at the reference temperature in TTS, isothermal data acquired by frequency sweeps at certain temperatures are moved along the frequency axis and overlaid. To determine if the temperature dependence of the physical changes follows the Arrhenius or Williams Landel and Ferry (WLF) equations, shift factors obtained during the transformation can be used. Thermally simple materials are those that adhere to the TTS principle.

Several factors can control the rheology flow and deformation behavior of food. Some of these factors include the following.

5.5.1. Ingredient composition

The presence and amounts of ingredients such as fats, proteins, carbohydrates, and additives can significantly impact the rheological properties of food. For example, fats can improve the spreadability and texture, while proteins can contribute to the viscosity and elasticity.

5.5.2. Temperature

Temperature has a significant effect on the rheology of food. Increasing temperature generally reduces viscosity and makes the food more fluid-like. At higher temperatures, certain ingredients like fats may exhibit melting or solidification behavior, impacting the overall rheology.

5.5.3. pH

The acidity or alkalinity of the food can influence its rheological properties. For example, acidic pH can cause protein denaturation and aggregation, leading to changes in viscosity and texture.

5.5.4. Processing methods

Various food processing techniques, such as mixing, heating, cooling, and shear forces, can alter the rheology of food. Processing can modify the molecular structure and arrangement, affecting the flow behavior.

5.5.5. Water activity

The amount of available water in the food, as determined by its water activity, can affect the rheology. Water acts as a plasticizer and can influence the overall viscosity, elasticity, and stickiness of food.

5.5.6. Particle size and distribution

The size, shape, and distribution of solid particles in food can impact its rheological properties. Larger particles can contribute to higher viscosity, while smaller particles may decrease it.

5.5.7. Time and shear rate

The rheological behavior of food can also depend on the time and shear rate applied. Food may exhibit different responses under different time scales and shear rates, such as shear thinning decreasing viscosity with increasing shear rate, or shear thickening increasing viscosity with increasing shear rate.

These factors can interact with each other, resulting in complex changes in food rheology. Understanding and controlling these factors is essential for achieving the desired food texture, consistency, and overall sensory experience.

6. Conclusion

Food rheology is the study of how food materials flow and deform under different conditions. It is a branch of rheology, which is the study of how materials flow and deform. Food rheology is important in understanding the texture, consistency, and overall quality of food products. It helps food scientists and engineers determine how ingredients and processing techniques affect the final product. Some key parameters of food rheology include viscosity, elasticity, and viscoelasticity. Viscosity refers to how easily a food material flows, while elasticity refers to its ability to recover its shape after deformation. Viscoelasticity is a combination of both viscosity and elasticity and describes how a material behaves under both stress and strain. Food rheology is also used in the development of food products with desirable texture and mouthfeel. It can help determine appropriate cooking and processing times, as well as the optimal amount of ingredients to achieve desired rheological properties. Overall, food rheology plays a critical role in the development and optimization of food products, ensuring that they have the desired texture, consistency, and overall quality.

Disclosure statement

The author declares no conflict of interest.

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