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Effect of pulsed electric field and pasteurisation treatments on the rheological properties of mango nectar (*Mangifera indica*)

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Summary

The rheological behaviour of pulsed electric field (PEF) processed and thermally pasteurised mango nectar (*Mangifera indica*) was evaluated using controlled stress rheometer. The mango nectar was subjected to pulsed electric field (PEF) as well as thermal processing. The rheological parameter shear stress was measured up to the shear rate of 750 s^{-1} using co-axial cylinder attachment at wide range of temperatures from 10 to 70 °C. The investigation showed that pulsed electric field (PEF) processed and thermally pasteurised mango nectar behaved like a pseudo plastic (shear thinning) fluid and obeyed Herschel-Bulkley model ($0.9780 < r < 0.9999$, $p \leq 0.01$). Results showed that the consistency coefficient (k) was significantly ($p < 0.05$) affected by processing temperature, whereas no significant change was observed in yield stress (τ_0) of mango nectar. The flow behaviour index (n) was significantly affected by processing condition as compared to that of control sample. The effect of temperature on consistency coefficient (k) of mango nectar was followed by Arrhenius equation ($r > 0.893$, $p < 0.05$) and flow activation energy (E_a) was significantly ($p < 0.05$) affected by processing conditions. The results indicated that the pulsed electric field (PEF) and thermal processing condition has affected the rheological properties of mango nectar. The combined equation relating to shear stress (τ) with temperature and shear rate of mango nectar was established.

Keywords: pulsed electric field, mango nectar, *Mangifera indica*, rheology, Herschel-Bulkley model, arrhenius equation

Introduction

Pulsed electric field (PEF) is one of the most promising non-thermal emerging technologies for the preservation of foods. PEF treatment is efficient enough to destroy microorganisms in fruit juices without greatly affecting their nutritional and sensory properties (Min and Zhang, 2003; Kathiravan et al., 2013). It involves the application of short pulses of high electric fields for micro to milliseconds at intensities between 15-80 kV/cm. The high electric pulses are generated when a pair of high voltage electrodes are charged and discharged in fractions of a second (Kumar et al., 2013a). PEF treatments could either be used alone or in combination with other conventional processes (Xiang et al., 2011). The structure and the chemical composition of the product treated, changes depending on their basic principle of processing. During thermal processing, such as pasteurization, the high temperature induces thermal softening of the pulp, thereby alters, its structure and composition. Whereas in PEF processing, it is due to electroporation and electro-permeabilisation resulted by application of high intensity electric field. The effect of PEF is minimal on the structure and chemical composition, compared to thermal processing (De Vito, 2006).

Rheological characterisation of food is one of the important for the design of unit operations, process optimization and high quality product assurance. Processing influence on the rheological properties of food is thus essential for an efficient product and process design (Augusto et al., 2012). Rheological data are required for computation of food processing operations such as mixing, grinding, filtration and extrusion etc. and it also determines the flow in processing operations such as pasteurization, concentration, dehydration and also in aseptic processing. Rheological behaviours of juices or nectars are largely influenced by their quantitative and qualitative composition; therefore, it will depend on the fruit type and on the treatments to which it is subjected during the manufacturing process. Rheological behaviours were described by different equations. The simplest type of rheological behaviour is Newtonian, in which there is a linear relationship between shear stress and shear rate. However, most fluid foods do not display this simple behaviour, requiring more complex models for their characterization. The most commonly used models for non-Newtonian fluid were those of Ostwald-De-Waele, Herschel-Bulkley, Bingham, Mizrahi-Berk and Casson (Vandresen et al., 2009).

Mango (*Mangifera indica*) is known as the king among the fruits in India, it is a tropical fruit relished for its characteristic flavour and taste. Moreover, India is the leading mango growing country sharing more than 50% of the world's production. Mangoes

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are processed both at raw and ripened stages (Kumar et al., 2013b). Ripe fruits are used in making pulp, nectars, squash, juice, canned slices, jam, ready-to-serve beverages, mango puree, mango powder and mango fruit bars. Fruit juices or nectars are composed of an insoluble phase (the pulp) dispersed in a viscous solution (the serum). The pulp is constituted of fruit tissue cells and their fragments, cell walls and insoluble polymer clusters and chains. The serum is an aqueous solution of soluble polysaccharides, sugars, salts and acids. The fruit juice rheological properties are thus defined by the interactions within each phase and between them (Augusto et al., 2012).

The effects of PEF on rheological behaviour of apple juice was studied and reported that Power law model was used to describe rheological behaviour of apple juice. The apparent viscosity of samples decreased as shear rate increased, suggesting that the apple juices followed the pseudo plasticity flow behaviour. Further author has reported that with increasing electric field strength, the consistency index (K) decreased significantly while flow behaviour index (n) increased (Bi et al., 2013). Similarly Xiang et al. (2011) studied the effects of PEF treatment on the flow behaviour and viscosity of the reconstituted skimmed milk, which resulted that the treated samples followed the Herschel- Bulkley model and exhibited shear-thinning behaviour. It could be concluded that PEF treatment could be used to alter the rheological properties of skimmed milk during processing. However, author has also suggested that further work is needed to assess the combined effect of PEF and temperature on the rheological properties. The rheological behaviour of enzyme treated mango pulp was evaluated and all the process variables such as enzyme concentration, incubation time and incubation temperature significantly affected the rheological properties of mango pulp (Bhattacharya et al., 1998).

Most of the researchers have studied the effect of pulsed electric field treatment on flavour compounds of watermelon juice (Aguilo-Aguayo et al., 2010); pectin methyl esterase and natural microbial flora inactivation (Rodrigo et al., 2003); vitamin C and antioxidant activity (Plaza et al., 2006); physical-chemical characteristics of blended orange and carrot juice (Rivas et al., 2006); flavour, colour and vitamin C (Ayhan et al., 2001); flavour and colour of tomato juice (Min and Zhang, 2003); inactivation of *Alicyclobacillus acidocaldarius* in mango nectar (Kumar et al., 2014) inactivation of *E. coli* O157:H7 (Evrendilek et al., 2003); and total carotene, colour and native micro flora (Kathiravan et al., 2013). The detailed literature collection has proved that, no such work was found in the literature describing the effect of PEF on the rheological properties of mango nectar. Being the case, the current work was focussed on the effect of PEF processing on the rheological properties of mango nectar. The main focus of the study was to observe and measure the effects of the treatments, such as pulsed electric field (PEF), pasteurisation treatments and their combination treatment, applied on the rheological behaviour, and also to apply rheological models.

Materials and methods

Mango nectar production and processing

Fresh ripe *Mallika* variety mangoes (*Mangifera indica*) were purchased from local market in Mysore. The procured mangoes were cleaned, de-stoned and cut into smaller pieces. The cut mangoes were pulped and then the mango nectar was prepared (Fig. 1). The prepared mango nectar was divided into four parts and subjected to the following treatments:

T_1: Control (Untreated)
T_2: PEF processed
T_3: Combination treatment (PEF followed by 120s of in-pack pasteurisation)
T_4: Thermal treatment (in-pack pasteurisation) for 600 seconds

PEF and combination treatment

An Elcrack® HVP5 type continuous PEF system (German Institute of Food Technologies (DIL), Quakenbruck, Germany) was used to treat the samples. The temperature was monitored by using type T thermocouples fixed to the coil and connected to a data acquisition system indicator. Pulse waveform, voltage, and intensity in the treatment chambers were recorded with a digital oscilloscope (Digital touch screen oscilloscope M/s. Siemens, Denmark). The tubes of 3, 5, 7 and 10 mm diameter used were co-linear to treatment chamber. The in-put process parameters such as output voltage, pulse width, frequency, rate of flow and electrode gap were set according to the requirement. The optimized PEF processing parameters are represented in Table 1. The parameters such as pulse width and electric field strength were optimized for the maximum inactivation of native microflora, retention of carotene content and overall acceptability of the mango nectar. The optimized pulsed width and pulse field strength for the mango nectar was 24µs and 38kV/cm for bipolar pulses at a 120Hz frequency (Kumar et al., 2014). Samples were collected after each PEF treatment (T_2), and filled into pouches at sterile conditions. For combination treatment (T_3), PEF treated samples were filled into pouches and subjected to pasteurisation (96 °C for 120 seconds). The treated mango nectar pouches were immediately cooled by immersing in cold water. The experiments were performed in triplicate.

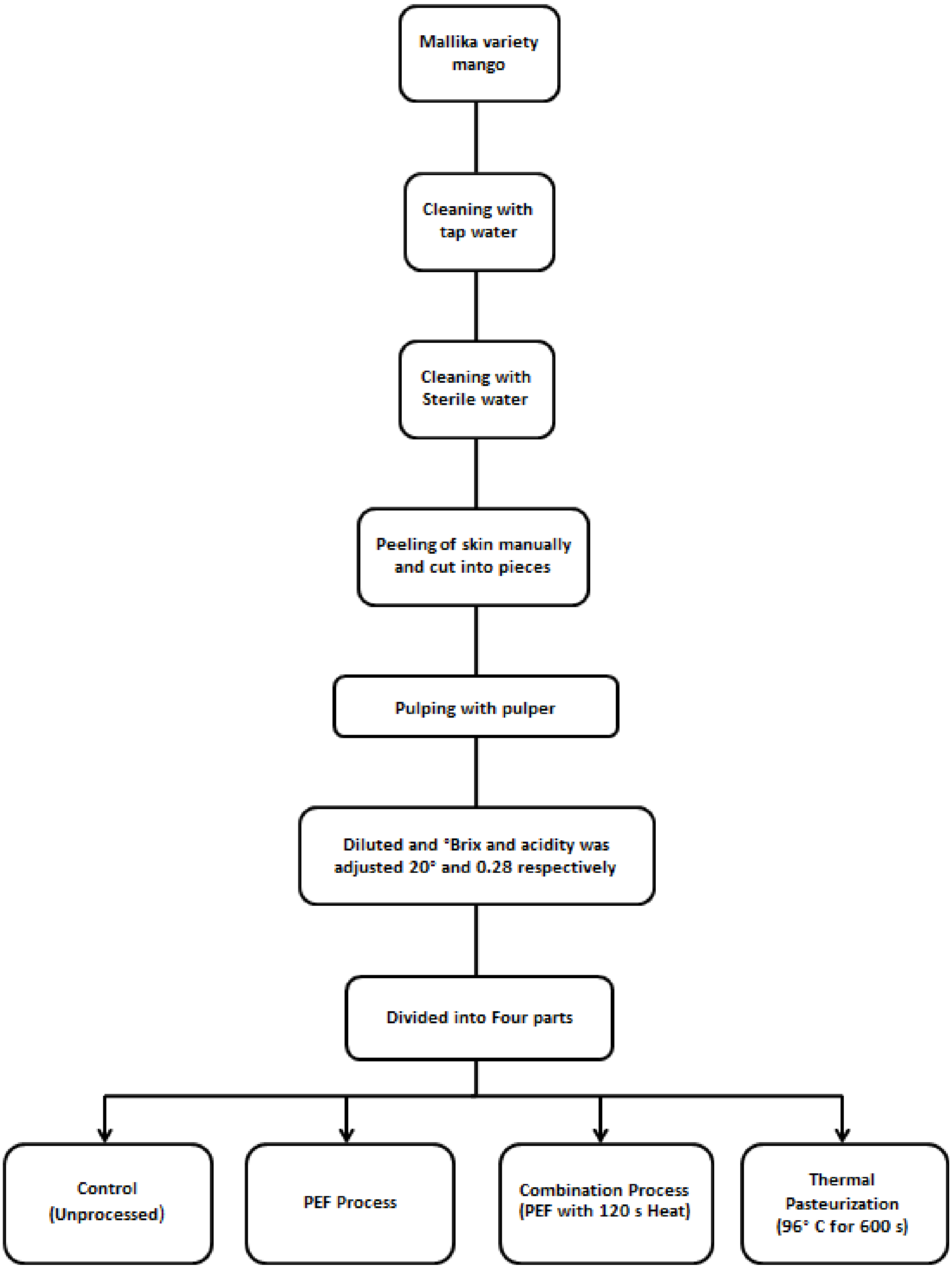

Fig. 1. Preparation and processing of mango nectar

Table 1. Optimized PEF processing parameters

Parameters	**Units**	**Values**	**Parameters**	**Units**	**Values**
In-put Parameters			Out-put Parameters		
Output Voltage	[%]	60	Flow rate	[ltr/hr]	41.2
Pulse width	[µs]	24	Pulse Field Strength	[kV/Cm]	38.0
Frequency	[Hz]	120	Energy	[KJ/ltr]	219.3
Flow rate	[ltr/hr]	45.0	Frequency	[Hz]	108.0
Electrode Gap	[mm]	10	Load Resistance	[ohm Ω]	113

(Source: Kumar et al., 2014)

Thermal pasteurization

The sample (T_4) was subjected to thermal treatment at 96 °C for 600 seconds (with a P- value of 8.03). Mango nectar pouches were subjected to pasteurization (thermal treatment) using steam jacketed kettle. For heat penetration studies, pouches were fixed with thermocouple glands through which copper-constantan thermocouples were placed at the geometrical centre of the steam jacketed kettle. A reference thermocouple was also placed to monitor the temperature of the steam jacketed kettle. Thermocouple outputs were connected to a data logger (Model: CTF 9004, M/s. Ellab, Denmark). The temperature of the juice and steam jacketed kettle was measured from the thermo-electro-motive-force at regular intervals of 60 seconds. After the completion of treatment, the baskets containing the pouches were removed and placed inside the cooling tank to bring down the temperature to 25-30 °C. The pasteurized (thermal treated) samples were used further analysis.

Analytical methods

Proximate and physico-chemical analysis

The samples (T_1, T_2, T_3 and T_4) were analysed for its proximate and physico-chemical properties. The proximate composition of the samples such as moisture, protein, fat, total ash, crude fibre and sugars were determined by the procedure reported by Ranganna (1986). The samples were also analysed for its total soluble solids, pH, total titrable acidity, ascorbic acid and the total carotenoid content using the methods suggested by Kumar et al. (2013b). The colour of the treated and the untreated samples were measured using Hunter colour meter (Mini scan XE plus, model 45/0-S Hunter laboratory Inc, Baton). Measurements were carried out at 10° observations, D65 illuminant source and instrument was calibrated using standard black and white tile provided by manufacturer. The colour values were expressed in CIE scale. Where L^* refers to lightness, a^* refers to redness, $-a^*$ refers to greenness, b^* refers to yellowness and '-b' refers to blueness.

Rheological measurements

The rheological measurements were carried out using MCR100 controlled stress rheometer (Paar Physica, Anton Paar, Gmbh, Germany) equipped with coaxial cylinders (CC 27) and the radii ratio of coaxial cylinders was 1.08477. The rheometer was equipped with an electric temperature controlled peltier system (TEZ-15P-C) to control the experimental temperature and to maintain constant temperature, a circulating water bath was used (Viscotherm VT-2). The rheological parameter, shear stress (Pa) was measured by increasing the shear rate linearly up to a maximum of $750 s^{-1}$ for duration of 10 minutes. A total of 30 shear stress-shear rate data points were collected and analyzed using universal software US200. The rheological measurements were carried out for fresh treated samples at different temperatures, ranging from 10 °C to 70 °C, in triplicates.

Rheological equations

The rheological data from the experiments were fitted to an existing rheological Herschel-Bulkley model. Various authors also used this model for evaluating rheological behaviour of mango pulp (Bhattacharya et al., 1998; Bhattacharya, 1999; Ahmed et al., 2005).

$$\text{Herschel-Bulkley model: } \tau = \tau_0 + k\,(\gamma)^n \quad (1)$$

where τ is shear stress (Pa), τ_0 is yield stress (Pa), k is consistency coefficient (Pa s^n), γ is shear rate (s^{-1}) and n is the flow behaviour index (-).

The Arrhenius equation used to describe temperature dependency of consistency coefficient of mango nectar was

$$\text{Arrhenius equation: } k = k_0\,\mathrm{Exp}(E_a/RT) \quad (2)$$

where k is the consistency coefficient (Pa s^n), k_0 is pre-exponential coefficient/frequency factor (Pa s^n), E_a is the flow activation energy (J/mol), R is gas constant (J/mol K) and T is the temperature (K).

The combined equation relating to shear stress with temperature and shear rate was evaluated by following equation

$$\text{Combined equation: } \tau = k_T\,\mathrm{Exp}(E_a/RT)\,(\gamma)^{n^*} \quad (3)$$

where τ is the shear stress (Pa), k_T is the pre-exponential constant, E_a is the flow activation energy (J/mol), R is gas constant (J/mol K), T is the temperature (K), γ is the shear rate (s^{-1}) and n^* is a constant (-) (Harper and Sahgiri, 1965).

Statistical analysis

All the experiments were performed in triplicate and the analysis of variance (ANOVA) was carried out for the experimental values to find out the significant difference (at 5% significant level) using statistical software (Systat 12.0).

Results and discussion

Physico-chemical properties of mango nectar

The control (untreated) (T1) and treated (T2, T3 and T4) mango nectar were analysed for its proximate and physico-chemical properties and the estimated values were presented in Table 2. The moisture, fat, protein, ash and crude fibre content of the treated samples were observed to be differing negligibly from the control sample. Significant differences were observed in parameters, such as pH, acidity, colour values (L*. a*, b*), ascorbic acid and total carotene content, in control and treated samples. The Ascorbic acid content was observed to be highly decreased in samples treated by pasteurisation (T_4- 5.172mg/100g) and Combination treatment (T_3-5.182mg/100g), when compared to the sample treated by PEF (T_2- 8.241mg/100g) treatment, because of its liability to temperature. The Carotene content of the samples was also observed to have the similar trend as that of the ascorbic acid. The carotene content was the least in combined (PEF + Pasteurization) processed sample (13.2±0.058mg/100g). The color values (L*, a* and b*) of the PEF processed sample was similar to that of the control untreated sample with a negligible difference. The color values of the samples T3 and T4, was found to be decreased when compared to both T1 and T2 samples.

Flow behaviour

Fig. 2 shows the relation between the shear stress - shear rate of different processing conditions such as fresh (T1), PEF processed (T2), PEF + pasteurized sample (T3) and pasteurized sample (T4) of mango nectar at constant temperature of 25 °C whereas Fig. 3 shows the shear stress - shear rate curves of PEF processed (T2) of mango nectar at different temperatures ranging from 10 to 70 °C. The rheograms showed that all the samples followed non-Newtonian pseudo-plastic (shear thinning) behaviour with an existence of yield stress. The extent of shear thinning was highest for T3 (PEF + pasteurisation) sample followed by PEF treated (T2) sample and it was lowest for pasteurized sample (T4). This indicated that PEF treatment remarkably affects the internal structure of nectar sample compared to that of other processing conditions. Similar type of shear thinning behaviour were observed in different processing conditions of different fruit pulps such as tomato juice with HP homogenisation (Augusto et al., 2012a; 2012b), siriguela (*Spondias purpurea* L.) pulp (Augusto et al., 2012c), HP treated mango pulp (Ahmed et al., 2005), enzyme treated mango pulp (Bhattacharya et al., 1998), enzyme treated papaya puree (Ahmed and Ramaswamy, 2004), carrot puree (Hecke et al., 2012), watermelon juice (Sogi et al., 2010), enzyme treated goldenberry (*Physalis peruviana*) juice. Several researchers reported that the mango pulp behaved like shear thinning fluid with existence of yield stress and obeyed the Hershel-Bulkley model (Bhattacharya et al., 1998; Bhattacharya, 1999; Ahmed et al., 2005) The rheograms showed that existence of similar behaviour and Hershel-Bulkley model was fitted for all the fresh and treated samples with appreciable correlation coefficient and significance level ($r > 0.97$, $p < 0.01$). The parameters of the model such as yield stress (τ_0), consistency coefficient (k) and flow behaviour index (n) were as reported in Table 3.

Table 2. Physico-chemical properties of mango nectar

Parameter	T1	T2	T3	T4
Moisture (%)	73.48 ± 0.07^{A}	73.00 ± 0.001 ^{A}	73.45 ± 0.001 ^{A}	74.00 ± 0.018 ^{A}
Ash (%)	0.767 ± 0.012 ^{A}	0.756± 0.005 ^{A}	0.757 ± 0.02 ^{A}	0.78 ± 0.02 ^{A}
Protein (%)	0.712 ± 0.003^{BC}	0.709 ± 0.002^{C}	0.722 ± 0.01^{AB}	0.726 ± 0.003^{A}
Fat (%)	0.091 ± 0.001^{A}	0.091 ± 0.014^{A}	0.099 ± 0.001^{A}	0.11 ± 0.001^{A}
Crude fibre (%)	0.351 ± 0.001^{B}	0.348 ± 0.00^{C}	0.354 ± 0.001^{A}	0.35 ± 0.001^{B}
Total soluble solid content (°brix)	20.00 ± 0.00^{A}	20.00 ± 0.00^{A}	20.00 ± 0.00^{A}	20.00 ± 0.00^{A}
Reducing sugar (%)	6.9 ± 0.08^{A}	6.6 ± 0.04^{C}	6.7 ± 0.072^{BC}	6.8 ± 0.1^{AB}
Total sugar (%)	17.8 ± 0.000^{A}	17.7 ± 0.000^{A}	17.5 ± 0.058^{AB}	17.3 ± 0.000^{B}
pH	4.36 ± 0.005^{B}	4.39 ± 0.010^{A}	4.30 ± 0.010^{D}	4.32 ± 0.020^{C}
Acidity (% citric acid)	0.22 ± 0.006^{B}	0.23 ± 0.006^{AB}	0.23 ± 0.006^{AB}	0.24 ± 0.006^{A}
Ascorbic acid (mg/100g)	9.2 ± 0.000^{A}	8.241 ± 0.001^{B}	5.182 ± 0.001^{C}	5.172 ± 0.000^{C}
Carotene (mg/100g)	21.6 ± 0.058^{A}	21.0 ± 0.000^{B}	13.2 ± 0.058^{D}	16.4 ± 0.058^{C}
L*	28.63 ±0.006^{A}	28.53 ± 0.006^{B}	25.44 ± 0.006^{D}	25.56 ± 0.006^{C}
a*	0.02 ± 0.006^{A}	0.14 ± 0.006^{A}	0.06 ± 0.010^{A}	0.20 ± 0.00^{A}
b*	15.58 ± 0.000^{C}	14.62 ± 0.006^{D}	17.34 ± 0.000^{A}	16.12 ± 0.012^{B}

Mean ± SD (n=3),
Different capital letter superscripts shown in a row represents the significant different at $p \leq 0.05$

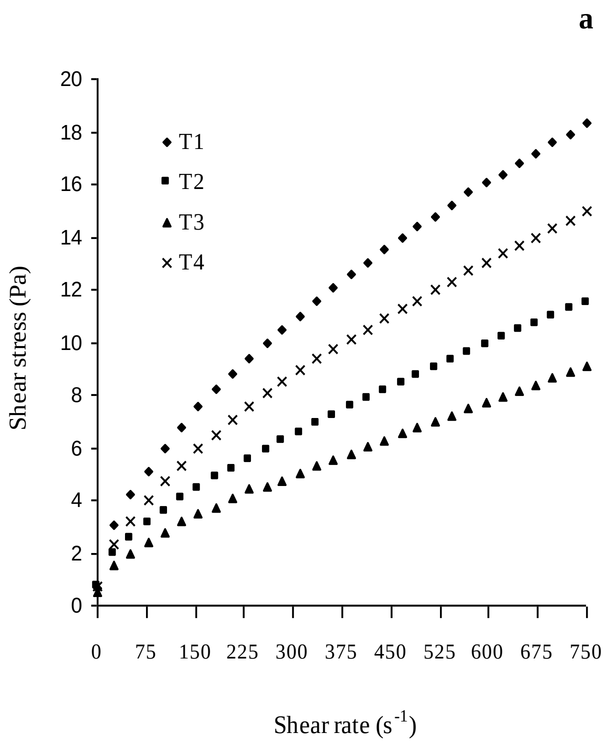

Fig. 2. Rheogram of mango nectar at different processing condition at constant temperature of 25 °C

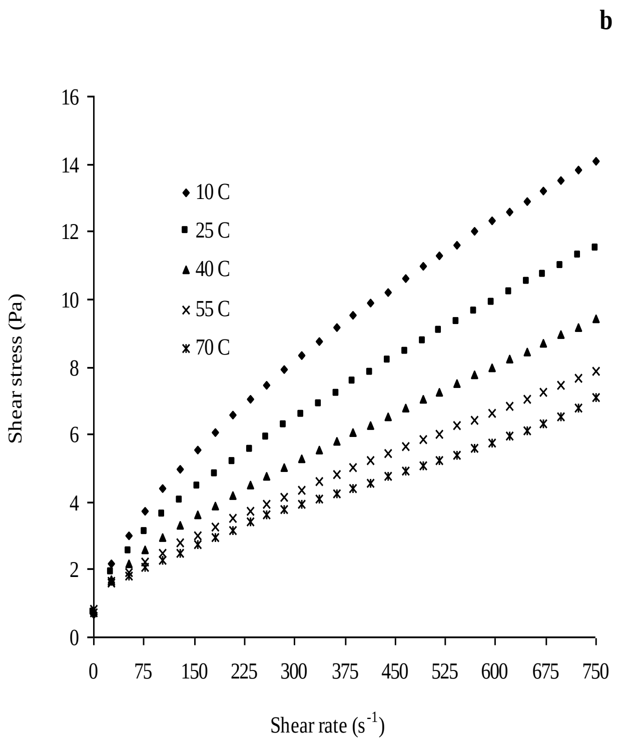

Fig. 3. Rheogram of mango nectar at different temperatures of pulsed electric field treatment (T_2)

Table 3. Rheological parameters of Hershel-Bulkley model of mango nectar at different processing conditions

Temperature (°C)	Yield Stress (Pa)				Consistency coefficient (k) (Pa s^n)				Flow behaviour index (n) (-)			
	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4
10	0.726^{aA}	0.649^{aA}	0.504^{aA}	0.689^{aA}	0.654^{aA}	0.191^{aB}	0.132^{aC}	0.333^{aD}	0.548^{aA}	0.644^{aBC}	0.670^{aB}	0.606^{aAC}
25	0.710^{aAB}	0.715^{aAB}	0.533^{aA}	0.761^{abB}	0.447^{bA}	0.137^{bB}	0.102^{bC}	0.219^{bD}	0.571^{aA}	0.658^{aB}	0.661^{aB}	0.634^{aB}
40	0.647^{aA}	0.761^{aAB}	0.663^{aA}	0.896^{bcB}	0.429^{cA}	0.094^{cBC}	0.089^{bB}	0.127^{cC}	0.527^{abA}	0.678^{aB}	0.670^{aB}	0.680^{bB}
55	0.613^{aA}	0.767^{aAB}	0.666^{aAB}	0.853^{abcB}	0.402^{dA}	0.079^{cBC}	0.062^{cB}	0.095^{dC}	0.513^{abA}	0.675^{aB}	0.690^{abB}	0.726^{aB}
70	0.640^{aA}	0.796^{aABC}	0.657^{aAB}	0.974^{cC}	0.391^{dA}	0.057^{dB}	0.036^{dC}	0.073^{eB}	0.485^{bA}	0.691^{aB}	0.750^{bB}	0.707^{bB}

Mean (n=3),
Different small letter superscripts shown in a column represents the significant different at $p \leq 0.05$,
Different capital letter superscripts shown in a row represents the significant different at $p \leq 0.05$

Yield stress

The yield stress is defined as the minimum stress required initiating the flow, which is very important in engineering point of view and it is related to internal structure of material, which breaks at yield stress. The material behaves like elastic solid below the yield stress and deforms elastically with applied stress. When it is exposed to stress, above yield stress it behaves like viscous liquid and starts flowing with applied stress. The presence of yield stress is typical characteristics of material of multiphase system which contains different components. In the case of fruit pulp and juices multiphase system consists of dispersion of insoluble components such as cell wall material in water solution (serum) containing minerals, sugars, protein and other polysaccharides. The yield stress of mango nectar varies from 0.504 to 0.974 Pa and there is no significant ($p > 0.05$) change in magnitude of yield stress of samples T_1, T_2 and T_3. Whereas in sample T_4 it increased significantly ($p < 0.05$) with increase in temperature of rheological analysis (Table 3). This indicated that the processing conditions and temperature were not affecting the yield stress values in T_2 and T_3 samples. Xiang et al. (2011) reported that the Herschel-Bulkley model was found to give the best fitting parameters for the pulsed electric field treated skimmed milk with yield stress of approximately 40 x 10^{-3} Pa and also observed there is no significant ($p > 0.05$) change in yield stress with increase in electric field strength. Ahmed et al. (2005) observed that the yield stress of mango pulp of *Chousa* variety and *Alphanso* variety varies from 1.09 to 6.14 Pa and from 3.81 to 6.24 Pa respectively. Bhattacharya (1999) found that the yield stress values of mango pulp were in the range 2.7 to 3.6 Pa. Bhattacharya et al. (1998) noticed that both raw and enzyme treated mango pulp behaved like pseudoplastic liquid with yield stress. The yield stress values vary from 3.5 to 3.9 Pa for untreated and from 2.9 to 4.9 Pa for enzyme treated mango pulp. The yield stress of tomato juice varied from 0.93 to 0.48 Pa with increase in temperature and it was found that temperature had a negative effect on yield stress. Whereas the yield stress of tomato juice increased significantly with homogenisation pressure during HP homogenisation (Augusto et al., 2012a; 2012b). The yield stress of siriguela pulp decreased from 13.26 to 1.37 Pa with increase in temperature of pulp from 20 to 80 °C (Augusto et al., 2012c). The yield stress was increased with increase in total soluble solid content and decreased with temperature of blue berry puree and goldenberry juice (Nindo et al., 2007; Sharoba et al., 2011). The yield stress of a material is dependent on particle size distribution, the amount of small particles at specific surface area and their interaction due to mechanical friction and chemical interactions (Servais et al., 2002).

Consistency coefficient

The consistency coefficient (k) is defined as the apparent viscosity of fluid at the shear rate of $1s^{-1}$.The consistency coefficient of mango nectar of different processing conditions at different temperatures was reported in Table 4. In the present study the k value was markedly affected by processing conditions as well as temperature. The consistency coefficient value was high for unprocessed samples (T1) whereas it was lower for combined processed samples (T3) at all temperature conditions. The pasteurised (T4) sample showed minimum change when compared with that of the PEF treated (T2) and combination processed (T3) samples. Mango nectar is a shear thinning liquid which contains fibrous material which includes pectin and other fibre materials and with the continuous phase of water. The rheological properties of mango nectar depends on amount of suspended matter such as fibres and dissolved soluble solids such as sugars, organic acids etc (Assis et al., 2005; Nindo et al., 2005; Manjuantha et al., 2012). The amount of water present in the mango nectar in untreated samples was in bound form with these substances which led to high consistency coefficient (Manjuantha et al., 2012). As PEF treatment leads to destruction of cell wall and degradation of fibrous material, it enhances the free water content, leading to low consistency coefficient. The increase in temperature increases the mobility of particles and their inter-particle distance, which lowers the consistency coefficient (Manjuantha et al., 2012; Vandresen et al., 2009). Our results were in accordance with those of Bi et al. (2013) who observed that the consistency index (k) decreased significantly in PEF treated apple juice. The k value for mango nectar in the present study was in accordance with the k values reported for other fruit and vegetable pulps and juices. The consistency coefficient of mango pulp, decreased with increase in enzyme concentration irrespective of incubation time and temperature, whereas incubation temperature had a curvilinear effect and the effect of incubation time was insignificant (Bhattacharya and Rastogi, 1998). The k value for *Chousa* mango pulp increased significantly with HP treatment whereas it decreased with HP treatment in case of *Alphanso* mango pulp (Ahmed et al., 2005). According to Augusto et al. (2012b), the k value of tomato juice increased with HP homogenisation pressure, due to increase in the surface area of particles with more mechanical friction and chemical interactions. The k value of apple, cranberry and blueberry juice and nectars was markedly affected by ultrasound treatment (Simunek et al., 2013). The consistency coefficient of siriguela pulp, guava puree, sumac concentrate, carob pekmez, sorghum pekmez, pummelo juice concentrate and sugar substitute syrups were found to significantly decrease with increase in temperature and followed the Arrhenius equation model (Augusto et al., 2012c; Sanchen et al., 2009; Ozkanli and Tekin, 2008; Akbulut and Ozcan, 2008; Chin et al., 2009; Chetana et al., 2004). The consistency coefficient of goldenberry (*Physalis peruviana*) juice increased with increase in total soluble solid content and decreased with increase in temperature as well as enzyme treatment (Sharoba and Ramadan, 2011). The consistency coefficient of carrot puree was reported to increase with addition of potato flakes and to decrease with increase in temperature. The power law relationship between the consistency coefficient and the amount of added potato flakes was also reported by Hecke et al. (2012). Sogi et al. (2010) observed that k value of watermelon juice depends on particle size, total soluble solid content and temperature and it also increased with increase in particle size and concentration, but, decreased with increase in temperature. Ahmed and Ramaswamy (2004) noticed that the k value of papaya puree was significantly affected by temperature, total soluble solid content and pH. The effect of α-amylase enzyme on k value of papaya puree also found to be dependent on pH of puree. Thereby it is observed that the consistency coefficient depends on several factors such as temperature, concentration, particle size, processing conditions etc.

Flow behaviour index

The flow behaviour index is referred as extent of non-Newtonian behaviour, if it is <1, it leads to shear thinning (pseudo plasticity) or if >1 referred to shear thickening (dilatant) behaviour. The flow behaviour index of mango nectar varies from 0.485 to 0.750 which indicated that it behaved like shear thinning (pseudoplastic) fluid and was confirmed by other reports available in literature (Bhattacharya and Rastogi, 1998; Ahmed et al., 2005). The flow behaviour index was significantly ($p < 0.05$) affected by processing conditions as compared to that of untreated samples, whereas there was no significant ($p > 0.05$) change observed. This indicated that processing conditions had marked effect on structure of mango nectar when compared to that of fresh sample. Bi et al. (2013) studied the flow behaviour of pulsed electric field treated apple juice and he reported that the flow behaviour index (n) increased with the increase in electric field strength. The magnitude of flow behaviour index was in accordance to that of other liquid foods such as mango pulp (Bhattacharya and Rastogi, 1998), papaya puree (Ahmed and Ramaswamy, 2004), water melon juice (Sogi et al., 2010), carrot puree (Hecke et al., 2012), frozen concentrated orange juice (Tavares et al., 2007), goldenberry juice (Sharoba and Ramadan, 2011), butia pulp (Haminiuk et al., 2006), carrot juices (Vandresen et al., 2009), tomato juice (Augusto et al., 2012a), pummelo juice concentrate (Chin et al., 2009), peach, papaya and mango purees (Guerrero and Alzamora, 1998). Ahmed and Ramaswamy (2004) reported that α-amylase concentration, pH, temperature, total soluble solid content had its effect on flow behaviour index of papaya puree and observed that it increased with processing temperature, TSS, and addition of enzyme. The flow behaviour index was observed to increase at low pH values. The flow behaviour index (n) of enzyme treated mango pulp showed curvilinear effect for enzyme concentration, incubation time and temperature. Bhattacharya and Rastogi (1998) reported that an increase in incubation time or increase in the enzyme concentration, results in a pulp with Newtonian behaviour, whereas the influence of incubation temperature on the flow behaviour is found to be of complex in nature. The effect of particle size and temperature on flow behaviour index (n) of watermelon juice at 40 °Brix, was in such a way that flow behaviour index, increased with large particle size and decreased with small particle size, marginally (Sogi et al., 2010). The flow behaviour index of sugar substitute syrups such as sorbitol, polydextrose and maltodextrin-polydextrose combination decreased with increase in solid concentration and increased with increase in temperature (Chetana et al., 2004). The flow behaviour index of mango puree increased with glucose addition and temperature marginally, while in case of papaya small and opposite trend was observed; whereas there was no specific trend observed for *kesar* mango juice (Guerrero and Alzamora, 1998; Dak et al., 2007). There was no specific trend reported in flow behaviour index of pomelo juice at different temperatures and concentration (Keshani et al., 2012). Ozkanli and Tekin (2008) reported that the flow behaviour index increased with temperature and decreased with total soluble solid content in case of sumac concentrates. Chin et al. (2009) reported that the flow behaviour index of pummelo juice increased with temperature and decreased with concentration. The flow behaviour index of fluid food mainly depends on nature material, solid content, temperature, particle size, structure of the food material and processing conditions.

Effect of temperature

The temperature had a major effect on the consistency coefficient for non-Newtonian fluids similar to the effect on the viscosity of Newtonian fluids. The increase in temperature of fluid leads to increase in mobility of the molecules and increase in intermolecular spacing, which decreases the flow resistance. The consistency coefficient of mango nectar decreased with increase in temperature. The effect of temperature on the consistency coefficient of mango nectar at different processing conditions was described using the Arrhenius equation (Eq. 2). The parameters of Arrhenius equation was estimated using method of least square approximation and the correlation coefficient is greater than 0.89. The parameters of Arrhenius equation such frequency factor and flow activation energy of mango nectars at different processing conditions was reported in Table 5. The flow activation energy (E_a) was defined as minimum energy required which overcomes the energy barrier before the elementary flow can occur. The viscous flow occurs as a sequence of events where the particles shift in the direction of shear force action, from one equilibrium position to another position by overcoming a potential energy barrier. The barrier height determines the flow activation energy of viscous flow. The flow activation energy was in the range 7.266 to 21.637 kJ/mol. Higher activation energy value indicates a greater influence of temperature on the consistency coefficient, i.e. more rapid change in consistency coefficient with temperature. The magnitude of energy of activation for viscous flow significantly ($p < 0.05$) affected by processing conditions. The activation energy for fresh sample is low compared to that of processed samples; this indicated that processed samples consistency coefficient is sensitive to temperature i.e. more rapid change will occur with temperature. When temperature increased, the thermal energy of the molecules and intermolecular spacing increased significantly, which lead to decrease in the magnitude of consistency coefficient (Rao, 2007). The magnitude of flow activation energy of Newtonian fluids increased significantly with increase in total soluble solid content (Krokida et al., 2001). The magnitude of flow activation energy was comparable to that of other fluid foods such as white guava puree (Sanchen et al., 2009), goldeberry juice (Sharoba and Ramadan, 2011), siriguela pulp (Augusto et al., 2012c), Tender coconut water (Manjunatha and Raju, 2013), peach, papaya and mango purees (Guerrero and Alzamora, 1998), pomelo juice (Keshani et al., 2012), pomegranate juice (Kaya and Sozer, 2005). Sharoba and Ramadan (2011) observed that the activation energy for viscous flow was affected by enzyme treatment of goldenberry juice. Shamsudin et al. (2013) also stated that the flow activation energy of pineapple juice was affected by processing parameters such ultraviolet irradiation and thermal pasteurisation compared to that of fresh juice. Addition of dehydrated potato flakes was found not to affect the flow activation energy of carrot puree by Hecke et al. (2012). The flow activation energy of concentrated orange juice was increased marginally with shear rate and a logarithmic model was reported for variation of flow activation energy with shear rate (Falguera and Ibarz, 2010).

Combined effect of temperature and shear rate

The combined effect of temperature and shear rate on shear stress of mango nectar is very important for the evaluation of process design and optimisation, which can be evaluated using the Eq. 3 (Harper and Sahgiri, 1965; Chin et al., 2009). The parameters of the model and correlation coefficient were reported in Table 4 and it was observed that the correlation coefficient (r) was greater than 0.99. The parameter $b=E_a/R$ was significantly ($p < 0.05$) affected by processing conditions compared to that of untreated mango nectar and the flow behaviour index (n*) was also significantly ($p < 0.05$) affected by processing conditions. It showed that shear stress of mango nectar was influenced by shear rate and temperature and it was in compliance with Harper and Sahrigi equation (Harper and Sahgiri, 1965).

Table 4. Parameters of Arrhenius equation relating to temperature and consistency coefficient of pulse electric field (PEF) treated, pasteurised and their combination of mango nectar

Treatment	Arrhenius equation: $k=k_0$ Exp (E_a/RT)		r
	Pre-exponential coefficient (K_0) (Pa s^n)	Flow activation energy (E_a) (kJ/mol)	
T_1	2.767 x 10^{-2a} ± 2.802 x 10^{-3}	7.266^a ± 0.245	0.8930
T_2	2.051 x 10^{-4b} ± 4.356 x 10^{-5}	16.175^b ± 0.598	0.9943
T_3	4.018 x 10^{-4b} ± 1.713 x 10^{-4}	13.849^c ± 1.036	0.9693
T_4	3.429 x 10^{-5b} ± 5.739 x 10^{-6}	21.637^d ± 0.354	0.9963

Mean ± SD (n=3),
Different superscripts shown in a column represents the significant difference at p ≤ 0.05

Table 5. Combined effect of temperature and shear rate on shear stress of mango nectar at different treatments of pulsed electric field and thermal pasteurisation

Treatments	Combined equation: $\tau = K_T$ Exp(E_a/RT) $(\gamma)^n$			r
	K_T (Pa s^n)	b=E_a/R (K)	n (-)	
T_1	5.462 x 10^{-3a} ± 2.639 x 10^{-4}	1403.65^a ± 6.15	0.5116^a ± 0.0028	0.9946
T_2	3.055 x 10^{-3b}± 5.213 x 10^{-4}	1323.73^{bc} ± 26.82	0.5874^b ± 0.0021	0.9974
T_3	1.823 x 10^{-3c}± 2.465 x 10^{-4}	1297.83^b ± 3.95	0.6265^c ± 0.0010	0.9941
T_4	3.697 x 10^{-3b}± 2.803 x 10^{-5}	1341.53^c ± 1.09	0.5769^d ± 0.0003	0.9983

Mean ± S D (n=3),
Different superscripts shown in a column represents the significant different at p ≤ 0.05

Conclusions

The rheological behaviour of pulsed electric field (PEF) processed and thermally pasteurised mango nectar (*Mangifera indica*) was evaluated. The investigation showed that pulsed electric field (PEF) processed and thermally pasteurised mango nectar behaved like a pseudo plastic (shear thinning) fluid with yield stress and obeyed Herschel-Bulkley model ($0.9780 < r < 0.9999$, $p \leq 0.01$). The results indicated that the consistency coefficient (k) of mango nectar was significantly ($p < 0.05$) affected by temperature and other processing conditions, whereas there was no significant ($p > 0.05$) change observed for yield stress (τ_0) of mango nectar. The flow behaviour index (n) was significantly ($p < 0.05$) affected by processing condition as compared to that of untreated sample. The effect of temperature on consistency coefficient (k) of mango nectar was followed by Arrhenius equation ($r > 0.893$, $p < 0.05$) and flow activation energy (E_a) was significantly ($p < 0.05$) affected by processing conditions. The results indicated that the pulsed electric field (PEF) and thermal processing condition affected the rheological properties of mango nectar. The combined equation relating to shear stress (τ) with temperature and shear rate of mango nectar was established with high correlation coefficient ($r > 0.99$, $p < 0.05$). The results indicated that the pulsed electric field treatment and thermal pasteurisation significantly affected the rheological properties of mango nectar.

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