LWT - Food Science and Technology 75 (2017) 393–401

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Rheology and botanical origin of Ethiopian monofloral honey

Abera Belay [a, b], Gulelat Desse Haki [c], Marc Birringer [d], Hannelore Borck [d], Admasu Addi [e], Kaleab Baye [a], Samuel Melaku [f, *]

[a] Center for Food Science and Nutrition, Addis Ababa University, Box 1176, Addis Ababa, Ethiopia
[b] Arsi University, Ethiopia
[c] Department of Food Science and Technology, Botswana University of Agriculture and Natural Resources, Botswana
[d] Fulda University of Applied Sciences, Germany
[e] Department of Plant Biology, Addis Ababa University, Box 1176, Addis Ababa, Ethiopia
[f] Department of Chemistry, Columbus State University, 4225 University Avenue, Columbus, GA 31907, USA

A R T I C L E I N F O

Article history:
Received 9 June 2016
Received in revised form
11 September 2016
Accepted 13 September 2016
Available online 14 September 2016

Keywords:
Botanical origin
Rheology
Arrhenius
Newtonian
Monofloral honey

A B S T R A C T

Rheology and botanical origin of Ethiopian monofloral honeys were investigated using harmonized method of melissopalynology and HAAKE VT 500 over a temperature range of 25–45 °C, respectively. The percent dominance of monofloral honeys ranged from 59.8% (*Croton macrostachyus*) to 90.3% (*Schefflera abyssinica*). Botanical origin and geographical location of honeys were categorized on principal component analysis (PCA) of pollen data. The PCA graph showed that honeys were divided into two separate groups or three sub groups, based on their close appearance in the plot. The highest viscosity value was observed in *Eucalyptus globulus* honey and the lowest in *Vernonia amygdalina*. Shear stress versus shear rate linearity indicated that all the monofloral honeys exhibited Newtonian behavior. The effect of temperature on the viscosity of honey followed the Arrhenius relationship. The activation energy ranged from 60,042.05 (*Eucalyptus globulus*) to 9858.741 kJ/mol (*Vernonia amygdalina*). Viscosity of honey was found to be time independent.

1. Introduction

Honey is a viscous, sweet and aromatic product. It consists of pollen grains and has been used by humans without being processed since ancient times. Pollen grains are mostly carried from the honey plants during foraging, which is used to fulfill the amino acid, fatty acid and mineral requirement of honey bees' diet (Avni, Hendriksma, Dag, Uni, & Shafir, 2014; Yang et al., 2013). Pollen contribution can possibly guide to determine the honey floral origin (Molan, 1998; Ohe, Oddo, Piana, Morlot, & Martin, 2004). Consequently, the floral origin of honey helps to provide a specific sensorial, chemical and flowing behavior for honey (Bogdanov, 2012; Crane, 1983).

Ethiopia has the highest bee density in Africa; and the annual honey production reached to about 53,693 tons. This makes the country first in Africa and tenth in the world. The production of honey in Ethiopia plays a great role in economic, environment, social and cultural benefit of the citizens; and greatly benefits the forest dwellers (CSA, 2015). At present there is an increasing interest on science and commerce to investigate monofloral honeys. Certainly, many consumers prefer monofloral to polyfloral honeys. The production of monofloral honeys has a benefit to compete with low priced polyfloral honeys. Furthermore, the botanical designation of honey is allowed and can possibly use in the therapeutic and technological intervention of the product (Escriche, Kadar, Juan-Borrás, & Domenech, 2014).

Botanical origin is determined based on the relative frequencies of the pollen types of nectariferous species, using harmonized methods of melissopalynology (Ohe et al., 2004). Honey can be called monofloral honey, if it primarily originated from a dominant floral source and show the typical flowing property of the corresponding type of honey (Arrigoni, Kast, & Walther, 2014; Ohe et al., 2004). Hence; if the relative frequency of the pollen of that *taxon* exceeds 45%, honey is considered to be monofloral in its botanical origin.

Floral source and ripening processes are important factors that affect the composition and flowing capacity of honey. Ripening of

* Corresponding author.
E-mail addresses: ab.berabelay@gmail.com (A. Belay), gulelatw@yahoo.com, hgulelat@bca.bw (G.D. Haki), Marc.Birringer@he.hs-fulda.de (M. Birringer), hannelore.borck@he.hs-fulda.de (H. Borck), admassuaddi@gmail.com (A. Addi), kaleabbaye@gmail.com (K. Baye), abegaz_samuel@columbusstate.edu, samuelmelaku@yahoo.com (S. Melaku).

http://dx.doi.org/10.1016/j.lwt.2016.09.021
0023-6438/

nectar into honey is a combination of mainly two processes: conversion of sucrose into glucose and fructose, and evaporation of excess water. This is mostly occurring to saturate sugar and other solid compounds (Ball, 2007). Saturation of sugar and reduction of moisture are instrumental for flow resistant behavior. As a result honey becomes a viscous and aromatic product. This can be the intrinsic characteristics of honey that possibly distinguished one monofloral honey from the other (Bogdanov, 2012; Escriche et al., 2014; Nita, Murith, Chisholm, & Engmann, 2013).

Viscosity is a measure of its resistance to gradual deformation by shear stress (Eroglu et al., 2016). Knowledge of the rheology of honey is important and applicable in all firms of honey processing technology at different unit operations; staring from uncapping the honey comb up to consumption (Lazaridou, Biliaderis, Bacandritsos, & Sabatini, 2004).

Rheological property of honey was used to categorize honey into Newtonian and non-Newtonian fluids. This fluid behavior of honey is a factor of botanical origin that offer structural organization of food, and play an important role in fluid heat transfer (Ahmed, Prabhu, Raghavan, & Ngadi, 2007). In Newtonian fluid, the shear rate is directly proportional to the shear stress and the plot begins at the origin. The majority of monofloral honeys showed Newtonian behavior and their viscosity strongly depends on temperature (Gómez-Díaz, Navaza, & Quintáns-Riveiro, 2009). In non-Newtonian fluid, shear stress and shear rate plot is not linear and does not begin at the origin. Heather, manuka, buckwheat and some eucalyptus honeys are examples of non-Newtonian type of honey (Fauzi, Farid, & Silva, 2014; Witczak, Juszczak, & Gałkowska, 2011; Yanniotis, Skaltsi, Karaburnioti, 2006).

Viscosity of carbohydrate rich foods is affected by temperature. The effect of temperature can be described by Arrhenius relationship. Within the temperature range of 0–40 °C, honey is Newtonian and the viscosity over this temperature range can be predicted using Arrhenius model (Lazaridou et al., 2004; Mossel, Bhandari, D'Arcy, & Caffin, 2000).

Currently, description of honey using pollen analysis and rheological characteristics has received several attentions. The findings of Ahmed et al. (2007) showed that honey collected from the same environmental and geographical location significantly differ in rheological characteristics. Contrary to the majority of the findings, some honey samples showed non-Newtonian behavior. Oddo and Piro (2004) described the main European monofloral honeys based on botanical origin. A number of researchers studied the rheology of honey. Juszczak and Fortuna (2006) reported the rheology of polish honeys and found that honeys were Newtonian flow behavior; Yanniotis et al. (2006) studied the rheology of pine, fir, thymus, orange, helianthus and cotton honeys and found that viscosity is more sensitive to temperature changes at low moisture contents and the samples showed Newtonian behavior; Witczak et al. (2011) analyzed heather honey and found that the honey was non-Newtonian; and Kędzierska-Matysek, Florek, Wolanciuk, Skałecki, and Litwińczuk (2016) examined *Brassica napus* honey of Lublin region of Polish honey and found that honeys had temperature dependence of viscosity. So far, there is no report on the rheological property of Ethiopian honey, which is based on botanical origin. The purpose of this study was, therefore, to investigate the botanical origin using Melissopalynology; and explore the rheology of Ethiopian monofloral honeys at various operating temperatures.

2. Materials and methods

2.1. Study area

This study was conducted in Ethiopia, where monofloral honeys originate (Fig. 1). The selection of these areas was based on reconnaissance survey and questionnaire. Eighty individuals, who are actively participating in the honey sector, were selected to complete questionnaires. These include honey consumers, collectors, processors, exporters, experts and technicians.

2.2. Sample collection

Three hundred and twenty honey samples were collected from potentially honey producing areas (Fig. 1), based on their floral calendar from May 2014 to March 2015. Beekeepers, at the farm gate, were selected using randomized lottery sampling methods and oriented about the methodology of honey sample collection. Researchers were involved in the majority of sample collection activities. The materials used to collect honey samples were smoker, bee brush, brood free combs, rust free metallic honey containers, 250 g and 500 g food grade glass jar, dry and clean plastic honey containers, uncapping fork and honey extractor.

Late in the afternoon the traditional beekeeper mounts on the tree using a long rope (about 50 m). The traditional hive was tightened using rope and transferred to the ground. One or two beekeepers took the hive and set on stick bed, which has a length of 50–75 cm. The beekeeper puff smoke from the back (opposite to the entrance) and opens the hive. The vertically positioned fixed honey combs were clip from the top, brushed and put in dry plastic bucket. The honey combs were transported to temporarily arrange straining room; and honey combs were broken into pieces and strained using honey sieve, and allowed to settle in a 50 kg metallic honey container. These were done mostly in the South and South Western part of the country. Sample from Northern part of the country were from frame hives, which are extracted honey. To harvest honey from frame hive, a beekeeper puff smoke at the entrance and then the lid was opened and smoked at the top. Honey containing frame combs were clipped from the super box using hive tool, and bees were swept from the comb using brush. The honey was transported to temporary extraction places using empty super box. The sealed frame combs were decapitated using uncapping fork and inserted into the honey extractor. Through centrifugation, the honey was drained from the cell and taken from the outlet of the honey extractor. Both the comb and extracted honey was strained, settled, and later poured in 250 and 500 g food grade glass jar (Belay, Solomon, Bultossa, Adgaba, & Melaku, 2015).

2.3. Botanical origin identification

For identification of botanical origin of honey, a number of possible indicators such as floral calendar, dominance of honey plant and sensorial detection (mainly honey color, taste and flavor) were considered. For sensorial detection 3–4 beekeepers, which have a common knowhow and practice of identifying honey type were selected from the local community. The local panelists were screened using blind coded honey samples. Likewise, a sort of duo-trio test was used to select panelists. Assessors were served with three honey samples (30–40 g), two blind coded and one labeled as a 'reference', using 150 mL odorless food grade glass cup. The panelists were asked to choose one of the blind coded honey sample, which was most similar with the 'reference' (Belay et al., 2015). Accordingly, judges were selected. Honey samples were collected with the recommendation of these panelists and the researcher. Finally, pollen analysis was used to verify botanical origin of honey.

Pollen analysis was carried out to determine the major honey source. Honey (10 g) sample was weighed in a pointed glass centrifuge tube (capacity ca. 50 mL) and dissolved in 20 mL of distilled water (20–40 °C). Then the solution was centrifuged for

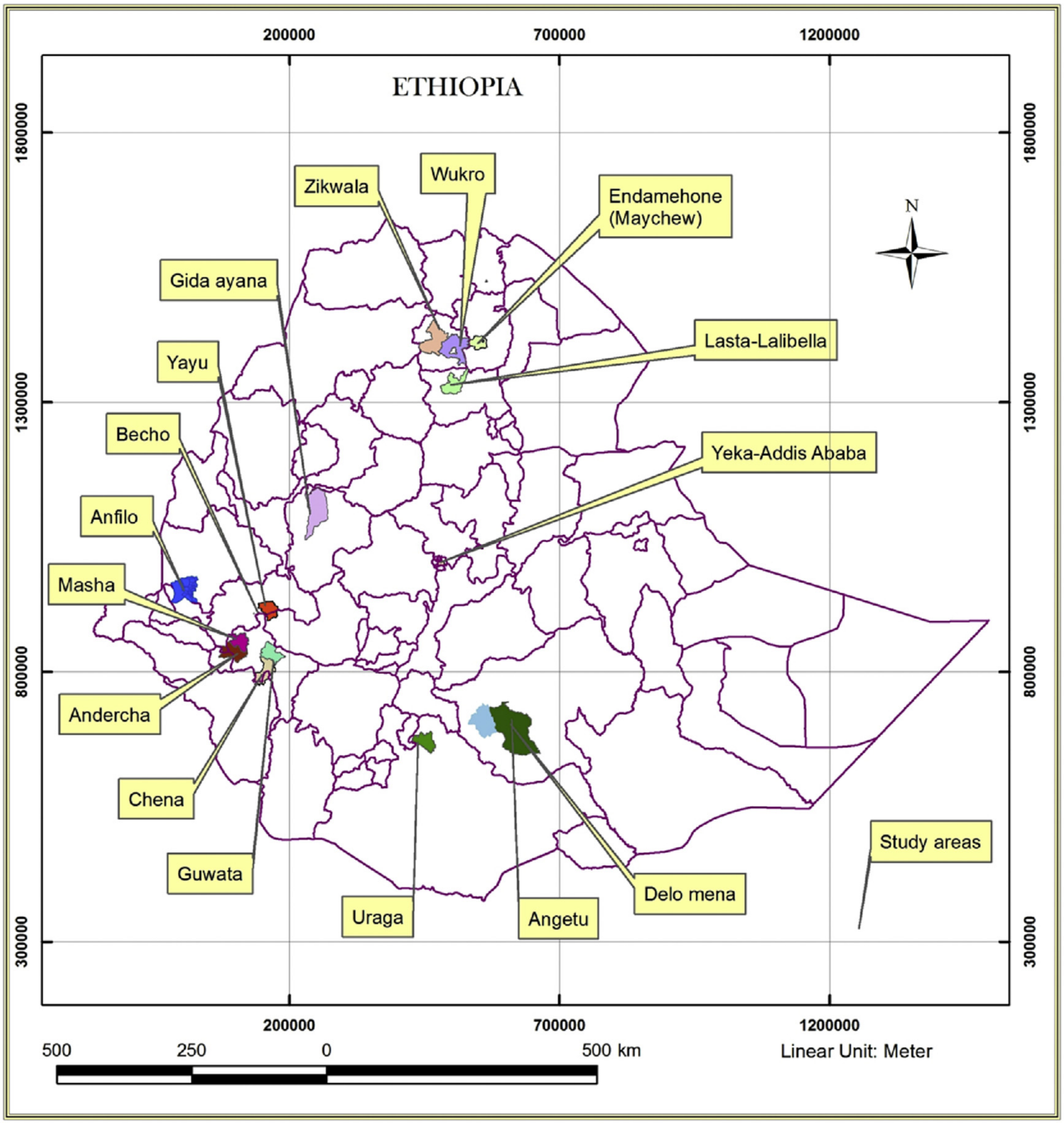

Fig. 1. The study area.

10 min and the supernatant was decanted. Another 20 mL of distilled water was added to completely dissolve the remaining sugar crystals and centrifuged for 5 min, and the supernatant was decanted. The residue was spread evenly with a micro spatula on a microscope slide and allowed to dry. One drop of glycerin jelly was applied to the cover slip and the sample was examined through the microscope. The pollen source plant was identified using reference slides and pollen atlas. Likewise to honey samples, reference slides were prepared, by collecting flowers of honey plant containing pollen grains. The solution of pollen grains centrifuged, supernatant was decanted and the filtrate mounted in a slide. These slides and the pollen atlas were used as a reference to cross check with the pollen morphology found in the honey (Adgaba, 2007). The frequency of occurrences was determined by counting 500 pollens from a single slide. Then, the pollen count was converted into percent to calculate the relative dominance (Belay et al., 2015; Ohe et al., 2004).

2.4. Rheological investigation

Moisture content of monofloral honeys was determined using ATAGO's Abbe Refractometer (Atago NAR-Series, Tokyo, Japan) based on AOAC method number 969.38 (AOAC, 1990). Water activity (a_w) of honey was measured at 25 ± 0.2 °C using LabMaster-a_w (CH8853 Lachen, Novasina, Switzerland).

Viscosity was measured using HAAKE model VT 500 concentric cylinder rotational viscometer with SVDIN sensor. SVDIN cylinder has an inner radius, outer radius and height of 10.61, 11.55 and 31.45 mm, respectively. About 150 g of honey sample was heated to 45 °C for 3 h in a thermostatically controlled water bath (GFL Labortechnikmbh D3006 Burgwedel) to dissolve any crystals present in the sample. Then, each sample was heated to 50 °C for 30 min. After 24 h, the honey sample was randomly selected, using lottery sampling method, from monofloral honeys. Sequentially, about 14 g of honey was poured in a sample holder sensor cup and measured at 25, 30, 35, 40 and 45 °C (Yanniotis et al., 2006). The viscosity of the honeys was measured over a range of shear rates (2.58–258.1 s^{-1}), 1/s, at 25, 30, 35, 40 and 45 °C.

The flow behavior of honey was described by fitting experimental data of shear stress and shear rate in the Newtonian fluid model (Rao, 2014; Recondo, Elizalde, & Buera, 2006):

$$\sigma = \eta\gamma \quad (1)$$

where, σ = is the shear stress; γ = is the shear rate; and η = is the viscosity fluid.

Temperature dependence of viscosity was described by fitting the experimental data with Arrhenius model:

$$\eta = \eta_0 exp(Ea/RT) \quad (2)$$

where, η = is the viscosity (Pa s); η_o = is rate constant (Pa s^n); Ea = is the activation energy (kJ/mol); T = is the absolute temperature (K); and R = the gas constant (kJ/mol/K).

Time independent flow behavior of monofloral honey was evaluated based on viscosity versus time record.

2.5. Statistical analysis

Monofloral honeys were used as a treatment, and the experimental design was completely randomized design (CRD). Moisture, a_w and viscosity data were generated from triplicate measurement of each honey samples. Statistical analysis was carried out using ANOVA, by SAS, 2002. In order to determine the significance differences in the viscosity of monofloral honeys, the mean separation was computed using least significant differences (LSD) at $p < 0.05$. Principle component analysis (PCA) was used to study correlations

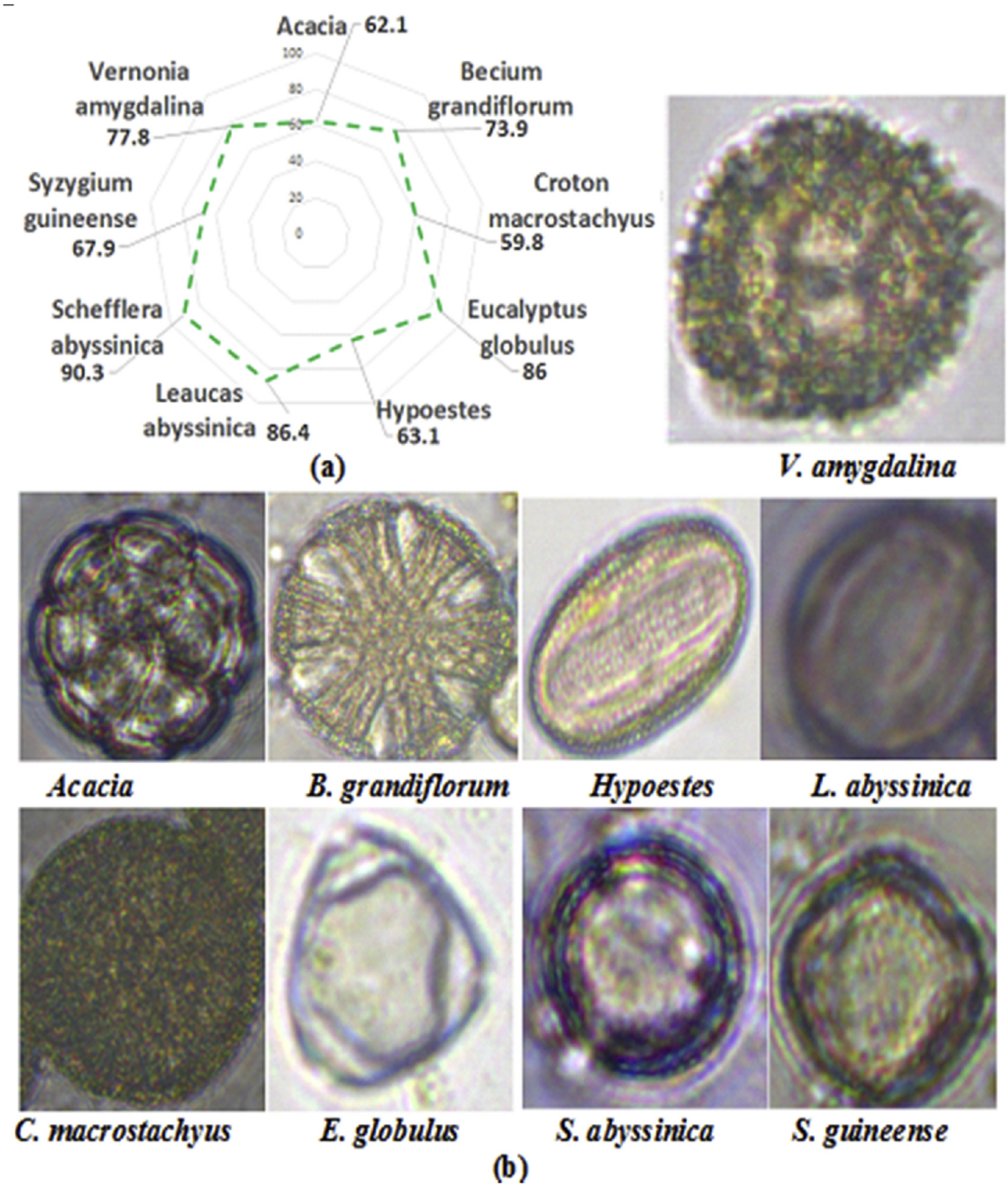

Fig. 2. (a) Spider web distribution for Monofloral honeys with their respected percent dominancy, and (b) Pollen morphology of dominant honey plant (40×).

among monofloral honeys.

3. Result and discussion

3.1. Botanical origin investigation of honey

The results of percent pollen dominance and pollen morphology of nine Ethiopian monofloral honeys are presented in Fig. 2a and b, respectively. The level of dominance ranged from 59.8 (*Croton macrostachyus*) to 90.3% (*Schefflera abyssinica*) (Fig. 2a).

Melissopalynology finding of this study indicated that honeys collected from Masha, Andercha, Chena, Guwata and Guji-Uraga were found to be *Schefflera abyssinica.* Becho, Yayu, Angetu and Mena honeys were *Croton macrostachyus*. *Becium grandiflorum* honey was produced from Lalibella, Maychew and Wokro areas. *Acacia, Leucas abyssinica, Hypoestes* and *Syzygium guineense* honeys were from Wag-himra-Zikwala, Maychew, Wukro and Guji-Uraga; respectively. Anfillo and Gida ayana of Wellega were known to produce *Vernonia amygdalina* honey; and *Eucalyptus globulus* honey was from the capital, Addis Ababa. Accordingly, pollen count percent dominance for *Schefflera abyssinica, Croton macrostachyus, Eucalyptus globulus, Becium grandiflorum, Acacia, Leucas abyssinica, Hypoestes*, *Syzygium guineense* and *Vernonia amygdalina* ranged from 60.4 to 99%, 53.4–73.2%, 81.2–90.6%, 60.4–80.6%, 61–63.2%, 78.4–94.4%, 61.8–64.4%, 67.6–68.2%, 74.4%–80.2%; respectively.

The spectrums of honey plant pollens and their contributions for specific monofloral honeys are presented in Fig. 3. The pollen spectra showed the relative percent contribution of each pollen type to the nine monofloral honeys. The total number of pollen grains found in the spectrum was thirty four. *Croton macrostachyus* was comprised of 21 spp. of honey plant pollen followed by *Schefflera abyssinica* with 19 spp. Other honeys; *Acacia, Becium grandiflorum*, *Syzygium guineense, Leucas abyssinica*, *Eucalyptus globulus, Hypoestes* and *Vernonia amygdalina* were made of 10, 8, 8, 7, 5, 4 and 3 spp. of honey plant pollen, respectively. *Eucalyptus* and *Guizotia* spp. were found in higher numbers of monofloral honeys. The *Eucalyptus* pollen was found in all monofloral honeys, except *Hypoestes* and *Leucas abyssinica* honeys. *Guizotia* spp. pollen was found in six monofloral honeys (*Hypoestes, Becium grandiflorum, Acacia, Schefflera abyssinica, Croton macrostachyus* and *Eucalyptus globulus* honeys). *Coffea* pollen was the 2nd most abundant contributor, next to the dominate monofloral honey, for *Vernonia amygdalina* (21.65%) and *Croton macrostachyus* (19.3%) honeys. The pollen spectrum sketch, in this study, was in line with the

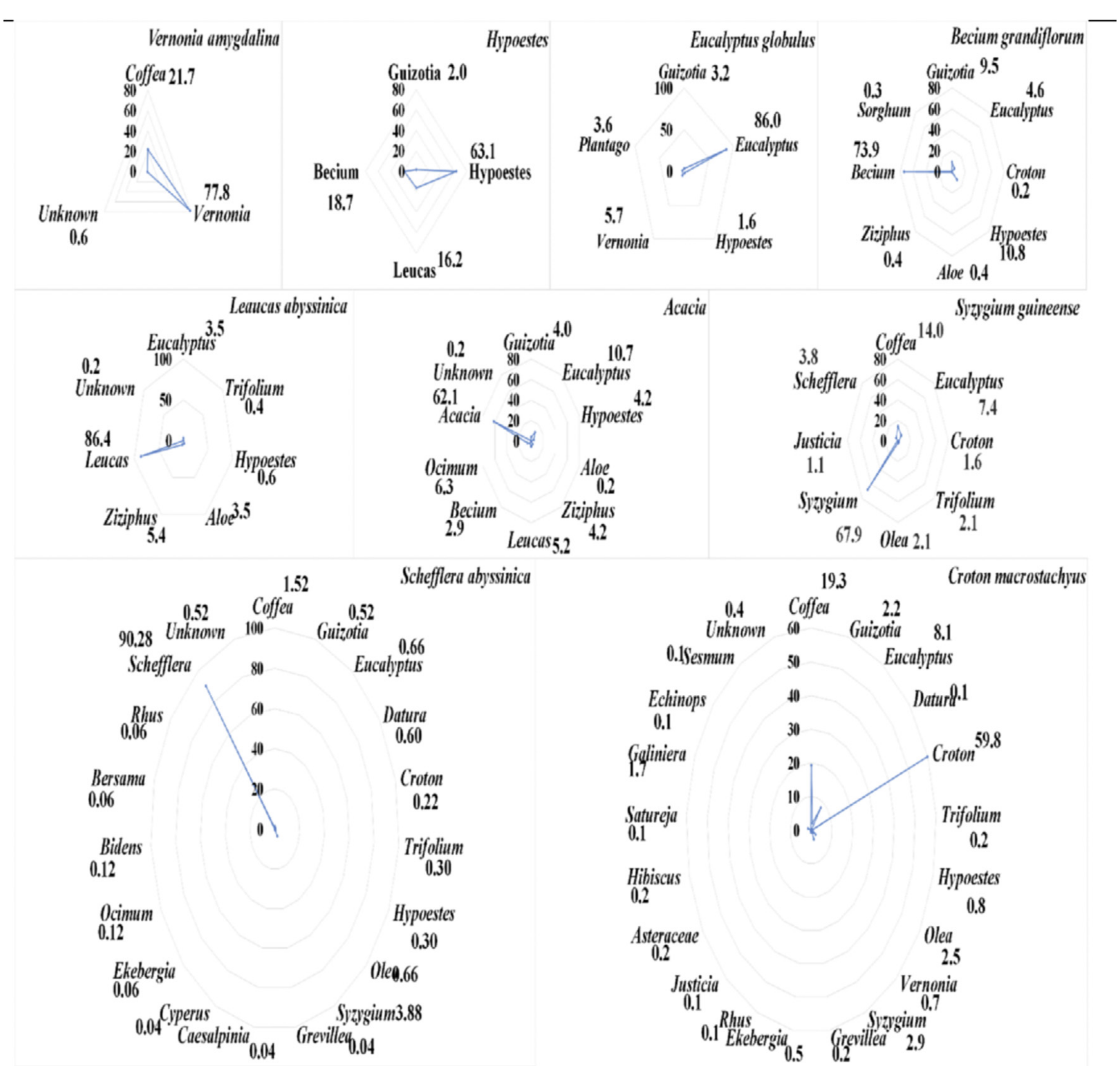

Fig. 3. Pollen spectrum of monofloral honeys with their relative contribution of each honey pollen type in percent.

description of Italian and east European honey (Corvucci, Nobili, Melucci, & Grillenzoni, 2015).

Principle component analysis (PCA) plot using rotated space for monofloral honey is presented in Fig. 4. PCA of pollen data categorize clearly the botanical and geographical origin of honeys. Honey plant origin displayed and represented in a graphic distribution of honeys according to their component scores (PC_1 and PC_2). The PCA graph showed that honeys were divided into two separate groups or three sub groups, based on their close appearance in the plot. This was largely associated with the floral origin and geographical position of the honey. Honeys from *Hypoestes, Leucas abyssinica, Becium grandiflorum* and *Acacia* were from the North; and *Schefflera abyssinica, Syzygium guineense, Vernonia amygdalina, Croton macrostachyus* and *Eucalyptus globulus* were from West, South-West and Central part of Ethiopia. The results of this study were in agreement with the findings of Addi, Wajkira and Kelbesa (2015), Fichtl and Adi (1994) and Shenkute et al. (2012).

The monofloral honeys on the left side of negative value of PC_1 were trees (*Schefflera abyssinica, Syzygium guineense, Croton macrostachyus, Eucalyptus globulus* and *Vernonia amygdalina*). These trees have a common characteristics of yielding higher amount of nectar and pollen, most of them grown in similar vegetation ecosystem and share similar flowering pattern, and considered as the major honey producing plant in the country. The flowering period of these trees were from March to July, after the small rainy season. Similarly, the trees are also used to hang the traditional beehives, which are mostly found far away from the homestead in the forest. The height of the plants ranged from 10 m (*Vernonia amygdalina*) to 45 m (*Eucalyptus globulus*). Honeys on the right side of the plot, with a positive value of PC_1 were herbs and shrubs (*Becium grandiflorum, Hypoestes, Leucas abyssinica* and *Acacia*). These honey plants are described as perennial herb or sub-woody herb, and some are small aromatic woody herb or shrub with a length of 1–4 m from the ground (Addi et al., 2015). These plant species flowers after a big rainy season in September to November. These plant species usually found in the exclusion areas and farm boundaries. The position of outlying samples in the top part of the plot, forming the sub group, was *Eucalyptus globulus* and *Acacia.* The PCA description on the floral origin of honey was in agreement with Fernández-Torres et al. (2005); Gan et al. (2016).

3.2. Rheology of honey

The results of moisture content and a_W value of monofloral honeys are presented in Table 1. The highest a_W (0.6) and moisture (20.54 g/100 g) contents were observed in *Schefflera abyssinica*; and *Eucalyptus globulus* had the lowest a_W (0.48) and moisture (14.14 g/100 g) contents. The moisture content of Ethiopian monofloral honey was in line with the findings of Belay, Solomon, Bultossa, Adgaba, and Melaku (2013).

The flowing behavior of Ethiopian monofloral honeys, obtained by fitting of the experimental data as a function of temperature, is presented in Table 1. The highest viscous honey was observed in *Eucalyptus globulus* and the lowest was in *Vernonia amygdalina*. Significant differences ($p < 0.05$) were observed between *Eucalyptus globulus* and *Vernonia amygdalina*, *Syzygium guineense*, *Schefflera abyssinica*, *Croton macrostachyus* and *Acacia*; and similarities ($p > 0.05$) between *Eucalyptus globulus* and *Becium grandiflorum, Hypoestes* and *Leucas abyssinica*.

The study on *Acacia* honey of Ethiopian origin was in agreement with findings of Polish origin of *Acacia* honey that had a viscosity of 13.3, 6.9, 3.8, 2.3 Pa s at 25, 30, 35 and 40 °C, respectively (Juszczak & Fortuna, 2006). *Acacia* honey of Ethiopian origin was found to be more viscous than the Polish origin at all operating temperatures,

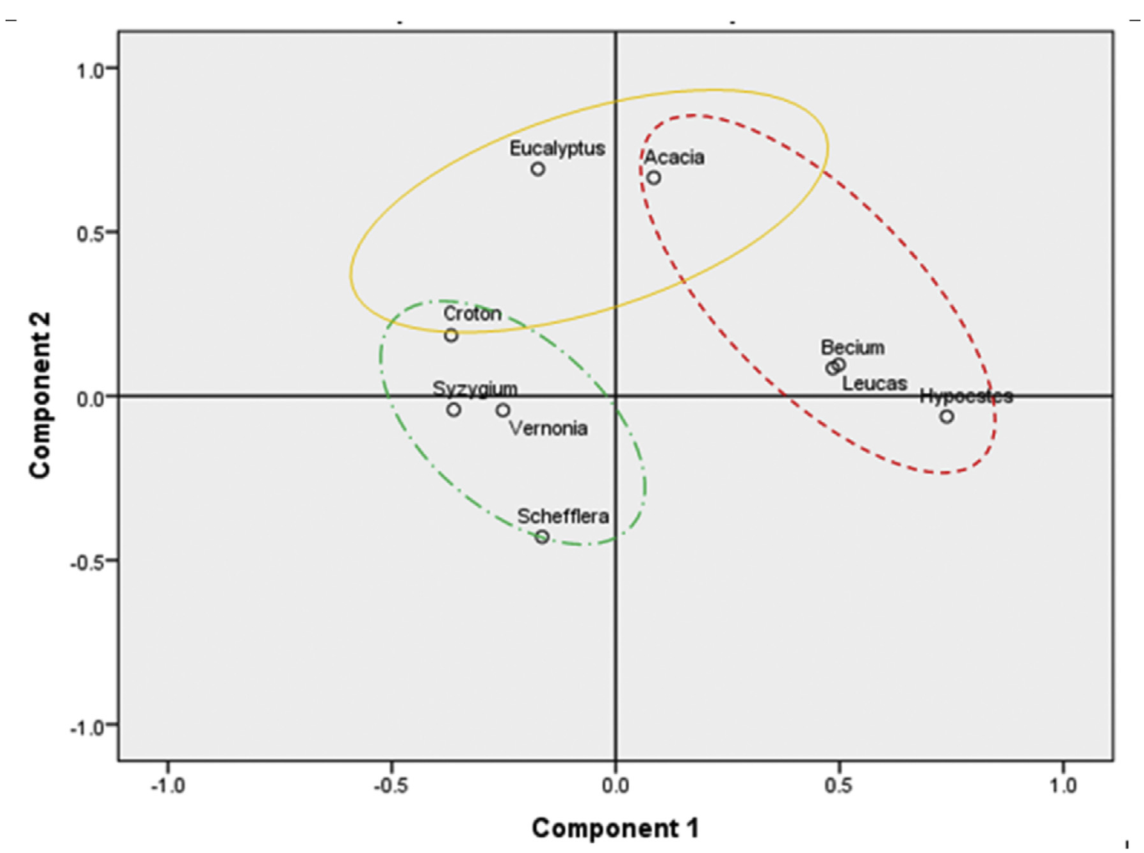

Fig. 4. PCA component plot in the function of floral origin in a rotated plot.

Table 1
Viscosity, Activation energy and shear rate: shear stress relation for monofloral honey at different temperatures.

Monofloral honeys	Moisture (g/100 g)	aw	Viscosity (Pa s) at different operating temperature					Ea (kJ/mol)	σ:γ (r^2)
			25 °C	30 °C	35 °C	40 °C	45 °C		
Acacia [bc]	15.75	0.53	12.30	8.40	6.74	6.34	5.69	28936.877	0.98
Becium grandiflorum[ab]	14.79	0.51	22.49	13.58	9.88	7.16	6.04	51740.52	0.96
Croton macrostachyus[c]	18.56	0.58	7.48	6.31	5.14	4.95	4.73	18351.49	0.99
Eucalyptus globulus[a]	14.14	0.48	29.21	17.19	10.81	8.27	6.31	60042.05	0.99
Hypoestes[abc]	14.97	0.52	21.14	12.97	9.03	6.60	5.72	52103.01	0.99
Leucas abyssinica[abc]	16.53	0.54	15.27	10.87	8.01	6.26	5.61	40425.16	0.99
Schefflera abyssinica[bc]	20.54	0.60	6.44	6.74	5.38	5.33	5.09	13492.79	0.99
Syzygium guineense[bc]	15.26	0.54	12.40	8.96	6.66	5.90	5.32	33458.03	0.99
Vernonia amygdalina[c]	17.30	0.54	6.14	5.42	4.93	4.85	4.76	9858.741	0.99

Monofloral honeys with different superscript letters showed significant different ($p < 0.05$) in viscosity across column.
Shear stress: σ; shear rate: γ.

except 25 °C. This could be due to the lower moisture content of Ethiopian honey and the species variation of the two Acacias, which could possibly cause a difference in other constituents of honey. *Eucalyptus* honey of Ethiopian origin showed a viscosity of 17.19 Pa s at 30 °C. This value was much higher than the *Eucalyptus* of Algerian origin, 0.0031 Pa s (Sereia et al., 2011), at the same operating temperature (30 °C). Both moisture and a_w had an effect on viscosity of monofloral honeys (Fig. 5a and b). The viscosity of honey substantially decreases with increasing moisture and a_w. Similar observations were reported by Recondo et al. (2006). Effects of moisture and a_w on the viscosity of honey was more manifested at lower moisture and a_w value in *Eucalyptus globulus* honey (moisture 14.14; and a_w 0.48). Even though both moisture and a_w had a significance contribution on the viscosity of honey, the effect of a_w ($r^2 = 0.7339$, at Pa s $= -75.333aw + 49.286$) was more pronounced ($p < 0.001$) and linearly regress than the effect of moisture ($r^2 = 0.6369$, at Pa s $= -1.2111$moisture $+ 28.669$) ($p < 0.01$) on the viscosity of monofloral honeys. This could be due to the tendency of the solid components attached to water molecules, which decreases the liquid phase of the honey. As a result, the viscosity of honey increased with reduced a_w at different shear rate (Belay et al., 2015; Gleiter, Horn, & Isengard, 2006).

Schefflera abyssinica honey had a higher moisture content and a_w than *Eucalyptus globulus* honey this tend to have a reduced viscosity. Contrary to the expected results, a lower viscosity was observed in *Vernonia amygdalina* honey at a relatively lower moisture content and a_w. Even though moisture content of the honey has a strong effect on the flowing capacity of the honey, the viscosity of honey also depends on its floral origin, which was directly related to its composition (Mossel et al., 2000).

The coefficient of determination (r^2) value of shear stress to the shear rate for monofloral honey ranged from 0.96 to 0.99 (Table 1). The higher r^2 obtained for all monofloral honeys indicated that the Newtonian model was adequately suitable for describing the Newtonian flow behavior of monofloral honeys (Model 1). This was in agreement with Greek honey which also exhibited Newtonian flow behavior at the temperature range of 20–60 °C (Lazaridou et al., 2004). Subsequently, the fluidity of the honeys had a constant viscosity, η, across all shear rates. This was in agreement with the findings of Razavi, Najafi, and Alaee (2007).

The amount of activation energy (Ea) needed for each type of monofloral honeys is presented in Table 1. The highest Ea needed was for *Eucalyptus globulus* (60,042.05 kJ/mol) and the lowest for *Vernonia amygdalina* (9858.741 kJ/mol). The results of Ea was significantly ($p < 0.01$) and inversely related to the moisture content ($r^2 = 0.6039$ at Ea $= -7803$moisture $+ 156,378$) and a_w ($r^2 = 0.6772$ at Ea $= -419198a_w + 259,703$) ($p < 0.001$) (Fig. 6a and b). Ea reflected the sensitivity of viscosity to temperature changes. Higher Ea was relatively sensitive to temperature changes than lower Ea. This was in line with findings of Lazaridou et al. (2004) on Greek honey. The calculated activation energy for flow on Greek honey was inversely related to the moisture content ($r^2 = 0:61$).

Temperature dependence of the viscosity of monofloral honey was assessed by applying the Arrhenius type model (Model 2). The fitting of the logarithmic of viscosity (ln Pa s) versus the reciprocal temperature (1/T) data (Fig. 7a) was examined at a temperature (K)

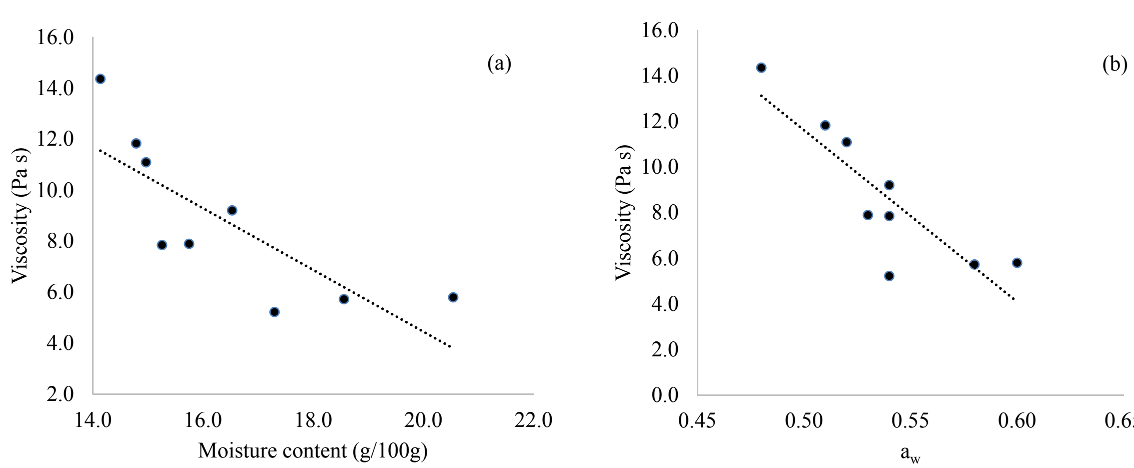

Fig. 5. Linear graph showing associations of viscosity with: (a) moisture (Pa s $= -1.2111$moisture $+ 28.699$, $r^2 = 0.6369$); and (b) water activity (Pa s $= -75.33aw + 49.286$, $r^2 = 0.7339$).

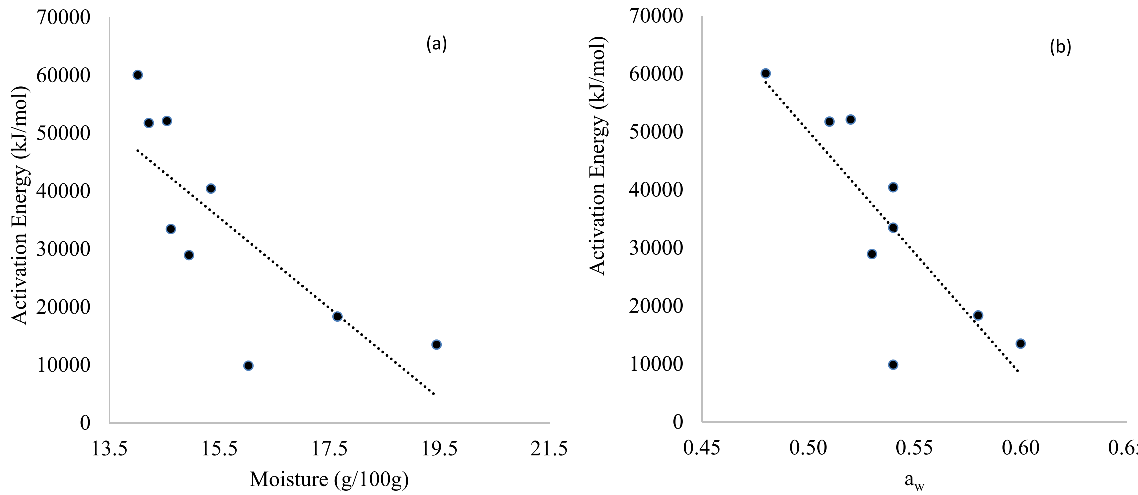

Fig. 6. Linear graph showing associations of activation energy with: (a) moisture (Pa s = −7803.1moisture + 156,378, r^2 = 0.6039); and (b) water activity (Pa s = $-419198a_w$ + 259,703, r^2 = 0.6772).

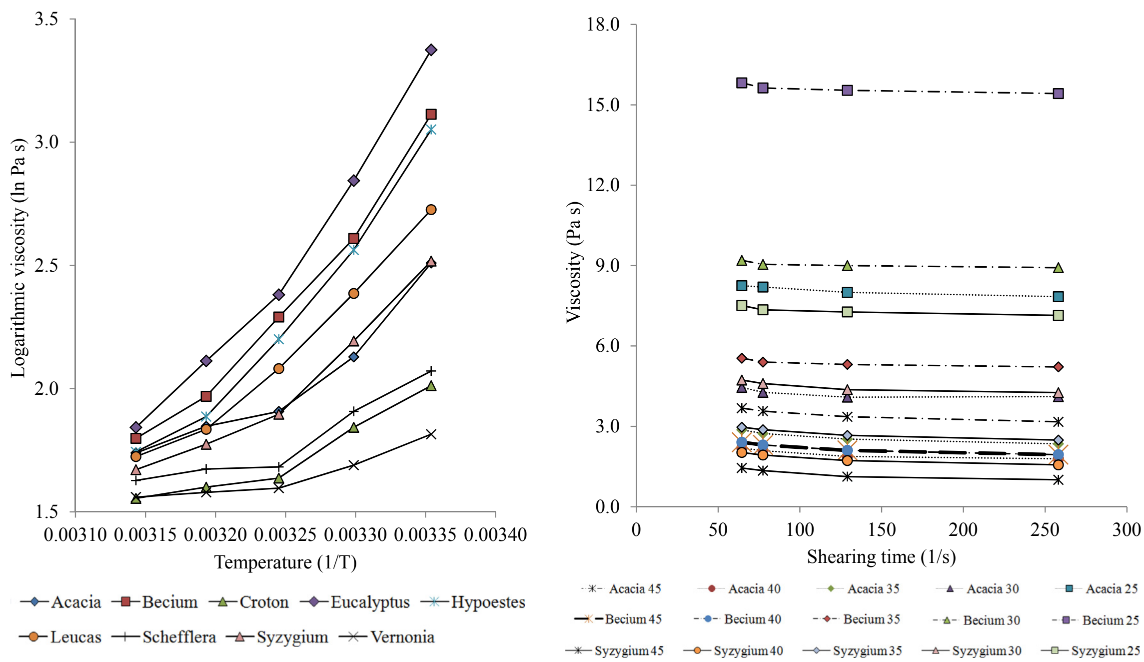

Fig. 7. Linear graph: (a) Logarithmic value of viscosity (ln Pa s) versus the reciprocal value of temperature (1/T) describing Arrhenius model; (b) Shearing time (1/s) versus viscosity (Pa s) in the function of temperature indicate time independence behavior for some monofloral honeys.

range of 298.15–318.15; and appropriately projected by Arrhenius model. The highest viscosity variations between the samples were observed at 25 °C (1/298.15 K), while at a temperature of 35 °C (1/308.15) and above the differences became smaller. This was in line with the finding of Polish honey (Juszczak & Fortuna, 2006). The logarithmic value of viscosity was significantly regressed with reciprocal value of temperature for all monofloral honeys. The highest significant value was in *Eucalyptus globulus* ($p < 0.001$) and the lowest was *Vernonia amygdalina* ($p < 0.05$).

The time dependent behavior, which was plotted Time (1/s) versus Pa s is presented in Fig. 7b. The results of the associated time dependent behavior study indicated that all monofloral honeys showed a time-independent behavior at constant shear rates of 64.5–258.1, and at a temperature range of 25–45 °C. This time independent behavior could possibly be used as an evidence for Newtonian fluid behavior of the monofloral honeys and are in agreement with the findings of Mossel et al. (2000), Yanniotis et al. (2006), Zaitoun, Ghzawi, Al-Malah, and Abu-Jdayil (2001).

4. Conclusion

In this study, nine monofloral honeys were investigated for botanical origin and rheological behavior. The monofloral honeys identified were *Acacia*, *Becium grandiflorum*, *Croton macrostachyus*, *Eucalyptus globulus*, *Hypoestes*, *Leucas abyssinica*, *Schefflera abyssinica*, *Syzygium guineense* and *Vernonia amygdalina*. The level of dominance in monofloral honeys ranged from 59.8 to 90.3% by *Croton macrostachyus* and *Schefflera abyssinica;* respectively. The most viscous honey was *Eucalyptus globulus* and the least was *Vernonia amygdalina*. The viscosity of honey was inversely related with moisture content and a_w. Within the temperature range of 25–45 °C, all the monofloral honeys exhibited Newtonian behavior. The plot of the logarithmic value of viscosity (ln Pa s) versus the reciprocal value of temperature (1/T) indicated the goodness of fit for Arrhenius model. The highest activation energy was observed for *Eucalyptus globulus* and the lowest for *Vernonia amygdalina*. Monofloral honeys with higher viscosity showed higher activation energy. The relation between viscosity (Pa s) and time (second) indicated that all monofloral honeys were time independent.

Investigation rheology of honey based on floral origin be in a great demand for science and market. The possibility of producing monofloral honey in Ethiopia could also have a worthily impact on the income of the rural household, the bee economy of the nation and environment, and the food industry. Monofloral honeys attract a premium price, which can be used as good incentive for beekeepers. It also gives the opportunity to conserve honey plants, and utilize the forest in a standing position. In addition, knowledge of rheological behavior of monofloral honeys significantly contributes on efficiency and cost effectiveness of the honey industry.

Acknowledgement

We would like to thank SNV Ethiopia, GIZ-SLM, MELCA Ethiopia for their logistic support; Fulda University of Applied Sciences; Holetta Bee Research Center, for laboratory service; and Dr. Jurgen Greiling, Prof. Mooha Lee for coordinating the field and laboratory works; Mr. Debele Abera for sketching the study area; and Mr. Martin, Hirut Abebe and Abate Geremew for assisting in the lab work.

Nomenclature

$1/s(s^{-1})$	shearing time
1/T	reciprocal value of temperature
a_w	water activity
Ea	activation energy
ln Pa s	logarithmic value of viscosity
Pa s	viscosity
R	the gas constant
r^2	coefficient of determination
T	absolute temperature in K

Greek letters

γ	shear rate
η	viscosity in Pa · s
ηo	rate constant
σ	shear stress

References

Addi, A., Wajkira, K., & Kelbesa, E. (2015). *Honey bee forage of Ethiopia*. Addis Ababa Ethiopia: United Printers.

Adgaba, N. (2007). *Atlas of pollen grains of major honeybee flora of Ethiopia*. Holetta, Ethiopia: Holetta Bee Research Center.

Ahmed, J., Prabhu, S. T., Raghavan, G. S. V., & Ngadi, M. (2007). Physico-chemical, rheological, calorimetric and dielectric behaviour of selected Indian honey. *Journal of Food Engineering, 79*(4), 1207–1213.

AOAC. (1990). *Official methods of analysis* (15th ed.) # 969.38, Association of Official Analytical Chemists, Washington, DC, USA.

Arrigoni, E., Kast, C., & Walther, B. (2014). Effects of dietary sugars from natural sources on health outcomes. *Dietary Sugars and Health, 59*.

Avni, D., Hendriksma, H. P., Dag, A., Uni, Z., & Shafir, S. (2014). Nutritional aspects of honey bee-collected pollen and constraints on colony development in the eastern Mediterranean. *Journal of Insect Physiology, 69*, 65–73.

Ball, D. W. (2007). The chemical composition of honey. *Journal of Chemical Education, 84*(10), 1643–1646.

Belay, A., Solomon, W. K., Bultossa, G., Adgaba, N., & Melaku, S. (2013). Physicochemical properties of the Harenna forest honey, Bale, Ethiopia. *Food Chemistry, 141*(4), 3386–3392.

Belay, A., Solomon, W. K., Bultossa, G., Adgaba, N., & Melaku, S. (2015). Botanical origin, color, granulation, and sensory properties of the Harenna forest honey, Bale, Ethiopia. *Food Chemistry, 167*, 213–219.

Bogdanov, S. (2012). Honey as nutrient and functional food: A review. *Bee Product Science*, 1–48.

Corvucci, F., Nobili, L., Melucci, D., & Grillenzoni, F. V. (2015). The discrimination of honey origin using melissopalynology and Raman spectroscopy techniques coupled with multivariate analysis. *Food Chemistry, 169*, 297–304.

Crane, E. (1983). *The archaeology of beekeeping*. Duckworth.

CSA. (2015). *Federal democratic republic of Ethiopia, central statistical agency agricultural sample survey 2014/15 [2007 E.C.] volume II*. Report on Livestock and Livestock Characteristics. Addis Ababa, Ethiopia.

Eroglu, A., Bayrambaş, K., Eroglu, Z., Toker, O. S., Yilmaz, M. T., Karaman, S., et al. (2016). Steady, dynamic, creep/recovery, and textural properties of yoghurt/molasses blends: Temperature sweep tests and applicability of Cox–Merz rule. *Food Science and Technology International, 22*(1), 31–46.

Escriche, I., Kadar, M., Juan-Borrás, M., & Domenech, E. (2014). Suitability of antioxidant capacity, flavonoids and phenolic acids for floral authentication of honey. Impact of industrial thermal treatment. *Food Chemistry, 142*, 135–143.

Fauzi, N. A., Farid, M. M., & Silva, F. V. (2014). High-pressure processing of manuka honey: Improvement of antioxidant activity, preservation of color and flow behaviour. *Food and Bioprocess Technology, 7*(8), 2299–2307.

Fernández-Torres, R., Perez-Bernal, J. L., Bello-Lopez, M. A., Callejon-Mochon, M., Jimenez-Sanchez, J. C., & Guiraúm-Pérez, A. (2005). Mineral content and botanical origin of Spanish honeys. *Talanta, 65*(3), 686–691.

Fichtl, R., & Adi, A. (1994). *Honeybee flora of Ethiopia*. Weikersheim (Germany), Margraf Verlag, 1994.

Gan, Z., Yang, Y., Li, J., Wen, X., Zhu, M., Jiang, Y., et al. (2016). Using sensor and spectral analysis to classify botanical origin and determine adulteration of raw honey. *Journal of Food Engineering, 178*, 151–158.

Gleiter, R. A., Horn, H., & Isengard, H. D. (2006). Influence of type and state of crystallisation on the water activity of honey. *Food Chemistry, 96*(3), 441–445.

Gómez-Díaz, D., Navaza, J. M., & Quintáns-Riveiro, L. C. (2009). Effect of temperature on the viscosity of honey. *International Journal of Food Properties, 12*(2), 396–404.

Juszczak, L., & Fortuna, T. (2006). Rheology of selected Polish honeys. *Journal of Food Engineering, 75*, 43–49.

Kędzierska-Matysek, M., Florek, M., Wolanciuk, A., Skałecki, P., & Litwińczuk, A. (2016). Characterisation of viscosity, colour, 5-hydroxymethylfurfural content and diastase activity in raw rape honey (Brassica napus) at different temperatures. *Journal of Food Science and Technology*, 1–7.

Lazaridou, A., Biliaderis, C. G., Bacandritsos, N., & Sabatini, A. G. (2004). Composition, thermal and rheological behaviour of selected greek honeys. *Journal of Food Engineering, 64*(1), 9–21.

Molan, P. C. (1998). The limitations of the methods of identifying the floral source of honeys. *Bee world, 79*(2), 59–68.

Mossel, B., Bhandari, B., D'Arcy, B., & Caffin, N. (2000). Use of an Arrhenius model to predict rheological behaviour in some Australian honeys. *LWT-Food Science and Technology, 33*(8), 545–552.

Nita, S. P., Murith, M., Chisholm, H., & Engmann, J. (2013). Matching the rheological properties of video fluoroscopic contrast agents and thickened liquid prescriptions. *Dysphagia, 28*(2), 245–252.

Oddo, L., & Piro, R. (2004). Main European unifloral honeys: Descriptive sheets. *Apidologie, 35*(Suppl. 1), S38–S81.

Ohe, W. V. D., Oddo, L. P., Piana, M. L., Morlot, M., & Martin, P. (2004). Harmonized methods of melissopalynology. *Apidologie, 35*, S18–S25.

Rao, M. A. (2014). *Rheology of fluid, semisolid, and solid Foods: Principles and applications* (3rd ed.). Springer, Food Engineering Series.

Razavi, S. M., Najafi, M. B. H., & Alaee, Z. (2007). The time independent rheological properties of low fat sesame paste/date syrup blends as a function of fat substitutes and temperature. *Food Hydrocolloids, 21*(2), 198–202.

Recondo, M. P., Elizalde, B. E., & Buera, M. P. (2006). Modeling temperature dependence of honey viscosity and of related supersaturated model carbohydrate systems. *Journal of Food Engineering, 77*, 126–134.

SAS. (2002). *SAS Guide to personal computers (Version 9)*. NC, USA: SAS (statistical analysis system) institute Inc.

Shenkute, A. G., Getachew, Y., Assefa, D., Adgaba, N., Ganga, G., & Abebe, W. (2012). Honey production systems (Apis mellifera L.) in Kaffa, Sheka and Bench-Maji zones of Ethiopia. *Journal of Agricultural Extension and Rural Development, 4*(19), 528–541.

Sereia, M. J., Alves, E. M., Toledo, V. A., Marchini, L. C., Serine, E. S., Faquinello, et al. (2011). Physicochemical characteristics and pollen spectra of organic and non-organic honey samples of *Apis mellifera* L. *Anais da Academia Brasileira de Ciências, 83*(3), 1077–1090.

Witczak, M., Juszczak, L., & Gałkowska, D. (2011). Non-Newtonian behaviour of heather honey. *Journal of Food Engineering, 104*(4), 532–537.

Yang, K., Wu, D., Ye, X., Liu, D., Chen, J., & Sun, P. (2013). Characterization of chemical composition of bee pollen in China. *Journal of agricultural and food chemistry, 61*(3), 708–718.

Yanniotis, S., Skaltsi, S., & Karaburnioti, S. (2006). Effect of moisture content on the viscosity of honey at different temperatures. *Journal of Food Engineering, 72*, 372–377.

Zaitoun, S., Ghzawi, A. A. M., Al-Malah, K. I., & Abu-Jdayil, B. (2001). Rheological properties of selected light colored Jordanian honey. *International Journal of Food Properties, 4*(1), 139–148.