Rheological and thermal properties of honey produced in Algeria and Ethiopia: a review

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ABSTRACT
Honey has medicinal benefits due to its substantial nutritional profile, wholesome, sweet, and active ingredient that is used for interdisciplinary purposes in the food industry. Honey quality can be characterized by its engineering properties besides potential functional features, such as antioxidant, antibacterial, and antimicrobial properties. However, there are many problems associated with the design of processes, product, equipment, and process control. Therefore, food engineers, scientists, processors, and beekeepers have a duty to understand the concept of engineering properties and to fix the problems occurred during harvesting, storage, transport, mixing, heating, cooling, refining, and pumping honey and honey products. In the case of the future-line work, there are few compressive reviews concerning with engineering properties of honey. However, in the present review, an emphasis has been given to explore the knowledge of some engineering properties of Algerian and Ethiopian honeys, such as viscosity, moisture content, minerals, specific gravity, hydroxymethylfurfural, glass transition, color, degree brix and sugar components.

Introduction
Honey is a very nutritious, sweet and viscous food. The nectar of flowers is turned into honey by honeybees. It can be stored for a long time and used as a primary food source and as an ingredient in the preparation of honey-based products.\(^{[1,2]}\) The key components of honey are carbohydrates such as monosaccharaides (glucose and fructose) and oligosaccharides such as sucrose, maltose, melezitose, and raffinose. Pure honey also contains proteins, fat, water, vitamins, and minerals. Honey is used as an antioxidant, anti-inflammatory, anti-proliferative, pro-apoptotic, anti-bacterial agent, immune-modulatory and anti-metastatic properties.\(^{[3–6]}\) It is highly nutritious and has prophylactic medicinal benefit. Honey quality can be measured by assessing its engineering properties such as its physiochemical, rheological and thermal properties. Some selected physical properties of honeys are presented in Table 1.

Knowledge of the engineering properties of food materials is essential for the proper design of equipment and processes for handling, storing, processing and distributing food products and transforming them into finished products.\(^{[5,7]}\) In the same way, basic information should be accessible to food engineers, scientists, processors and beekeepers who are urgently in need of it for modeling, equipment and process design, and manufacturers. Engineering properties of food materials are critical to addressing the problems associated with the design of equipment or study of the actions of food products and agricultural processes. The engineering properties of honey can be categorized in rheological, physiochemical, thermal and electrical properties.

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Table 1. Selected physical properties of honeys.

| S.no | Botanical Origin                  | Country | Moisture content % | pH    | Water activity | HFM mg/kg | Ash% | Electrical conductivity mS/cm | Sucrose% |
|------|-----------------------------------|---------|--------------------|-------|----------------|-----------|------|-------------------------------|----------|
| 1    | Honeydew (mono floral honeys)     | Algeria | 19.0               | 4.4   | ND             | ND        | 0.5  | 1.6                           | 4.9      |
| 2    | Blossom (poly floral honey)       | Algeria | 14.6–16.8          | 3.7–3.6| ND             | ND        | 0.06–0.2 | 0.2–0.4                       | 3.5–5.3  |
| 3    | Blossom (poly floral honey)       | Algeria | 16.5–16.8          | 3.6–3.8| ND             | ND        | 0.09–0.2 | 0.2–0.5                       | 0.2–3.4  |
| 4    | Mono floral honeys (Acacia honeys)| Ethiopia| 15.7               | ND    | 0.5            | ND        | ND    | ND                           | ND       |

Rheology is a study of the flow and deformation properties of a substance when force is applied to it. It focuses on the flow properties of individual food components, which may already have a complex rheological response mechanism, the flow of the composite food matrix, and the effect of processing on the structure and properties of the food. It is an important parameter for controlling the design of the process, preserving the shelf life of honey in the food industry where it was used as a food ingredient for the preparation of honey-based products. Furthermore, the rheological aspects of honey are of great importance in terms of quality control of the final product, growing efficiency and connecting modern technology in all stages of production, such as pipe transport, centrifugation, filtration and heating. Honey viscosity is a prevailing rheological parameter in the processing of honey and is influenced by temperature, moisture content and presence of crystallization, sugar content, pollen grains, air bubbles and small particles. Crystallization and viscosity have an effect on the sensory properties of honey and hence the acceptability of consumers.\(^{13,8}\) The stability and quality of the honey can be predicted on the basis of physiochemical properties. General physiochemical properties of honey depend on the water content, Brix, electrical conductivity, free acidity, pH, 5-hydroxymethylfurfural (HMF) content and main parameters such as sugar composition and HMF content, which are essential components that decide the quality of honey.\(^{9}\) Several studies have showed that the physiochemical parameters of honey are affected by botanical origin, floral origin, geographical origin, climatic condition during harvest, production system, honey maturity, processing and storage conditions.\(^{8,10–13}\)

Knowledge of thermal properties of food materials is required to understand theoretical and empirical relationships when developing or operating thermal processes for handling or manufacturing food products.\(^{7}\) Thermal properties of honey are characterized by differential calorimetric scanning (DSC), which is used to study the thermal behavior of authentic honey and to detect the effects of moisture content and sugar profile on glass transition and melting point temperatures. Transitional glass is a very critical parameter for assessing the stability and consistency of honey.\(^{13,14}\) Some preliminary studies investigated the thermal parameters of honey, such as glass transition temperature (Tg), melting enthalpy and heat capacity.\(^{13,15}\)

Physiochemical, rheological, and thermal properties of honey are important measures of the quality and origin of the honey. These properties are highly influenced by geographical origin, floral origin and climatic conditions, as well as by the chemical components of honey. From harvesting to packaging, the engineering aspects of honey are important in order to improve its shelf life and quality of honey. However, there is a limited understanding of engineering properties during processing, production, and transporting honey and honey products as well as lacking literature review of engineering properties of honey in previous researchers for future line work. Thus, the goal of this review is to explore knowledge of the engineering properties of honey, in particular viscosity, moisture content, minerals, specific gravity, HFM, glass transition, color, Brix grade and sugar components.

Algeria is well-known country for honey production in western. Although beekeeping is not the primary revenue-generating for Algerian farmers, many beekeepers still practicing a good complementarity with beekeeping. This sector ranks second after the other branches of agriculture and honey produced from Algeria has been given significant importance in the level of production of quantity
and quality. In Ethiopia, where 85% of all jobs are in agriculture, industry experts say the beekeeping (apiculture sector) is still a long way from harvesting its full potential. In this review, special emphasis has been given in to discuss about the rheological and thermal properties of honey that produced in Algeria and Ethiopia as a narrative review.

**Honey**

Honey is a natural complex food and a nutritious commodity prepared by honey bees from plant nectar or honey dew, which is gathered, transported, processed, packed and stored in a comb it is a viscous fluid and the oldest sweetener. It is used as a popular human food and has high nutritional and prophylactic medicinal values.\(^\text{[16]}\) In addition, it is a food ingredient for the manufacture of honey-based products. The composition of the honey decides how beneficial it is for human health.\(^\text{[17]}\) As discussed earlier, it is a source of energy food and is used as an ingredient in the development of a variety of food products, primarily cereal-based products.\(^\text{[18]}\) Honey is a super-ingredient and combines with various cereals, improving food product consistency, food safety and customer satisfaction. In addition, honey is also used as a dietary antioxidant source and high amounts of free radicals which used to resulting in cell damage, affecting the wound healing process and causing premature aging or even neoplastic transformation.\(^\text{[7,19]}\) A few studies characterized honey by rheological, physicochemical, thermal and electrical analysis.\(^\text{[14,20–22]}\)

**Physicochemical properties of honey**

The physicochemical properties of honey are important for the process of accreditation that determines the quality of the honey.\(^\text{[2]}\) The physiochemical parameters of honey, such as moisture, sugar reduction, sucrose, ash, free acid, Brix grade, pH and specific gravity, are the quality indicators of hone.\(^\text{[23]}\) The physicochemical properties of honey are important factors that decide its price on the world market, as well as its acceptability by consumers.\(^\text{[19]}\) They depend on geographical origin, botanical origin, floral origin, climatic factors as well as harvesting methods, beekeeping techniques, handling, transport and storage conditions.\(^\text{[2,14,24,25]}\) Previous studies have showed that all specific honey varieties have reduced sugars, primarily fructose and glucose, in large portions and even small amounts of disaccharides and trisaccharides.\(^\text{[50]}\) According to\(^\text{[18,26]}\) the key components of honey are influenced by botanical composition, climatic conditions and species of bees. Honey contains 78% sugars, 18.5% water and 1.5% minerals and organic acids. In addition, it has more than 200 bioactive components and comprises 67.5% sugar components.

**Moisture content**

The moisture content is an important quality indicator for the shelf life of the honey and indicates the degree of maturity of the honey. Higher moisture content can increase the fermentation of honey during storage.\(^\text{[27]}\) The moisture content of Romania’s honey ranges from 15.4% to 20%,\(^\text{[28]}\) and follows the standards laid down by the Council of the European Commission. A related study recorded a moisture content ranging from 17.5 to 19.1% within the range recommended by Codex Alimentarius.\(^\text{[20]}\) The moisture content is therefore a good parameter to indicate the degree of maturity of the honey. The water content of Caatinga’s honey ranged from 17.4% to 21.5%.\(^\text{[27,29]}\) However, some authors found that the water content of honey ranged from 14.6% to 17.8%.\(^\text{[2,30]}\) The value of the moisture content depends on the botanical origin, the climatic factors and the geographical location.\(^\text{[31]}\) The moisture content of honey, as investigated by several authors, is below 20% as recommended by Codex Alimentarius and the maximum value permitted by the ECC.
Sugar

Previous studies have showed that sugar is the main component of honey, accounting for around 95% of the dry weight of honey. Total sugar in four varieties of honey samples from the Indian Kashmir Valley ranged from 73.89 to 78.45%, which is comparable to that of honey in bloom[20] but less than that observed for Algerian honey.[27,32] indicated that the quantity of total sugar and the reduction of sugars in some Algerian honeys ranged from 71.25 to 84.25% and 67.83 to 80.25% respectively. The average reduction in honey sugar, consisting of fructose and glucose, was 67.79–74.62%, 66.3–88%, 67.25–84.25%, and 62.80–70.00%, respectively.[30,32] The results of these studies are consistent with the ECC 110/2001 guideline, which recommends a reduction of ≥60% in sugars in all forms of honey. Found[30] that the removal of sugars is a major component of the dry weight of honey. The honey in the Harenna forest have higher levels of fructose than glucose, which is similar to the honey in flowers. The levels of sugar reduction recorded in previous studies comply with the Ethiopian, CA and EU standards, which allow minimum acceptable values of 65 g/100 g.[29] higher amounts of fructose (37.58–43.95 g/100 g) and lower amounts of glucose (27.41–33.80 g/100 g) are recorded in five samples of selected Caatinga honey from Brazil. The aldose content is the key part of the glucose present in the honey, which ranged from 29.4% to 42.0%. [27] glucose levels in the Kashmir Valley of India ranged from 30.56°C to 33.98°C.[20] However, if the glucose content of the honey is greater than 30% and higher than the fructose content, the honey is crystallized.[33] Kahraman et al.[20] recorded the fructose content of four Unifloral honeys from the Indian Kashmir Valley ranging from 36.42% to 40.61% and the highest percentage is found in apple honey and the lowest percentage in cherry honey. This is similar to that recorded for Spanish unifloral honey.[34] In addition, the amount of fructose present in acacia and black locust honey ranged from 41.3% to 43.30% and 37.70% to 49.10%, respectively.[35,36] These findings showed the fluid state of the honey when the amount of fructose is higher than the glucose content.

Fructose and glucose (F/G) ratio

Fructose-to-glucose (F/G) ratio is a measure of the crystallization state; it depends on the form of honey. The F/G ratio of four types of honey in the Indian Kashmir Valley, namely strawberry, saffron, Pogonomyrmex rugosus, and apple is 1.07, 1.23, 1.24 and 1.25%, respectively.[20] Among these, cherry honey has a higher tendency to crystallize rapidly than other honeys because it has lower moisture content and higher glucose content. The F/G ratio of the five samples of Caatinga is higher than the four forms of honey in the Indian Kashmir Valley, varying from 1.24% to 1.39%.[29] Honey is rapidly crystallized when the F/G ratio is greater than 1.11%.[37] The crystallization time depends mainly on the F/G ratio and the glucose-to-moisture (G/M) content. Some authors have pointed out that the ratio of G/M can be a relevant predictor of honey crystallization. [38,39] Honey crystallization is rapidly growing when the ratio of G/M is greater than 2.0 and steadily when it is less than 1.7. [38] Earlier investigation revealed that the G/M ratio of four forms of honey from the Kashmir Valley, supposed to be saffron honey is greater than 1.7, with slow crystallization.[20] According to Ouchemoukh et al.[29] the G/M ratio ranges from 1.55% to 1.80%. With a reduction in the moisture content of the honey, the crystallization of the honey increases.

Sucrose

The study of sucrose content in different types of honey can be used to identify the adulterated honey. Also, the assessment of presence of sucrose content suggests about the purity of natural honey respect to with or without the addition of table sugar or cane sugar.[30] According to Daniel et al.[30] the average sucrose content of honey in the Harenna forest ranged from 0.75 to 4.45 g/100 g. This is lower than the recommended amount of ≤10% for Algerian honey varieties. [27] The concentration of sucrose content in honey obtained from the Kashmir Valley ranged from 1.05 to 1.4. This value of sucrose content also observed to be low compared to the Algerian-type honey, which is ranged from 1.8% to 2.54%.[32,40] The average sugar content in northern Algerian honey is 6.54%, but does not meet the
Ethiopian quality limit of ≤5%. Increased sucrose content in certain forms of honey shows “unripening honey” due to the incomplete fermentation of sucrose, which is transformed into fructose and glucose by the action of the natural enzyme present in the honey. The purpose of determining the sucrose content of all forms of honey is to find natural honey and adulterated honey. Currently, some forms of honey produced in Ethiopia are being adulterated. This affects the consistency of natural honey and is not appropriate to consumers.

**Water activity**

Another essential parameter of honey is water activity, which maintains the stability and shelf life of honey as well as inhibits or prevents microbial growth. The water activity of honey in the Indian Kashmir Valley ranged from 0.514% to 597%, which is comparable to that of Greek honey (0.530% to 0.670%), and Indian honey (0.570% to 0.700%).\(^{20,41}\) The reason for increased water activity of honey is the existence of higher amount of moisture content.

**Acidity property**

Honey has acidic properties, which are due to organic acids such as gluconic acid and inorganic ions. It is used to add flavor and inhibit microbial growth or because of its antimicrobial properties.\(^{31}\) The acidic content of all forms of honey from the North West of Algeria ranged from 3.7 to 4.78 and the pH of the honeydew and bloom honey mixture ranged from 3.5 to 4.5. The acidic content of northern Ethiopian honey collected from traditional hives and modern hives is not significantly different (\(p > .05\)). The pH of honey from all varieties in India ranged from 3.01 to 4.35 and a statistically significant difference was observed.\(^{20}\) The average acid content of honey from the Harenna forest in Bale, Ethiopia is 3.87%, which is comparable to the Sekota district of northern Ethiopia, the Algerian honeys, the North West Algerian honeys and the Kashmir Valley honeys.\(^{30}\) The pH of all Algerian honeys ranged from 3.49 to 4.43, which is equivalent to the pH of honeydew and bloom honey blends.\(^{27}\) The pH of all honey types depends on the geographical origin of the honey.

**Ash content**

The ash content of Algerian honey ranged from 0.06% to 0.54%. Variation in the ash content depends on soil and climatic characteristics. According to Taylor P et al.\(^{27}\) the ash content of the blossom honey is lower than that of the honeydew honey due to its botanical sources. Brazil’s ash content of Caatinga honey ranged from 0.02 to 0.19% and was equivalent to that of Algerian honey, Harenna forest honey and Sekota northern Ethiopia honey.\(^{27,30,42}\) The ash content of all samples of Harenna forest honey was significantly different while the average ash content of Sekota northern Ethiopia honey was not significantly different. Ogdanova et al.\(^{43}\) showed that the ash content of northern Algerian honey ranged from 0.019 to 0.37%, which is substantially different (\(p < .05\)). The average mineral content of the honeys ranged from 0.04% to 0.2%. The mineral content of the honey depends on its climatic conditions, soil type, floral origin, and fertilization.\(^{44,45}\)

References\(^{20,27,30,41}\)

**Electrical conductivity**

Electrical conductivity (EC) is another significant physical property of honey.\(^{46}\) It varies with the mineral content, protein content, certain complex sugar content, and polypeptide content and depends on the botanical sources of the honey.\(^{30}\) The EC value of Harenna forest honey ranged from 0.63 to 0.79 mS/cm, while the EC mean values for both conventional and frame hives were 0.71 and 0.68 mS/cm, respectively. The EC average values for conventional and frame hives depend on the location and form of hives and are substantially different.\(^{30}\) Taylor et al.\(^{27}\) reported that the EC of 10 samples of
Algerian honey was below 0.70 mS/cm. Several studies have recorded an EC value of less than 0.8 mS/cm for nectar or floral honey and an EC value of more than 0.80 mS/cm for honey dew and honey blossom blends.\cite{47,48}

**Hydroxymethylfurfural**

Hydroxymethylfurfural is a physical feature of the honey that indicates the degree of freshness of the honey and the HMF quality, which are important requirements for the shelf life of the honey. In addition, the amount of HMF in honey is a parameter for the isolation of mature honey and heated honey.\cite{30,49} However, HMF is not observed in unheated honey or in ripened honey. According to, the value of HMF of Harenna forest honey is below the maximum limit (40 mg/kg) recommended by Codex Alimentarius. The same is true of honey in the Kashmir valley.\cite{20} The Algerian honey level of HMF is not substantially different in all samples, ranging from 22.60 mg/kg to 24.21 mg/kg,\cite{32} which is close to the levels found for honey in the Kashmir valley.\cite{20} Previous studies showed that the honey content of HMF increases due to prolonged overheating and storage of honey due to storage temperature and pH of the honey.\cite{32,50}

**Color**

Color is a critical indicator of the quality of honey and depends on its chemical composition, mineral content, botanical origin and the method of heating. Chlorophyll, carotene, xanthophylls and yellow-green pigments decide the color of the honey.\cite{19} According to the United States of America, Department of Agriculture, the honey color can be divided into seven colors: white water, white extra, white extra light amber, light amber, amber and dark amber. According to,\cite{32} the samples of the Algerian honey have a dark amber color and a maximum pound value.

**Rheological behavior of honey**

Food rheology is an analysis of the deformation and flow of all food materials: liquid, semi-solid and solid. Knowledge of the rheological behavior of honey is important in the food processing industry, particularly for food scientists and food engineers during the selection of ingredients, process design, and product modification, design of new products, optimization, equipment selection, packaging design and storage strategies. In addition, honey rheology is crucial for the handling, mixing, heating, cooling, output, processing, quality control, transport, pumping, storage, distribution and sensory evaluation of honey.\cite{5,41,51} Several authors from different countries investigated the rheology of honey.\cite{30,39–43} Several researchers reported Newtonian honey flow behavior.\cite{21,40,53–62} However, some authors also reported non-Newtonian flow behavior.\cite{3,22,57,53,64} Boukraa et al.\cite{65} showed that increasing the viscosity of the Tunisian honeys exhibited non-Newtonian flow at shear rates ranged between 0.01 to 500 s\(^{-1}\) as shown in Figure 1.\cite{66} showed that when the viscosity increased, Tunisian honeys displayed a non-Newtonian flow due to their long chain structure in Figure 2. The rheological characteristics of the honey mainly depend on the moisture content, temperature and other chemical substances, such as glucose, fructose and the F/G ratio.\cite{41,57,39,61,68,69} A few researchers analyzed the rheological parameters of honey, such as viscosity, loss modulus (G") and storage modulus (G').\cite{20,38,56,70}

**Viscosity**

Knowledge of honey viscosity is essential for food processors, controllers, processors, beekeepers and producers.\cite{51} Viscosity is a very useful parameter and depends on moisture content, fructose, glucose, water activity, proteins, the presence of crystallized glucose and its geographical and floral origin.\cite{20} Ahmad et al.\cite{72} studied the rheology of mono floral honey in Ethiopia and found that the honey of Eucalyptus globulus has a high viscosity and that of Vernonia amygdalina has a low viscosity. The
viscosity of various forms of honey depends on the moisture content and behavior of the bath. The viscosity of the honey increases as a result of reduced moisture content and water activity.\cite{20,51,59,71} However, viscosity decreases substantially as moisture content and temperature increase,\cite{20,58} as shown in Figures 3 and 4.

Reduction in the moisture content of forest honey has showed an increase in the viscosity of honey, but the viscosity of ivy honey has been the least affected.\cite{51} Several studies have showed a decrease in viscosity due to a rise in moisture content and temperature.\cite{16,20,29,38,41,51} Acacia honey of Ethiopia
has a higher viscosity than polished honey within a range of 30–45°C, due to its lower moisture content and chemical variation. The viscosity of four varieties of honey from the Kashmir Valley of India is not affected by the shear rate or frequency of the Newtonian flow.\textsuperscript{[20]} Similar findings have also been revealed on the viscosity of honey from the Kashmir valley.\textsuperscript{[25,46,53,54,59,72]}

According to Primorac et al\textsuperscript{[38]} the viscosity of different varieties of honey from the Romanian region ranged from 17.2 p.s. (honeydew honey) to 2.7 p.s. (linden honey) at 20°C, although a decrease was observed as the temperature exceeded 30°C. Viscosity decreased dramatically with an rise in temperature for all selected Israeli honey varieties, and honey varieties with reduced calories were less
viscous compared to natural honey.\textsuperscript{[62]} Moisture content and temperature are factors that influence the viscosity of the honey.\textsuperscript{[30,49]} The decreased viscosity of the honeys is due to low intermolecular friction, hydrodynamic strength and sugar content.\textsuperscript{[20,41,53]}

**Storage ($G'$) and loss modulus ($G''$)**

The dynamic frequency sweep test can be used to evaluate the storage ($G'$) and loss modulus ($G''$). Storage modulus and loss modulus are the rheological parameters of the honey and the frequency function. The viscosity of the honey is independent of the frequency or rate of shearing.\textsuperscript{[16]} Ghazal\textsuperscript{[73]} determined that the magnitude of the loss modulus (more viscous) was higher than that of the storage modulus (elastic viscous) for three honey varieties in the Kashmir Valley. Some authors have found similar findings in rheological activity for different types of honey.\textsuperscript{[20,38]} Previous research has showed an improvement in the magnitude of loss modulus (more viscous) and storage modulus (elastic) due to an increase in angular frequency\textsuperscript{[73]} as shown in Figure 5. The four varieties of honey from the Kashmir Valley of India displayed Newtonian behavior, i.e. loss modulus is greater than storage modulus or elastic modulus due to their different floral origins.\textsuperscript{[20]}

The loss modulus ($G''$) or viscous part value in Acacia honey ranged from 0.9 to 1085.49 Pa at 0–30 AC while the storage modulus or elastic part ranged from 0.01 to 15.3 Pa at the same temperature.\textsuperscript{[73]} Primorac et al.\textsuperscript{[38]} revealed that the loss modulus ($G''$) or viscous component value for linden varieties of honey from different regions of Romania ranged from 610 to 2229 Pa, while the storage modulus ($G'$) or elastic part for sunflower ranged from 13.8 to 315.6 Pa. Variations in the complex rheological or viscoelastic properties of honeys (i.e. $G'$ and $G''$) are affected by moisture content, temperature sugar content, degree Brix concentrations and polymeric compounds.\textsuperscript{[56,70,74]} Some authors have documented data on the viscoelastic behavior or dynamic rheological properties of honey, such as loss and storage modulus.\textsuperscript{[20,38,56]}

**Mathematical model of viscosity of the honeys**

The connection between temperature and viscosity can be represented in the Arrhenius model, the Power Law model, the Williams – Landel – Ferry model, and the Vogel – Tamman – Fulcher model.\textsuperscript{[3,20,29,41,69,75]}

![Figure 5. Loss modulus at 20°C in dynamic oscillatory for all honey samples\textsuperscript{[20]} (S = saffron; C = cherry; P = Plectranthus rugosus; A = apple).](image-url)
Figure 6. Behavior obtained by fit models for viscosity data corresponding to honey.\textsuperscript{[75]}.
hones. The activation energy of the Spanish honeys measured by the Arrhenius model ranged from 90.78 to 100.28 kJ/mol due to the magnitude of the activation energy of the Arrhenius model $\eta$. Correlation coefficient (R$^2$) values of shear stress vs. shear rate for mono floral honey ranged from 0.96 to 0.99, suggesting Newtonian action. Similar findings are reported by different authors, indicating a non-Newtonian flow.

Maria et al. [78] reported that the higher soluble solid content (degree brix concentration) showed higher honey viscosity, this could be defined in the Power Law model. The Power Law Model explains the effects of the concentration on the magnitude of the viscosity, loss and storage modules. A drop in the magnitude of the viscosity ($\mu$), loss ($G''$), and storage ($G'$) modules is observed by increasing the temperature and decreasing the concentration of the °Brix. [78] Arrhenius models are more suitable for predicting the effects of the concentration of Arrhenius on viscosity and loss modules. The exponential models are stronger than the power law model in predicting the relationship between the activation energy and the concentration of the Brix. [78] The power and exponential models to estimate the effects of TTS on steady shear and complex viscosity at 10–60°C and the correlation coefficient, and correlation coefficient ($R^2$) ranged from 0.9161 to 0.9803 and 0.7295 to 0.9717, respectively. [54] Ghazal [73] revealed that the gradient in dynamic rheological parameters for the loss and storage modulus of all honey varieties can be defined in the Power Law Model as proposed by.

$$G'' = K''(\omega)^{n'}(1)$$
$$G' = K'(\omega)^{n''}(2)$$

where $k'$ and $k''$ are Storage and Loss Module Consistency Coefficients $n'$ and $n''$ represent Storage (elastic) and loss (viscous) modulus activity indexes, respectively. Ghazal [73] showed that all varieties of honey displayed Newtonian behavior as the magnitude of the viscous coefficient of consistency ($k'$) is higher than that of the storage coefficient of consistency ($k''$). Similar findings for consistency coefficients of loss ($k''$) and storage modulus ($k'$) are found by other authors. [20] Khalil et al. [79] showed a decrease in the energy law parameters of the storage (elastic) and loss (viscous) moduli of the Tunisian honey with a rise in temperature, and the coefficient $k''$ of the viscous moduli was greater than the storage modulus $k'$. The relationship between temperature and viscosity can be defined in the Williams–Lande – Ferry model and the parameter of this model can be calculated by nonlinear regression. [55] Maria et al. [61] has showed that the mathematical model of food rheology is useful for predicting the effects of temperature and concentration on viscosity, loss modulus (viscous) and storage modulus (elastic) as well as for developing efficient industrial processing, mixing, heat pumping, transporting and quality control of honey and manufactured honey products.

**Thermal properties of honey**

Awareness of the thermal properties of food materials is indispensable for food processing involving heat transfer, such as cooling and heating of food products. [7] Glass transition temperature ($T_g$) is a honey parameter that can be measured by a differential calorimeter. [16,41,45,55] as shown in Figure 7. The glass transition temperature is a particular temperature range at which a partly or amorphous substance transitions from a rubber viscous to a solid state. Glass temperature is known to be the reference temperature (i.e., $T-T_g$). Awareness of $T_g$ is crucial in the determination of honey efficiency, production, thermal protection and shelf life and the predictability of its stability. [16]

**Glass transition**

Values of the glass transition temperature of the Tunisian honeys ranged from -41.55°C to -47.06°C (-41.55°C). [79] Similar findings have been published by other authors. [18,22] The glass transition temperature of honey is affected by moisture content, water activity, and crystallization. [79] The moisture content of the honey increases from 10.2 g/100 g to 26.9 g/100 g and decreases from -25 g to -69.5 g/100 g. The decrease in $T_g$ with increase in moisture content is due to the capacity of water to
plasticize. In the same way, the $T_g$ of the honey can be measured using the Williams – Landel – Ferry model, which ranged from -59.6 to -42.5°C. A few authors have also reported similar results.

**Conclusion**

Honey is a natural, complex food and nutritional commodity prepared by honeybees. The key components of honey are carbohydrates such as monosaccharaides, glucose and fructose. Honey has numerous purposes such as antioxidants, anti-inflammatory agents and antibacterial agents. The quality of the honey depends on the moisture content, temperature, sugar content, botanical origin and the geographical location. It can be characterized by engineering properties such as physiochemical, rheological and thermal properties. The physiochemical, rheological and thermal properties of the honey play an important role in the regulation, design, optimization, and modeling and maintain of the shelf life of the honey. Previous studies focused more on the physiochemical properties of honey. However, there are lacks of literature references on rheological and thermal properties of honey in case of the future investigation. Further studies in the field of honey engineering are therefore needed to develop successful handling, processing, development, design, optimization, modeling, control and shelf life. In addition, studies are required adequate knowledge of engineering properties of honey for the development of honey-based products at industrial level.

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