Thermophysical properties of enzyme clarified Lime (*Citrus aurantifolia* L.) juice at different moisture contents

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Abstract Thermophysical properties of enzyme clarified lime (*Citrus aurantifolia* L.) juice were evaluated at different moisture contents ranging from 30.37 % to 89.30 % (wet basis) corresponding to a water activity range of 0.835 to 0.979. The thermophysical properties evaluated were density, Newtonian viscosity, thermal conductivity, specific heat and thermal diffusivity. The investigation showed that density and Newtonian viscosity of enzyme clarified lime juice decreased significantly ($p < 0.05$) with increase in moisture content and water activity, whereas thermal conductivity and specific heat increased significantly ($p < 0.05$) with increase in moisture content and water activity and the thermal diffusivity increased marginally. Empirical mathematical models were established relating to thermophysical properties of enzyme clarified lime juice with moisture content/water activity employing regression analysis by the method of least square approximation. Results indicated the existence of strong correlation between thermophysical properties and moisture content/water activity of enzyme clarified lime juice, a significant ($p < 0.0001$) negative correlation between physical and thermal properties was observed.

Keywords Thermophysical properties · Lime juice · *Citrus aurantifolia* L. · Density · Viscosity · Specific heat · Thermal conductivity · Thermal diffusivity

Introduction

The modelling and designing of equipment for fluid flow and heat transfer operations involved in juice processing at

different concentrations requires data on several engineering properties. One of the main limitations in process design, control and optimisation in food processing is the scarcity of information on the thermophysical properties of the material. The knowledge of both theoretical and empirical relationships on thermophysical properties of food are highly essential in processing of food and designing of the equipments such as evaporators, pumps, heat exchangers, filters, mixer, driers etc to obtain optimal flow properties and quality. When considering heating or cooling of foods, some of the physical properties such as density and viscosity must be considered because of their intrinsic relationship with the thermal properties. A group of thermal and related physical properties known as thermophysical properties provide a powerful tool for design and prediction of heat transfer operations during handling, processing, canning and distribution of foods. The variation in composition of food generally affects the thermophysical properties such as density, viscosity, specific heat, thermal conductivity and thermal diffusivity. Thermophysical properties have been modelled as function of major food components such as water, protein, fat and carbohydrate as well as temperature. The values estimated by these empirical equations show significant discrepancies due to the complex physicochemical structure of food products. The variation in thermal properties of Roselle (*Hibiscus sabdariffa* L.) and Guna (*Citrullus colocynthis*) seeds at different moisture and temperatures were investigated (Aviara et al. 2008; Bamgboye and Adejumo 2010). The thermophysical properties such as density, heat capacity and thermal conductivity of mango pulp were determined at different moisture content and at wide range of temperatures. Several mathematical models were established relating to thermophysical properties with moisture content and temperature using multi variant analysis (Bon et al 2010). The influence of water, fat contents and temperature on thermophysical properties of milk was reported

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(Minim et al. 2002). The mathematical models that represent the variation of thermophysical properties based on different constituents of food are very useful for implementations of computer-aided process automation and equipment design.

Fruit juices and juice concentrates have a major share in the commercialisation of processed juice products. The fruit juice concentrates have higher stability because of low water activity levels and they can be used as basic ingredients in many products such as the fruit syrup, squash, Ready to serve (RTS), carbonated and non-carbonated beverages (Shamsudin et al. 2007a, b). The liquid products are easier to process in terms of cooling, heating, freezing, evaporation, etc., than solid food. In determining quality of fruit juices the mouth feel which is defined as the experience derived from the sensation of skin of the mouth after consumption of beverage relates to physical properties of the sample material such as viscosity, density etc., as the complex mouth feel function is the physical interaction of the tongue and palate. The physical, rheological and thermal properties of fruit juices are gaining more importance as thermophysical characteristics of fruit juices had been evaluated and quantified (Ingate and Christensen 2007).

Water activity of food is defined as the ratio of the equilibrium vapour pressure exerted by the food to the vapour pressure of pure water at the same temperature and which indicates the amount of water available for microbial growth. It is the escaping tendency of water fugacity in the system by the tendency of pure water. The fugacity of food systems is closely approximated by vapour pressure. The water activity is a measure of the energy state of the water in the system and it is measure of free, unbound and available water in the food system. There are several factors that control water activity in a food system, the colligative effect of dissolved species (salts, sugars and acids) interact with water through dipole–dipole, ionic and hydrogen bonds. Influence of water activity may induce profound changes in the quality and stability of a food products and it is an important requirement for packaging of food material. Water activity is a critical factor that determines the shelf life of the food. The water activity of food is important, rather than total water content for deciding the quality and stability of food (Fennema 2005)

The production of Citrus fruits has been increasing mainly due to the extended cultivation of citrus fruits in countries like India, USA, Brazil, Spain, Iran, etc. because of the conducive temperate and dry climatic conditions. The genus Citrus includes several important fruits such as limes, lemons, oranges, mandarins and grapes. Citrus fruits are since classified as acid fruits; their soluble solids are composed of mainly organic acids and sugars. The acidity of citrus fruits is primarily due to citric and malic acids and the fruits also contain complex mixture of flavonoid compounds, which includes flavanone and flavones. Citrus fruits contain a host of active phytochemicals and there are more than hundred

bioactive compounds in citrus fruits. Citrus fruits are among the most prominent cancer preventing agents. Flavonoids play a wide range of biological activities, such as inhibition of key enzymes in mitochondrial respiration, protection against coronary heart diseases and are also anti-inflammatory, antioxidative, anticytotoxic, antitumor and antimicrobial in terms of functionality (Harborne and Williams 2000).

Lime (*Citrus aurantifolia* L) is a highly poly-embryonic species with greenish-yellow colour, smooth surface, thin skinned at maturity and has highly acidic juice. Lime juice is used for preparation of several beverages such as, ready to serve (RTS), carbonated and non-carbonated, squash, cordials and other lime juice based drinks with sugar and flavouring agents. Lime juice is concentrated and stored in frozen conditions mainly for use as the base material in the preparation of lemonade (A carbonated beverage which contains 11° Brix and sugar-acid ratio in the range of 15:1 and peel oil content 0.003 to 0.004 %). Lime cordial is prepared using clarified lime juice to an extent of 25 %, TSS 30° Brix, acidity not more than 3.5 % and preservatives had a refreshing tartness and highly distinctive flavour. Lime-Barley water is prepared using lime squash and addition of Barley starch. Enzyme clarification is one of most important techniques to increase the qualitative and quantitative quality characteristics of juice for preparation of novel products from lime. The enzyme hydrolysis of lemon juice was carried out using commercial pectinase enzyme and the reduction in particle size due to enzyme had been reported (Carvalho et al. 2006). Production of these beverage products in large quantity requires several equipments for processing and packing. The thermophysical properties of lime juice are very important for process design and optimisation for development of novel quality lime juice products. Thermal and physical properties of some tropical fruits and their juices in Nigeria were reported (Ikegwu and Ekwu 2009). Alvarado (1991) reported specific heat of dehydrated pulps and fruits at different moisture levels. There is a dire need of information on thermophysical properties of lime juice and its concentrate, which could be useful for commercial scale production of lime juice and their products. The present investigation was carried out to study the thermo-physical properties of enzyme clarified lime juice at different moisture and water activity levels and also mathematical modelling of these properties.

Materials and methods

Raw material

Fresh Lime (*Citrus aurantifolia* L.) fruits with optimal maturity, uniform size and shape, without visible infections

were procured from local market, Mysore, India. The fruits were washed with tap water thoroughly twice and halved with sharp stainless steel knife. The juice was extracted using stainless steel hand-held juice squeezer was filtered in a stainless steel sieve. The juice was pasteurised in water bath at 80 °C for 2 min to inactivate the enzymes and cooled to room temperature with chilled water. The enzyme clarification was carried out using commercial enzyme pectinex ultra SPL (Novozyme, Denmark). The concentration of enzyme used was 0.15 % and was incubated for 150 min at 45 °C in a constant temperature water bath as described by the method (Vandhana and Das Gupta 2006). The enzyme was heat inactivated by placing in a water bath maintained at 90 °C for 2 min and cooled immediately in ice cold water. The juice was centrifuged at 15000 rpm using continuous centrifuge (CEPA, Lahr/Baden, West Germany) and the clarified lime juice was subjected to concentration by vacuum evaporation.

Juice concentration

The lime juice was concentrated by vacuum evaporation technique using laboratory rotary vacuum evaporator (Model; Laborata 4001, Heidolph, Germany) at temperature 60 °C with reduced pressure. The Lime juice was concentrated to different moisture levels and thermophysical properties of lime juice were measured.

Analytical methods

Moisture content of lime juice was measured by vacuum oven method and expressed as % wet basis. Total ash content of the juice was measured gravimetrically by drying the juice in hot air oven in a silica crucible and placed in muffle furnace at 550 °C for 16 h; the ash content was calculated by difference in weight and expressed in %. Protein content was determined by micro kjeldhal method. Crude fibre was determined as described by Ranganna (1986). Fat content of lime juice was measured by solvent extraction method using chloroform as extracting agent and solvent was evaporated in hot air oven and fat content expressed in %

Total soluble solids

Total soluble solids were determined using digital hand-held refractometer (Atago co., Ltd., Tokyo, Japan) and the total soluble solid content was expressed as ° Brix.

pH

A digital pH meter was used to measure pH of the lime juice (Cyber scan, India) at 25 °C.

Titration acidity

Acidity was determined by titration method with standard 0.01 N NaOH solution using phenolphthalein as indicator and expressed as % citric acid (Ranganna 1986).

Ascorbic acid

Ascorbic acid content of the juice was determined by titration method using 2, 6-dichloro-phenol Indo-phenol dye as indicator and expressed as mg/100 ml of juice (Ranganna 1986).

Water activity

The water activity (a_w) of lime juice at different concentration was measured using digital water activity meter at 25 °C (Aqua Lab, model 3T E, Decagon devices, USA).

Colour measurement

The tri-stimulus colour co-ordinates of clarified lime juice were measured using Hunter color meter (Mini scan XE plus, model 45/0-S Hunter laboratory Inc, Baton). Measurement was carried out at 10° observations with D65 bulb as illuminating source and expressed as L^* , a^* and b^* values in CIE scale. ' L^* ' refers to lightness, ' $-a^*$ ' refers to greenness and ' $-b^*$ ' refers to blueness.

Density

The density (ρ) of lime juice was measured at 25 °C using 25 ml pycnometer (Constenla et al. 1989), the pycnometer was previously calibrated with distilled water and expressed as kg m^{-3} by the following relation

$$\rho = \frac{m_s - m_p}{v_p} \quad (1)$$

Where, m_p is the mass of empty pycnometer (kg), m_s is the pycnometer + sample mass (kg) and v_p is the exact volume of pycnometer (m^3)

Viscosity measurement

The viscosity of lime juice was measured using MCR 100 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 is equipped with an electric temperature controlled peltier system (TEZ-15P-C) to control the experimental temperature and to maintain a constant temperature at 25 °C. A circulating water bath was used (Viscotherm VT-2, Paar Physica, Anton Paar

GmbH, Germany). The rheological parameter shear stress (Pa) was measured linearly up to shear rate of 600 s^{-1} with 10 min duration of time. Thirty data points were collected and analyzed using universal software US200 (Paar Physica, Anton Paar GmbH, Germany). The viscosity of lime juice was measured at a constant temperature. All the measurements were carried out in triplicate and fresh sample was used in each measurement. The viscosity values were obtained by experimental shear rate and shear stress data fitting with Newton's equation

$$\sigma = \eta \dot{\gamma} \quad (2)$$

where, σ is shear stress (Pa), η is coefficient of viscosity (m Pa s) and $\dot{\gamma}$ is the shear rate (s^{-1})

Thermal conductivity

The thermal conductivity of lime juice was determined using a thermal properties analyser type KD2 (Decagon Devices, USA). It was operated based on line heat source method. The measurement was carried out by placing liquid sample in 50 ml test tube and a rubber cork was inserted into the test tube. The needle of thermal conductivity meter was inserted into the sample through rubber cork and sample was kept in water bath maintained at 25°C and thermal resistivity values were obtained directly from the digital readout. The thermal conductivity was calculated from thermal resistivity values and expressed in $\text{W m}^{-1} \text{K}^{-1}$.

Specific heat

The specific heat of Lime juice was measured by the method of mixtures using Joule's calorimeter. A sample of known mass (m_s) and known temperature (T_s) was dropped into a calorimeter of known specific heat (C_v) and known vessel mass, containing a known mass of liquid (water) (m_l) and temperature (T_l). The unknown specific heat was computed from the heat balance equation. The temperature of the mixture was measured by multiple probes at different locations of the mixture using temperature monitoring system (CTF 9008, ELLAB A/S, Denmark). Temperature of the mixture was recorded at equilibrium (T_{eq}) point and specific heat of liquid was calculated by heat balance using the following equation (Mohsenin 1980; Souza et al. 2010)

$$C_s = \frac{(m_v C_v + m_l C_l)(T_{eq} - T_i)}{m_s(T_s - T_{eq})} \quad (3)$$

where, C_s , C_v and C_l are the specific heats of sample, vessel (copper) and liquid present in the vessel. m_s , m_v and m_l are the mass of sample, vessel (copper) and liquid present in the vessel, T_s and T_i are temperature of sample, initial temperature

of the liquid water (room temperature) and T_{eq} is equilibrium temperature of mixture (water and juice). The specific heat of lime was expressed in $\text{J kg}^{-1} \text{K}^{-1}$

Thermal diffusivity

The thermal diffusivity (α) of lime juice is derived from the combination of three thermo-physical properties of that result from derivation of Laplace equation of conduction

$$\alpha = k / \rho C_p \quad (4)$$

where, α is thermal diffusivity ($\text{m}^2 \text{s}^{-1}$), k is thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), ρ is density and C_p is the specific heat ($\text{J kg}^{-1} \text{K}^{-1}$) of lime juice.

Modelling

Several empirical models were suggested by different authors for establishing the relationship between thermophysical properties and moisture content/water activity. These model parameters were evaluated by method of least square approximation (Telis-Romero et al. 1998; Muramatsu et al. 2005; Fontan et al. 2009; Jagannadha Rao et al. 2009; Garza and Ibarz 2010)

$$\begin{aligned} TP &= a + b X_w \\ TP &= a + b X_w + c X_w^2 \\ TP &= a \exp(b X_w) \\ TP &= a(X_w)^b \\ TP &= a + b a_w \\ TP &= a + b a_w + c a_w^2 \\ TP &= a \exp(b a_w) \\ TP &= a(a_w)^b \end{aligned} \quad (5)$$

where, TP is thermophysical property, a , b and c are empirical constants, X_w is moisture content (% wet basis) and a_w is the water activity.

Statistical analysis

Experimental data were subjected to analysis of variance at 5 % significance level ($p \leq 0.05$), correlation coefficient and different mathematical models were fitted by method of least squares at 95 % confidence level using statistical software (Statistica 7.0, Stat soft, Tulsa, USA). The suitability of the models fitting was evaluated by determining the correlation coefficient (r) and per cent root mean square error (rmse %) which was evaluated by the following equation

$$\text{rmse}\% = 100/n \left[\sum (W_{\text{exp}} - W_{\text{cal}}) / W_{\text{exp}} \right]^2 \quad (6)$$

where, W_{exp} is the experimental value, W_{cal} is the calculated value and n is number of data sets. The suitability of the model was decided based on higher correlation coefficient (r) and low percent root mean square error (rmse %) values and level of significant ($p < 0.05$).

Results and discussions

Physico-chemical characteristics

The physico-chemical characteristics of enzyme clarified Lime juice is reported in Table 1. The moisture, total soluble solids and water activity was 89.3 %, 8.4° B and 0.979 respectively. The colour values L^* , a^* and b^* was very low which indicated that the lime juice was clear; this was due to appreciable clarification of lime juice by pectinase enzyme. The acidity of the juice was 7.51 % which indicated that the clarified lime juice soluble solids were mainly organic acids and marginally sugars.

Density

The density of liquids defined as mass per unit volume, plays an important role in heat and mass transfer mechanism. The density of liquid foods depends on the nature of solvent, solute (sugars, organic acids and other macromolecules) and their interaction with solvent (water). The density of enzyme clarified lime juice was decreased significantly ($p < 0.05$) from 1011.92 to 1265.33 kg m^{-3} with increase in moisture content and water activity as shown in Table 2. The decrease in density of lime juice is due to decrease in soluble

solids content of lime juice by dilution phenomena. The increase in water content resulted in a decrease of water-solute aggregations. The soluble solids interact with substantial number of water molecules, resulting in non-ideal solution behaviour. The specific volume of solute is markedly lower compared to that of solvent (water). Therefore, the density of lime juice decreased with increase in water content which tends to cause increase in specific volume. The specific volume of water contributes mainly from structured free-solvent regions and that of solute is affected by hydration as well as solute–water interactions. The specific volume of lime juice is highly dependent on concentration of solute and temperature. In lime juice the solid content mainly consists of organic acids, sugars and marginal quantities of other macro molecules. The solute and solvent play an important role in density of the liquid and in general, density of soluble solute is high compare to that water. The magnitude of density values of enzyme clarified lime juice was comparable to that of other juices as reported in literature (Telis-Romero et al. 1998; Shamsudin et al. 2005; Assis et al. 2006; Chin et al. 2008; Jagannadha Rao et al. 2009; Garza and Ibarz 2010).

Different empirical models were fitted relating the density and water content/water activity of enzyme clarified lime juice. The parameters of the models and correlation coefficients of the models and root mean square error percent (rmse%) were reported in Table 3. The exponential type equation ($r = 0.9985$, $\text{rmse}\% = 0.157$, $p < 0.001$) was appropriate to describe the relation between density and water content, whereas linear equation ($r = 0.9604$, $\text{rmse}\% = 0.879$, $p < 0.01$) was better to describe the relation between densities of enzyme clarified lime juice with water activity. The correlation coefficient (r) was 0.9985 and 0.9604 respectively. The suggested models were reported as

$$\rho = 1410.57 \cdot \exp(-0.0037X_w) \quad (r = 0.9985, \text{rmse}\% = 0.157, p < 0.001)$$

$$\rho = 2644.91 - 1626.69a_w \quad (r = 0.9604, \text{rmse}\% = 0.879, p < 0.01)$$

where, ρ is density of lime juice kg m^{-3} , X_w is moisture content in % w b and a_w is the water activity. The coefficient of X_w and a_w were negative which indicated that with increase in water content/water activity the density of lime juice decreased significantly ($p < 0.01$). Similar type relation was reported in case of passion fruit juice (Gratao et al. 2005), whereas several researchers were reported second order polynomial equations for relating to density and moisture content for different food products such as lemon juice, umbu pulp, stone fruits such as plum, peach & nectarine (Phomkong et al. 2006; Minim et al. 2009; Souza et al. 2010). The linear model was suggested for Brazilian orange juice and reported that water content of juice had significant effect on density than temperature (Telis-Romero et al.

Table 1 Physico-chemical characteristics of enzyme clarified Lime juice

Parameter	Quantity
Moisture (%)	89.30±0.01
Ash (%)	0.326±0.005
Protein (%)	0.41±0.008
Fat (%)	0.122±0.002
Crude fibre (%)	0.132±0.013
Water activity (a_w)	0.979±0.00
Total soluble solids (°Brix)	8.40±0.00
acidity (% as citric acid)	7.51±0.08
pH	2.10±0.004
Ascorbic acid (mg/100 ml)	10.71±0.06
Density (kg m^{-3})	1011.92±0.06
Colour values	
L^*	11.45±0.27
a^*	-0.876±0.009
b^*	-1.092±0.031

Mean±S D ($n=3$)

Table 2 Thermophysical properties of enzyme clarified Lime (*Citrus aurantifolia* L) juice at different moisture content and water activity levels at 25 °C

Moisture level (X_w) (% wb)	Water activity (a_w) (–)	Density (ρ) (kg m^{-3})	Newtonian viscosity (η) (mPa s)	Thermal conductivity (k) ($\text{W m}^{-1} \text{K}^{-1}$)	Specific heat (C_p) ($\text{J kg}^{-1} \text{K}^{-1}$)	Thermal diffusivity (α) ($\text{m}^2 \text{s}^{-1}$) $\times 10^{-7}$
30.37	0.835	1265.33 ^f ±1.71	41.635 ^f ±0.576	0.4196 ^a ±0.0010	2794.37 ^a ±19.1	1.187 ^a ±0.010
39.25	0.886	1215.25 ^e ±1.75	22.754 ^e ±0.010	0.4601 ^b ±0.0012	3118.90 ^b ±22.5	1.214 ^a ±0.005
50.07	0.921	1164.23 ^d ±0.54	9.370 ^d ±0.004	0.4983 ^c ±0.0014	3252.68 ^c ±21.2	1.316 ^b ±0.011
59.84	0.945	1134.43 ^c ±1.03	7.127 ^c ±0.007	0.5392 ^d ±0.0014	3467.28 ^d ±23.4	1.371 ^c ±0.009
73.38	0.968	1076.20 ^b ±1.07	5.866 ^b ±0.006	0.5515 ^e ±0.0018	3664.95 ^e ±12.8	1.398 ^c ±0.009
89.30	0.979	1011.92 ^a ±0.06	4.848 ^a ±0.013	0.5800 ^f ±0.0017	3934.83 ^f ±50.7	1.457 ^d ±0.017

Mean ± SD ($n=3$), Different superscripts within a column shows significantly different at $p<0.05$

1998). The density of mango pulp decreased significantly with increasing moisture content as well as temperature and was described by multivariate linear model. The average variation in density was 173.1 kg m^{-3} between moisture content of 1.1 to 9 kg kg^{-1} (db) where as the average variation was 28 kg m^{-3} between temperature 20 to 80 °C (Bon et al. 2010). The bulk density of yoghurt decreased linearly above 50 % moisture content and decreased non-linearly by power law relation below 50 % moisture content. This was due increased amount of free water content above 50 % water content, whereas below 50 % moisture content the bound water will increases which leads to deviation (Kim and Bhowmik 1997). Tansakul and Chaisawang (2006) reported that the density of coconut milk was decreased significantly with increase in fat content as well as temperature. The fat content of coconut milk had significant effect than temperature and linear model was reported. The density of fat is significantly lower compare to that of water. The magnitude of density of each food constituent is different which lead to change in magnitude of density of food with change in mass fraction of food constituents. The different models reported in literature for different foods were might be due nature of solute, solute–solvent interaction, state of hydration, temperature and range of moisture content studied.

Newtonian viscosity

Viscosity is defined as the internal friction of a liquid or its tendency to resist flow. The Newtonian viscosity of lime juice at different moisture contents and water activity was in the range 41.635 to 4.878 mPas depending upon the moisture content/water activity as shown in Table 2. The magnitude of viscosity decreased significantly ($p<0.05$) with increase in moisture content/water activity. The viscosity of enzyme clarified lime juice was strongly depended on the water–solute interactions and inter-molecular forces, which results from the inter-molecular spacing and the strength of bonds. The water–solute interactions and inter-molecular forces were highly affected by concentration and temperature. As the water content increases, the viscosity decreases due to decrease in hydrated molecules and bonding with solute molecules. The increase in moisture content leads to decrease in intermolecular forces, hydration state and solute aggregation mechanisms. In the case of lime juice total soluble solid content mainly organic acids and marginally sugars, this plays an important role in the magnitude of viscosity. The moisture content of lime juice has a strong non-linear effect on viscosity of Newtonian fluids. The magnitude of viscosity of enzyme clarified lime juice was comparable to that of other juices (Juszczak and Fortuna 2004; Altan and

Table 3 Parameters of different models relating density (ρ) to moisture content (X_w)/water activity (a_w) of enzyme clarified lime juice

Model	a (kg m^{-3})	b (kg m^{-3}) (%) ⁻¹	c (kg m^{-3}) (%) ⁻²	r	rmse%
$\rho = a + b X_w$	1383.98***±1.45	−4.198***±0.021	–	0.9976	0.197
$\rho = a + b X_w + c X_w^2$	1416.46***±4.92	−5.424**±0.154	0.010 ^{ns} ±0.001	0.9985	0.158
$\rho = a (X_w)^b$	2505.78***±11.6	−0.198***±0.001	–	0.9891	0.462
$\rho = a \exp(b X_w)$	1410.57***±1.80	−0.0037***±0.000	–	0.9985	0.157
$\rho = a + b a_w$	2644.91***±9.79	−1626.69**±10.35	–	0.9604	0.879
$\rho = a + b a_w + c a_w^2$	5200.2 ^{ns} ±238.8	15710.7 ^{ns} ±524.1	−9547.8 ^{ns} ±278.0	0.9894	0.459
$\rho = a (a_w)^b$	1031.75***±0.47	−1.233***±0.008	–	0.9515	1.014
$\rho = a \exp(b a_w)$	4050.7**±32.3	−1.373**±0.008	–	0.9531	0.956

Mean ± SD ($n=3$), *** $p<0.001$, ** $p<0.01$, * $p<0.05$, ^{ns} $p>0.05$, (ρ in kg m^{-3} , X_w in %, a_w is dimensionless)

Maskan 2005). The viscosity of fluid depends on nature of solute, size, shape, state of hydration and solute–solvent interactions (Nindo et al. 2005).

Different empirical models were fitted relating Newtonian viscosity to water content/ water activity of enzyme clarified lime juice. The parameters of the models and correlation coefficients of the models and root mean square error percent (rmse%) were reported in Table 4. The exponential model ($r=0.9844$, $\text{rmse}\%=10.61$, $p<0.05$) was optimal to describe the relation between Newtonian viscosity and water content of lime juice, whereas power law type equation ($r=0.9911$, $\text{rmse}\%=5.41$, $p<0.01$) described better the relation between Newtonian viscosity and water activity. The suggested models were

$$\eta = 275.84 * \exp(-0.063X_w) \quad (r=0.9844, \text{rmse}\%=10.61, p<0.05)$$

$$\eta = 3.891 * (a_w)^{-13.24} \quad (r = 0.9911, \text{rmse}\% = 5.41, p < 0.01)$$

where, η is the Newtonian viscosity in mPa s, X_w is the water content in % w b and a_w is water activity of lime juice. In the above two equations the coefficients of water content and water activity were negative, which indicated that viscosity of lime juice decreased significantly ($p<0.05$) with moisture content by exponentially. Several authors were reported exponential relation between viscosity and total soluble solid content for different fruit juices such as beet-root juice (Juszczak et al. 2010), cherry juice (Juszczak and Fortuna 2004), clarified peach juice (Ibarz et al. 1992a), choke berry (*Aronia melanocarpa*) juice (Juszczak et al. 2009), pineapple juice (Shamsudin et al. 2007a), clarified orange juice (Ibarz et al. 2009), clarified cherry juice (Giner et al. 1996) and pomegranate juice (kaya and Sozer 2005; Altan and Maskan 2005). Whereas in present investigation observed that exponential decrease in viscosity of enzyme clarified lime juice with increase in water content. The viscosity of lime juice decreased significantly ($p<0.01$) with water activity by power law relation. Several authors reported similar power law relation with viscosity and water activity. The magnitude of power of power law model was

found to be -18.54 at 25°C in case blackcurrant juice, whereas -21.89 and -19.85 at 20°C and 30°C respectively in case of orange juice (Ibarz et al. 1992b, 1994). The deviation was due to variation in nature of solute, its molecular weight, shape, solute–solvent interaction and state of hydration (Fennema 2005; Nindo et al. 2005).

Thermal conductivity

Thermal conductivity is an intrinsic physical property which can be defined as the quantity of heat that flows in unit time through unit thickness and unit area having unit temperature difference between faces. The thermal conductivity of food material is highly dependent on water, other food constituents and structure of the food material. The thermal conductivity of enzyme clarified lime juice was increased significantly ($p<0.05$) from 0.4196 to $0.58 \text{ Wm}^{-1}\text{K}^{-1}$ with increase in moisture content and water activity as shown in Table 2. The magnitude of thermal conductivity of food and their products strongly depends on moisture content/water activity, structure, state of hydration. The moisture content of lime juice was most important in determining thermal conductivity than that of non-aqueous phase. The magnitude of thermal conductivity of pure water is markedly about 2.5 times higher than other food constituents and thermal conductivity of carbohydrate is about 2.5 times lower than water so the mass fraction of water present in the food markedly decides the thermal conductivity of food material. The enzyme clarified lime juice soluble solid content (mainly organic acids and sugars) which has lower thermal conductivity values than water and it showed increased magnitude of thermal conductivity with increase in water content/water activity. The magnitude of thermal conductivity of enzyme clarified lime juice at different moisture content and water activity levels was comparable with other fruit juices and other food products as reported (Rapusas and Driscoll 1995; Telis-Romero et al. 1998; Azoubel et al. 2005; Shamsudin et al. 2005; Muramatsu et al. 2005; Assis et al. 2006; Phomkong et al. 2006; Jagannadha Rao et al. 2009).

Different empirical models were fitted relating thermal conductivity to water content/water activity of enzyme clarified lime juice. The parameters of the model and correlation

Table 4 Parameters of different models relating Newtonian viscosity (η) to moisture content (X_w)/water activity (a_w) of enzyme clarified lime juice

Model	a (mPa s)	b (mPa s) (%) ⁻¹	c (mPa s)(%) ⁻²	r	rmse%
$\eta = a + b X_w$	46.43* $\pm$ 0.46	-0.546* $\pm$ 0.006	–	0.8257	34.28
$\eta = a + b X_w + c X_w^2$	108.89** $\pm$ 1.59	-2.90* $\pm$ 0.05	0.0197* $\pm$ 0.0004	0.9771	15.22
$\eta = a (X_w)^b$	224508 ^{ns} $\pm$ 2383	-2.516*** $\pm$ 0.003	–	0.9936	9.36
$\eta = a \exp(b X_w)$	275.84* $\pm$ 11.19	-0.063** $\pm$ 0.001	–	0.9844	10.61
$\eta = a + b a_w$	250.83** $\pm$ 3.20	-255.39** $\pm$ 3.36	–	0.9582	19.83
$\eta = a + b a_w + c a_w^2$	1662.88* $\pm$ 58.02	-3435.98 ^{ns} $\pm$ 194.7	1718.52 ^{ns} $\pm$ 58.0	0.9960	4.19
$\eta = a (a_w)^b$	3.891** $\pm$ 0.037	-13.24*** $\pm$ 0.12	–	0.9911	5.41
$\eta = a \exp(b a_w)$	11592492.2 ^{ns} $\pm$ 1478225.3	-14.99*** $\pm$ 0.14	–	0.9923	5.20

Mean $\pm$ SD ($n=3$), *** $p<0.001$, ** $p<0.01$, * $p<0.05$, ^{ns} $p>0.05$, (η in mPa s, X_w in %, a_w is dimensionless)

coefficient of the models are reported in Table 5. The second order polynomial equations were better to describe the relation between thermal conductivity to water content and water activity because the correlation coefficient was higher as compared to other models. The suggested models are as follows

$$k = 0.2403 + 0.0070X_w + 0.000036X_w^2$$

($r = 0.9954$, $\text{rmse}\% = 0.394$, $p < 0.001$)

$$k = 0.0632 * \exp(2.2536a_w)$$

($r = 0.9931$, $\text{rmse}\% = 0.511$, $p < 0.001$)

where, k is thermal conductivity in $\text{W m}^{-1} \text{K}^{-1}$, X_w is the water content in % w b and a_w is water activity of lime juice. In this present study it was observed that the thermal conductivity of enzyme clarified lime juice at different water content follows the second order polynomial equation and whereas it followed exponential relation with water activity ($r > 0.99$, $p < 0.001$). Some authors reported linear relationship between thermal conductivity and water content of fruit juices and other food products such as passion fruit juice (Gratao et al. 2005), Brazilian orange juice (Telis-Romero et al. 1998), lemon juice (Minim et al. 2009), onion slices (Rapusas and Driscoll 1995), Borage seeds (Yang et al. 2002), stone fruits such as plum, peach & nectarine (Phomkong et al. 2006). The thermal conductivity of mango pulp increased significantly with moisture content as well as temperature and thermal conductivity is more dependent on moisture content than on temperature. The multivariate linear model was established between thermal conductivity with moisture content and temperature of mango pulp (Bon et al. 2010). Several authors reported linear decrease of thermal conductivity with increase in total soluble solid content and the magnitude of decrease were in the range 0.0041 to 0.0097 per percent increase in brix (Assis et al. 2006; Jagannadha Rao et al. 2009; Muramatsu et al. 2010). Gratao et al. (2005) reported that thermal conductivity of

passion fruit juice increased linearly with water content and thermal conductivity was most affected by temperature among the thermal properties. The thermal conductivity of yoghurt increased logarithmically with moisture content and linearly with temperature (Kim and Bhowmik 1997), whereas it increased linearly with moisture content and decreased linearly with fat and protein contents for different dairy products (Tavman and Tavman 1999). Thermal conductivity of coconut milk increased linearly with temperature but decreased linearly with fat content and the influence of fat content on thermal conductivity was stronger than that of temperature; among all basic food components water has the highest thermal conductivity and fat has lowest (Tansakul and Chaisawang 2006). The deviation models may be due to nature of solute, its molecular weight, their interaction with solvent and state of hydration.

Specific heat

Specific heat of a food material plays an important role in heat transfer phenomena. When heating or cooling of foods, it is necessary to know the specific heat which determines the quantity of energy that needs to be added or removed from the food. Specific heat of a food is defined as the amount of heat required to increase the temperature at unit mass by unit degree at given temperature, which indicates that the variation of the temperature with the quantity of heat stored within the substance. The specific heat of liquid food mainly depends on water and solid content. The moisture content of liquid food plays an important role in magnitude of specific heat. The specific heat of enzyme clarified lime juice increased significantly ($p < 0.05$) from 2.794 to 3.934 $\text{KJkg}^{-1} \text{K}^{-1}$ with increase in moisture content and water activity as shown in Table 2. The increase in moisture content that leads to increase in specific heat due to magnitude of specific heat of water was high compared to other food constituents. In the case of clarified lime juice and their concentrate the solids mainly of organic acid and marginally sugars lower the magnitude of specific heat. The specific

Table 5 Parameters of different models relating thermal conductivity (k) to moisture content (X_w)/water activity (a_w) of enzyme clarified lime juice

Model	a ($\text{W m}^{-1} \text{K}^{-1}$)	b ($\text{W m}^{-1} \text{K}^{-1}$) (%) ⁻¹	c ($\text{W m}^{-1} \text{K}^{-1}$) (%) ⁻²	r	rmse%
$k = a + b X_w$	0.3555*** $\pm$ 0.0016	0.00267*** $\pm$ 0.00003	—	0.9681	1.124
$k = a + b X_w + c X_w^2$	0.2403*** $\pm$ 0.0038	0.0070*** $\pm$ 0.0002	0.000036*** $\pm$ 0.0000021	0.9954	0.394
$k = a (X_w)^b$	0.1559*** $\pm$ 0.001	0.2955*** $\pm$ 0.0028	—	0.9879	0.668
$k = a \exp(b X_w)$	0.3785*** $\pm$ 0.0013	0.00508*** $\pm$ 0.00004	—	0.9568	1.327
$k = a + b a_w$	-0.507** $\pm$ 0.007	1.100*** $\pm$ 0.007	—	0.9896	0.644
$k = a + b a_w + c a_w^2$	1.578 ^{ns} $\pm$ 0.344	-3.509 ^{ns} $\pm$ 0.762	2.538 ^{ns} $\pm$ 0.421	0.9944	0.436
$k = a (a_w)^b$	0.5977*** $\pm$ 0.0006	2.048*** $\pm$ 0.015	—	0.9917	0.570
$k = a \exp(b a_w)$	0.0632*** $\pm$ 0.001	2.2536*** $\pm$ 0.017	—	0.9931	0.511

Mean $\pm$ SD ($n=3$), *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ^{ns} $p > 0.05$, (k in $\text{W m}^{-1} \text{K}^{-1}$, X_w in %, a_w is dimensionless)

heat of water is markedly higher by three times compare to that of other solids present in the food so, the mass fraction of water present in the food decides the specific heat of food material and the average specific heat was about $1.5 \text{ KJkg}^{-1} \text{ K}^{-1}$ of other constituents of food in the food material. The specific heat food is temperature dependent; there is a marginal increase in specific with temperature (Lewis 1987). The specific heat of several fruits and fruit pulps at different moisture contents are reported in literature and the magnitude of specific heat of enzyme clarified lime juice were comparable with reported values (Alvarado 1991; Jagannadha Rao et al. 2009; Telis-Romero et al. 1998; Rapusas and Driscoll 1995; Assis et al. 2006; Souza et al. 2010; Phomkong et al. 2006). Minim et al. (2009) reported that specific heat of lemon juice increased significantly with water content as well as temperature and water content had larger impact on specific heat of lemon juice than temperature.

Different empirical models were fitted relating specific heat to water content/ water activity of enzyme clarified lime juice. The model parameters and correlation coefficient of the models were reported in Table 6. The power law model was better to describe the relation between moisture content and water activity to specific heat of enzyme clarified lime juice at different moisture contents and water activity levels. The model equations were

$$C_p = 1003.7 * (X_w)^{0.303}$$

$$(r = 0.9947, \text{rmse}\% = 0.485, p < 0.001)$$

$$C_p = 3973.0(a_w)^{2.082}$$

$$(r = 0.9799, \text{rmse}\% = 0.928, p < 0.01)$$

where, C_p is the specific heat in $\text{J kg}^{-1} \text{ K}^{-1}$, X_w is the water content in % w b and a_w is the water activity. The specific heat decreased linearly with total soluble solid content for clarified apple juice and almost constant with temperature, at high water content specific heat almost equal to specific heat of pure water (Constenla et al. 1989). Similar types of result were reported for

other fruit juices such as pineapple, orange, grape, sugarcane, Palmyra-palm, date-palm juices (Jagannadha Rao et al. 2009; Muramatsu et al. 2010). The specific heat of pineapple and Thai guava juice increased linearly with temperature as reported (Muramatsu et al. 2010; Shamsudin et al. 2005). The linear model was reported relating to specific heat and water content for different fruit juice and other products such as passion fruit juice, orange juice, lemon juice, umbu pulp, stone fruits (plum, peach & nectarine), plain yoghurt and onion slices (Gratao et al. 2005; Telis-Romero et al. 1998; Minim et al. 2009; Souza et al. 2010; Phomkong et al. 2006; Kim and Bhowmik 1997; Rapusas and Driscoll 1995). The specific heat of coconut milk decreased linearly with increase in fat content and marginal increase with temperature (Tansakul and Chaisawang 2006). The specific heat capacity of mango pulp increased significantly with moisture content and moisture content had significant effect on magnitude of heat capacity of mango pulp than temperature (Bon et al. 2010). The specific heat of milk increased linearly with water content as well as temperature (Minim et al. 2002). Several authors have reported linear Siebel's equation for relating to moisture content to specific heat of food products (Alvarado 1991; Souza et al. 2010; Mohsenin 1980). The Siebel's equation which relates to water content and specific heat was applicable above 50 % of moisture levels. This was due to increased free water content, whereas below 50 % moisture content the bound water will increase which leads to deviation from Siebel's equation and exponential model was suggested for wide range of moisture content of different pulps, juices and foods (Alvarado 1991). In the present study power law equation was better to describe the relation between specific heat and moisture content/water activity of enzyme clarified lime juice. This may be due to the clarification and nature of solids, solute–solvent interactions and state of hydration in lime juice.

Thermal diffusivity

Thermal diffusivity (α) is described as the rate at which heat diffuses through food material, which could be obtained

Table 6 Parameters of different models relating specific heat (C_p) to moisture content (X_w)/water activity (a_w) of enzyme clarified lime juice

Model	a ($\text{J Kg}^{-1} \text{ K}^{-1}$)	b ($\text{J Kg}^{-1} \text{ K}^{-1}$) (%) ⁻¹	c ($\text{J Kg}^{-1} \text{ K}^{-1}$) (%) ⁻²	r	rmse%
$C_p = a + b X_w$	2324.8***±43.9	18.38***±0.93	—	0.9893	0.720
$C_p = a + b X_w + c X_w^2$	2074.9***±38.8	27.81 ^{ns} ±0.30	-0.078 ^{ns} ±0.008	0.9934	0.555
$C_p = a (X_w)^b$	1003.7***±55.4	0.303***±0.014	—	0.9947	0.485
$C_p = a \exp(b X_w)$	2476.6***±31.6	0.0053***±0.0003	—	0.9840	0.882
$C_p = a + b a_w$	-3329.0*±291.9	7265.4**±324.0	—	0.9720	0.999
$C_p = a + b a_w + c a_w^2$	22123.4 ^{ns} ±5268.5	-48983.6 ^{ns} ±11833.5	30976.6 ^{ns} ±6633.3	0.9778	0.677
$C_p = a (a_w)^b$	3973.0***±32.5	2.082**±0.056	—	0.9799	0.928
$C_p = a \exp(b a_w)$	417.66*±39.5	2.261**±0.105	—	0.9784	0.857

Mean ± SD (n=3), ***p<0.001, **p<0.01, *p<0.05, ^{ns}p>0.05, (C_p in $\text{J Kg}^{-1} \text{ K}^{-1}$, X_w in %, a_w is dimensionless)

Table 7 Parameters of different models relating thermal diffusivity (α) to moisture content (X_w)/water activity (a_w) of enzyme clarified lime juice

Model	a (m ² s ⁻¹)	b (m ² s ⁻¹) (%) ⁻¹	c (m ² s ⁻¹) (%) ⁻²	r	rmse%
$\alpha = a + b X_w$	$(1.054^{***} \pm 0.0142) \times 10^{-7}$	$(4.725^{**} \pm 0.305) \times 10^{-10}$	–	0.9706	0.707
$\alpha = a + b X_w + c X_w^2$	$(9.022^* \pm 0.553) \times 10^{-8}$	$(1.047^* \pm 0.209) \times 10^{-9}$	$(-4.80^{ns} \pm 1.86) \times 10^{-12}$	0.9881	0.480
$\alpha = a (X_w)^b$	$(5.977^{***} \pm 0.264) \times 10^{-8}$	$0.199^{**} \pm 0.012$	–	0.9841	0.548
$\alpha = a \exp(b X_w)$	$(1.082^{**} \pm 0.0112) \times 10^{-7}$	$(3.493^* \pm 0.221) \times 10^{-3}$	–	0.9649	0.775
$\alpha = a + b a_w$	$(-4.24^* \pm 0.88) \times 10^{-8}$	$(1.89^* \pm 0.0981) \times 10^{-7}$	–	0.9676	0.790
$\alpha = a + b a_w + c a_w^2$	$(6.62^{ns} \pm 3.10) \times 10^{-7}$	$(-1.35^{ns} \pm 0.686) \times 10^{-6}$	$(8.47^{ns} \pm 3.80) \times 10^{-7}$	0.9864	0.496
$\alpha = a (a_w)^b$	$(1.47^{***} \pm 0.011) \times 10^{-7}$	$1.338^{**} \pm 0.07$	–	0.9690	0.773
$\alpha = a \exp(b a_w)$	$(3.382^{***} \pm 0.242) \times 10^{-9}$	$1.478^{**} \pm 0.079$	–	0.9727	0.726

Mean $\pm$ SD ($n=3$), *** $p<0.001$, ** $p<0.01$, * $p<0.05$, ^{ns} $p>0.05$, (α in m² s⁻¹, X_w in %, a_w is dimensionless)

from Fourier's general law of conduction equation. The thermal diffusivity of food depends on chemical composition, physical nature, state of substance and temperature. It is very useful for the estimation of proceeding time for different types of processes like canning, heating, cooling, freezing, cooking and frying. The thermal diffusivity of enzyme clarified lime juice increased marginally from 1.187×10^{-7} to 1.457×10^{-7} m² s⁻¹ with increase in moisture content and water activity as reported in Table 2. With the increase in moisture content the propagation of heat or diffusion through the medium speeds up. Thermal diffusivity of food and their products depends on other thermophysical properties such as thermal conductivity, density and specific heat of the material. The thermal diffusivity of food was directly related to thermal conductivity and inversely related to density and specific heat. These properties are strongly influenced by the moisture content. With increase in water fraction in fruit juices, there is an increase in thermal diffusivity of the product. This can be explained by higher magnitude of thermal diffusivity values of water than that of solid present in juices. The variation of solid mass fraction fat, protein, and carbohydrate had a small influence on thermal diffusivity than mass fraction of water (Azoubel et al 2005). The magnitude of thermal diffusivity values of enzyme clarified lime juice was within the range

of other fruit juices, pulps and other food products (Fontan et al. 2009; Telis-Romero et al. 1998; Rapusas and Driscoll 1995; Muramatsu et al. 2010; Assis et al. 2006; Cabral et al. 2007; Ikegwu and Ekwu 2009).

Different empirical models were fitted relating thermal diffusivity to water content/ water activity of enzyme clarified lime juice. The model parameters and correlation coefficient of the models were reported in Table 7. The power law type equation was better to describe the relation between thermal diffusivity to moisture content, whereas exponential type relation was suited with water activity of enzyme clarified lime juice at different moisture content and water activity levels. The suggested model equations were

$$\alpha = 5.977 \times 10^{-8} * (X_w)^{0.199}$$

($r = 0.984$, $rmse\% = 0.548$, $p < 0.01$)

$$\alpha = 3.382 \times 10^{-9} * \exp(1.478a_w)$$

($r = 0.9727$, $rmse\% = 0.726$, $p < 0.01$)

where, α is thermal diffusivity in m² s⁻¹, X_w is moisture content in % w b and a_w is water activity. Thermal diffusivity was high at low fat content and at higher temperature for coconut milk and linearly related with fat content as well as

Table 8 Correlation matrix between moisture content (X_w), water activity (a_w) and thermo physical Properties of enzyme clarified lime juice

	Moisture content (X_w)	Water activity (a_w)	Density (ρ)	Newtonian viscosity (η)	Thermal conductivity (k)	Specific heat (C_p)	Thermal diffusivity (α)
Moisture content (X_w)	1.0000						
Water activity (a_w)	0.9462***	1.0000					
Density (ρ)	-0.9976***	-0.9604***	1.0000				
Newtonian viscosity (η)	-0.8250*	-0.9580***	0.8554**	1.0000			
Thermal conductivity (k)	0.9681***	0.9897***	-0.9744***	-0.9239***	1.0000		
Specific heat (C_p)	0.9884***	0.9708***	-0.9924***	-0.8764**	0.9815***	1.0000	
Thermal diffusivity (α)	0.9693***	0.9658***	-0.9718***	-0.8874**	0.9857***	0.9593***	1.0000

*** $p<0.000001$, ** $p<0.00001$, * $p<0.0001$

with temperature (Tansakul and Chaisawang 2006). Several authors reported thermal diffusivity increased linearly with moisture content as well as temperature, water content had strong influence on thermal diffusivity than temperature for fruit juices such as orange, grape, pineapple, lemon, cashew, black berry, yellow mombin and other product (Telis-Romero et al. 1998; Minim et al. 2009; Muramatsu et al. 2010; Assis et al. 2006; Azoubel et al. 2005; Cabral et al. 2007; Yang et al. 2002). The deviation in modelling may be due to clarification, nature of solute, solute–solvent interaction and state of hydration in lime juice.

Interrelation between thermophysical properties

The intercorrelation between moisture content/water activity and thermophysical properties of enzyme clarified lime juice was reported in Table 8. High correlation among thermophysical properties and moisture content/water activity ($0.8250 \leq r \leq 0.9924$, $p \leq 0.0001$) was observed. A significant positive correlation ($0.9656 \leq r \leq 0.9897$, $p < 0.000001$) between moisture content/water activity of lime juice and thermal properties was observed, whereas negative correlation ($-0.9976 \leq r \leq -0.8250$, $p < 0.000001$) with physical properties was observed. There is a significant negative correlation between thermal properties and physical properties such as density and viscosity of lime juice ($-0.9924 \leq r \leq -0.8764$, $p \leq 0.0001$) and there was significant Interrelation among its thermal properties of lime juice ($0.9593 \leq r \leq 0.9857$, $p \leq 0.0001$). In general there is a strong negative correlation between physical and thermal properties of enzyme clarified lime juice at different moisture content and water activities. It was evident that thermophysical properties of enzyme clarified lime juice were significantly dependent on moisture content and water activity of lime juice.

Conclusions

The investigation showed that density and Newtonian viscosity of enzyme clarified lime juice decreased significantly ($p < 0.05$) with increase in water content and water activity from 1265.33 to 1011.92 kg m⁻³ and 41.635 to 4.879 mPas respectively depending on moisture content and water activity levels. The thermal conductivity and specific heat increased significantly ($p < 0.05$) from 0.4196 to 0.58 W m⁻¹ K⁻¹ and 2.794 to 3.934 KJ kg⁻¹ K⁻¹ with increase in moisture content and water activity respectively. The thermal diffusivity increased marginally from 1.187×10^{-7} to 1.457×10^{-7} m² s⁻¹ with increase in moisture content and water activity. Different empirical mathematical models relating to thermophysical properties of enzyme clarified lime juice with moisture content/water activity were established. Investigation showed that there was significant inter-

correlation between thermophysical properties and moisture content and water activity of enzyme clarified lime juice. It was evident that there was significant negative correlation between physical properties such as density, viscosity and thermal properties of enzyme clarified lime juice at different moisture content/water activities. A significant positive inter-correlation between thermal properties such as thermal conductivity, specific heat and thermal diffusivity was observed. It was concluded that thermophysical properties of enzyme clarified lime juice significantly depend on moisture content and water activity of lime juice. The results obtained from this study may be useful in determining heat and mass transfer phenomena. It is also useful in process design, process control and optimisation for the preparation of novel lime juice product in large scale commercial production.

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