Modeling the Impact of the Soluble Solids Content and Temperature on the Thermophysical Properties of Lime Juice (Mexican Lime)

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ABSTRACT: *It is necessary to determine the thermophysical properties of the various types of agricultural products in order to control thermal operations, as well as processes such as drying, freezing, cooling, and pasteurization. Moreover, most of the products' thermophysical properties vary by the temperature changes and the percentage of water content. Therefore, the mathematical models expressing the relationship of these properties serve as a beneficial tool for designing automatic processes and equipment. The present research entails the examination of the impact of four levels of soluble solid content 15, 20, 25, and 30 %, and nine levels of temperature 28.6, 35.4, 40.5, 47.6, 56.1, 63.3, 72.3, 83.2, and 90 °C on the thermophysical properties of lime juice including density, specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient. Based on the results, soluble solid content and temperature had a significant impact ($p \leq 0.05$) on the thermophysical properties of lime juice. By increasing the percentage of the soluble solid content, the properties such as specific heat (from 3321 to 2897 J/kg°C), thermal conductivity coefficient (from 0.69 to 0.54 W/m°C), and thermal diffusivity coefficient (from 2.10×10^{-7} to 1.61×10^{-7} m^2/s) decreased but the density was increased (from 1013 to 1057 kg/m^3). Furthermore, by increasing the temperature, the values of specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient increased but the density was decreased. Consequently, to model the thermophysical properties, the multivariable regression method and MATLAB software were employed and the results of the examination were fitted. The coefficient of determination of linear models of density 0.94, specific heat 0.93, thermal*

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conductivity, and thermal diffusivity 0.98. In accordance with the results, all thermophysical properties had a linear relationship with the independent variables such as temperature and soluble solid content.

KEYWORDS: *Thermal conductivity coefficient; Thermal diffusivity coefficient; Specific heat; Density.*

INTRODUCTION

Lime was one of the earliest citrus fruits used as a flavor in producing various food products and it has two types, i.e. acidic and alkaline. Lemon is an alkaline fruit and Persian lime, Mexican lime, and Key lime are the acidic types. In Iran, the Mexican lime variety is known as Jahrom Lime [1]. The amount of national production of lemon products from the total area of 141 thousand hectares of orchards is 628 thousand tons of lemon product and in the meantime, Fars province in the field of lemon production, including Lime lemons with an area of 14.800 hectares and an average annual production of 340.000 tons, is the first production site in the country [2]. In Iran, lemons are also dried to consume in food cooking and therefore, the development of a drying process is necessary. In 2011, Iran, with an annual production of about 560000 tons of lemon and lime, became the ninth-producing country in the world after China, Mexico, India, Argentina, Brazil, the United States, Turkey, and Spain [3]. One of the main nutritional components of lemon is Vitamin C or ascorbic acid and its value in the Iranian varieties is reported to be approximately 10.5 mg/100g [4, 5]. Iran is numbered among the old fruit producers in the world; however, it has not made considerable progress concerning the export and industrial process and does not possess a proper position in the world market. Furthermore, food waste is another serious challenge that most countries, especially developing countries face in this regard. Therefore, creating and developing the processing and complementary industries, designing, and constructing various types of machines required for the juice and concentrates production industries are among the factors that can result in controlling the processes, preserving the final quality, and reducing the wastes of the agricultural products including lime. There must be a precise and accurate understanding of the thermophysical properties of agricultural products to be able to analyze the behaviors of these biological matters. The thermophysical properties of food products including specific heat, thermal conductivity coefficient, thermal diffusivity coefficient, and density are necessary to estimate the heat transfer rate, control, evaluate, and model the operation of processing food products such as freezing, pasteurization, drying, concentration, cooling, as well as producing, transporting, and preserving food products, especially when the cost of energy, quality, and safety of food products are important. Furthermore, designing and engineering equipment including thermal processes depend on the information about the thermophysical properties of the food products including specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient since most food products the thermophysical properties change upon the changes in the water content and temperature, which is due to the high specific heat and thermal conductivity coefficient of water [6, 7]. *Constenla et al.* (1989), measured the thermophysical properties of the clarified apple juice in the temperature range of 20 to 90 °C and the soluble solid content of 12 to 70 %. Following the results, the specific heat decreased linearly by increasing the soluble solid content, and it was increased by raising the temperature. Besides, the thermal conductivity of water decreased linearly by increasing the soluble solid content and it was increased by a linear rise of the temperature [8]. *Shariaty-Niassar et al.* (2000), employed the method of hot wire to measure the thermal conductivity of potato starch gel in the temperature range of 25 to 80 °C, the water content of 50-80 %, and pressure of 0.2-10 MPa. Per the results, the thermal conductivity increased by raising the temperature and water content. By increasing the pressure up to 1 MPa, the thermal conductivity was increased, however, in higher pressure, the thermal conductivity remained the same [9]. *Polley et al.* (1980), determined the density, specific heat, and thermal conductivity of egg including egg white, yolk, and a combination of both in the temperature range of 273 to 311 K and water content between 51.8 and 88.2, and suggested the linear polynomial regression models for demonstration of the impact of temperature and water content on these properties. According to the results, the density was changed from 1023 to 1143.5 kg/m^3, specific heat from 2.6 to 3.7 J/g.K, and thermal conductivity from 0.2 to 0.6 W/m°C for the pure yolk, pure white, and their combination in the aforesaid temperature range and water content [10]. In another research, *Cabral et al*. (2007), measured the thermophysical properties of black mulberry juice and examined the impact of the soluble solid content and temperature on specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient of the said matter. Based on the results, all three indices were increased by the increase of the soluble solid content, while, density was decreased by increasing the temperature and decreasing the soluble solid content [11]. *Fontan et al*. (2009), investigated the impact of temperature on the thermophysical properties of coconut water. In this study, density and viscosity decreased by increasing the temperature, while, the thermal conductivity coefficient and thermal diffusivity coefficient were increased significantly [12]. Another research studied the impact of temperature and soluble solid content on the thermophysical properties of pomegranate juice. The results revealed that the soluble solid content possessed more thermophysical properties than temperature [13]. *Minim et al.* (2009), the thermophysical properties of lemon juice were determined at a water mass fraction of (0.381 to 0.900) and a temperature of (273.45 to 353.75) K. Density and thermal conductivity varied from (962.3 to 1282.8) kg/m^3 and (0.344 to 0.624) W/m^2.K, respectively. Heat capacity and thermal diffusivity varied from (2446.5 to 4060.1) J/ kg·K and (0.1160 · 10^{-6} to 0.1785 · 10^{-6}) m^2/s, respectively. Simple polynomial functions were fitted to the experimental data, and good agreements were obtained. In the tested range, water content showed greater influence on the thermophysical properties [7]. According to the literature review, there is no research on determining the thermophysical properties of lime juice (Mexican lime) as the most cultivated variety in Iran. In an attempt to fill this gap, the present research investigated the thermophysical properties of lime juice as a function of temperature and different levels of soluble solid content and developed simple empirical correlations for predicting these properties.

EXPERIMENTAL SECTION

The limes used in the present research were completely ripe (yellow) weighed between 20.50±2.5g and were purchased from the local market of Jahrom (Province of Fars) in July 2020. The fruits were cleaned by hand and the damaged fruits were separated and kept in plastic containers in the refrigerator at 4 °C until the time of the experiment (Fig. 1). The juice was extracted using a manual juicer and in order to separate the pulp and tissue particles, the extracted juice was passed through a sieve with mesh 170. Afterward, the thermophysical properties of this product were examined in the soluble solid range of 15 to 30 % and a temperature between 28 to 90 °C. The results indicated that the value of the ingredients of lime juice per 100g was measured to be water (87-88 g), anti-oxidant (250 ppm), Vitamin C (22-34 mg), carbohydrates (7 g), fat (0.3 g), fiber content (0.3 g), and protein (0.4 g).

Solid content measurement

To measure the soluble solid content, 20g lime juice was completely dried using a Freeze dryer for 12 h and subjected to a pressure of -20 atm at a temperature of -40 °C. The soluble solid content was determined by weighing the sample before and after drying. To concentrate the lime juice and provide other levels of solid matter, a drying oven was used. The samples were concentrated using a hot airflow and at various speeds that led to the vaporization of the water and the concentration of the samples [5].

Density measurement

To measure density, a 50 mL volumetric pycnometer was employed. The pycnometer was filled with the respective liquid and weighed using a precision scale (Fig. 2). Then, the density value was calculated considering that the volume of the pycnometer was already specified. To examine the density in various temperatures, the pycnometer was filled with the respective liquid and placed inside a bath at the same temperature. The volume of the liquid inside the pycnometer was increased after heating however, considering that the volume of the pycnometer remained the same, the extra liquid started to overflow from the pycnometer’s lid due to the increase of

Fig. 1: Sample photos, Processing of lemon, Preservation and Analysis.

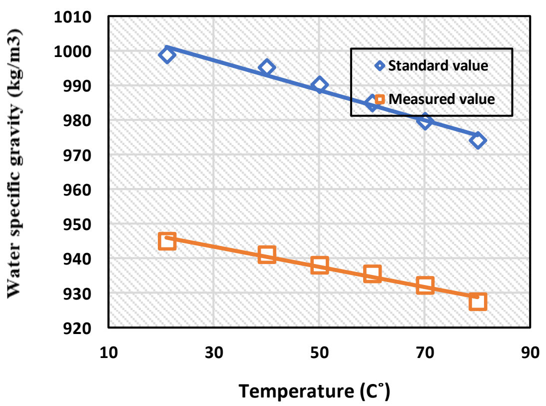

Fig. 2: Standard and measured density of water by 50mL pycnometer in different temperatures

the volume. The pycnometer filled with liquid was reweighed to calculate the reduction of weight caused by the increase in the volume of liquid exiting the pycnometer. Taking into account the steady volume of the pycnometer (50 mL), the density of lime juice in four levels of solid content was measured to be, 15, 20, 25, and 30 %, and in nine temperature levels to be 28.6, 35.4, 40.5, 47.6, 56.1, 63.3, 72.3, 83.2, and 90 °C [5]. By adding the error values in each temperature to the density values obtained by the pycnometer, the real density of the soluble solid content and temperature was acquired in each state.

Measurement of thermal conductivity coefficient

The thermal conductivity coefficient of the lime juice samples was measured using a device comprised of two coaxial cylinders. First, water was used for calibration of the device considering that the quantity of its thermal conductivity coefficient in atmospheric pressure and different temperatures are already specified [14]. Then, the thermal conductivity coefficient of the samples was calculated in 4 levels of soluble solid content and 9 levels of the temperature of the heater and in the steady state were all calculated as Equation (1).

$$k = \frac{q \times \ln\left(\frac{r2}{r1}\right)}{(T1 - T2)2\pi L} \qquad (1)$$

Where: k- thermal conductivity coefficient of the respective liquid (W/m°C), q- heat flux (W), T_1 and T_2- temperature of both sides of the liquid layer (°C), r_1 and r_2- radius of cylinders (mm), L- length of two cylinders (210 mL).

Specific heat measurement

The specific heat of the Jahrom lime juice was determined through Differential Scanning Calorimetry. This method is widely used in measuring the thermal capacity and heat transfer rate as a function of the temperature, and it measures the changes of the thermal energy in the matter in the temperature range of 170 to 770 °C. The scanning calorimetry is comprised of two containers, inside one of which the sample is filled and inside another the base matter. Then, the thermal energy variations of the main matter and the base matter were measured in the same temperature range and the value of the thermal energy absorption and desorption by the main matter was calculated [14]. In the present research, prior

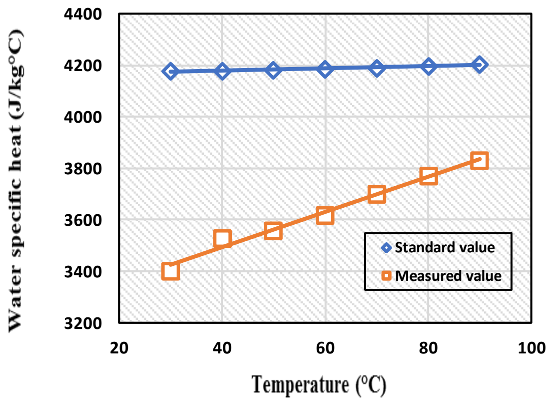

Fig. 3: Standard and measured specific heat by differential scanning calorimetry.

to the experiment, the calorimetry device was calibrated by water, due to which by comparing the values measured by the calorimetry and the standard specific heat of water, the measurement error of the device, i.e. the obtained deviation values by the standard values were calculated in each temperature. Fig. 3 shows the standard value of the specific heat of the water and measured values by the scanning calorimetry. Taking into account the calibration curve and identifying the error value in each temperature, and by adding them to the measured values, the real values of the capacity of the specific heat in four levels of the soluble solid content and nine levels of temperature levels were measured.

Measurement of thermal diffusivity coefficient

The thermal diffusivity coefficient is the temperature diffusivity rate in a matter and the ratio of the thermal conductivity coefficient to volumetric heat capacity. The thermal diffusivity coefficient of lime juice in four levels of soluble solid content and nine levels of temperature was calculated by identifying the thermal conductivity coefficient, density, and specific heat and using Equations (2) and (3) [5].

$$C_W = \rho C \tag{2}$$

$$\alpha = \frac{k}{C_W} \tag{3}$$

Where: k- thermal conductivity coefficient (W/m°C), α- thermal diffusivity coefficient (m^2/s), C- specific heat (J/kg°C), C_W- volumetric heat capacity (J/m^3°C).

Statistical analysis of data

In the present research in order to analyze the data, the factorial experiment in a completely randomized design was employed and the means were compared through Duncan's multiple range test and on the probability level of 5 %. Accordingly, the multivariable linear regression method and Matlab software R2021a (MATLAB 9.10) were used for fitting the data and determining the best model. Besides, the R^2 index was used to assess the validity of the models.

RESULTS AND DISCUSSION

With respect to Table 1, the different levels of the soluble solid content levels and the different values of the temperature had a significant impact on the value of density of the samples ($p \leq 0.05$). By increasing the soluble solid content, the value of the sample density of Jahrom lime juice was increased. This is because by increasing the soluble solid content in the lime juice, the value of the solid matter in the volume unit increases as well. On the other hand, in each level of the solid content, by increasing the temperature, the value of the density of the samples was decreased. Since by increasing the temperature, the activity and molecular motion of the samples were increased, consequently, the number of the molecules in the unit of volume was decreased.

In Fig. 4, the density variations with the different soluble solid content and temperature are demonstrated. Besides, the linear equations of 4 to 7 indicated a high correlation between the impact of temperature in various levels of solid content on the density of the samples.

$$\rho = -0.3357T + 1088.1 \qquad R^2 = 0.9888 \;,\; B_x = 15 \tag{4}$$

$$\rho = -0.3132T + 1063.3 \qquad R^2 = 0.9923 \;,\; B_x = 20 \tag{5}$$

$$\rho = -0.3035T + 1048 \qquad R^2 = 0.9913 \;,\; B_x = 25 \tag{6}$$

$$\rho = -0.2887T + 1040 \qquad R^2 = 0.9831 \;,\; B_x = 30 \tag{7}$$

Where: B_x - soluble solid content (%), T - temperature (°C), ρ - density (kg/m^3).

Besides, relation 8 shows the density variation of lime juice in different soluble solid content and temperature using multivariable regression.

Table 1: Comparing the means of lime juice density (Kg/m^3) in different levels of solid content & temperature Different letters indicate significant difference between means at $p \leq 0.05$.

	Temperature (°C)								
Soluble solid (%)	28.6	35.4	40.5	47.6	56.1	63.3	72.3	83.2	90
15	1031±3.1^{hi}	1030±3.2^{hi}	1028±2.7^{ij}	1027±3.1^{ij}	1025±5.1^{ij}	1021±3.4^{ij}	1019±3.1^{jk}	1017±3.5^{jk}	1013±3.3^{k}
20	1040±3.3^{fg}	1038±3.6^{fg}	1035±3.1^{gh}	1033±3.3^{gh}	1030±3.2^{hi}	1029±3.1^{hi}	1026±2.4^{ij}	1023±2.7^{j}	1021±3.1^{j}
25	1054±4.1^{de}	1052±2.1^{e}	1050±3.3^{e}	1049±2.8^{e}	1046±4.1^{ef}	1043±3.5^{f}	1040±4.1^{fg}	1038±3.5^{fg}	1035±2.2^{gh}
30	1077±3.2^{a}	1076±3.3^{a}	1075±2.5^{a}	1073±4.2^{ab}	1070±3.5^{ab}	1067±2.5^{bc}	1064±2.5^{bc}	1060±3.7^{cd}	1057±2.2^{d}

Table 2: Comparing the means of lime juice specific heat (J/Kg.°C) in different levels of soluble solid content and temperature Different letters indicate significant difference between means at $p \leq 0.05$.

	Temperature(°C)								
Soluble solid (%)	28.6	35.4	40.5	47.6	56.1	63.3	72.3	83.2	90
15	3125±10^{fg}	3130±10^{fg}	3145±13^{ef}	3170±10de	3179±10^{d}	3186±10^{d}	3259±11^{b}	3293±15.2^{a}	3321±10.2^{a}
20	3105±10^{g}	3110±14^{g}	3127±12^{fg}	3145±13^{ef}	3152±10^{e}	3166±10de	3184±12^{d}	3227±10^{c}	3265±10^{b}
25	2889±17^{m}	2927±9^{l}	2930±14^{kl}	2953±12^{k}	2993±10^{j}	3015±15^{ij}	3034±14^{i}	3071±9^{h}	3112±10^{g}
30	2698±8^{s}	2712±15^{rs}	2733±12^{qr}	2749±15^{pq}	2771±15^{op}	2793±17no	2825±15^{n}	2861±18^{m}	2897±10^{m}

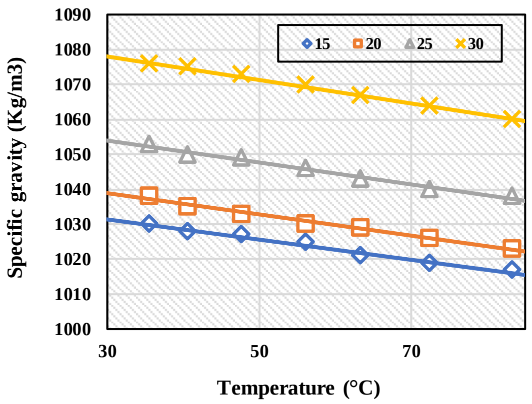

Fig. 4: Density variations at different soluble solid content and temperature.

$$\rho = 992.0019 + 3.0156B_x - 0.3103T \qquad (8)$$
$$R^2 = 0.9494$$

Telis-Romero et al. (2000) found similar results when investigating the density variations of coffee extract in different temperatures (25-90 °C) and different soluble solid content levels (60-80%) [15]. *Rostapour et al.* (2011) examined the density variations of pomegranate juice in the temperature range of 25-70 °C and different soluble solid content levels of (12-65%). Based on the results, by increasing the temperature and soluble solid content, the density of the samples decreased and increased, respectively [13].

According to Table 2, the different levels of the soluble solid content and the different values of the temperature had a significant impact on the value of the specific heat of the samples ($p \leq 0.05$). By increasing the temperature from 28 to 90 °C and increasing the soluble solid content from 15 to 30 %, the value of specific heat was increased and decreased, respectively. The results were obtained due to the fact that by increasing the temperature, the thermal charge of the matter was increased, consequently, the specific heat of the samples was increased. However, considering that the specific heat of the water is higher in comparison to the other solid content of the lime juice, therefore, the specific heat was decreased by increasing the soluble solid content in the matter, i.e. by decreasing the water content.

Fig. 5 shows the specific heat variations with different temperature and soluble solid content. Besides, the linear equations of 9 to 12 demonstrated a high correlation between the impact of temperature on the different levels of solid matter on the specific heat of the samples.

$$C = 3.2838T + 3012.3 \qquad (9)$$
$$R^2 = 0.9487 \quad , \quad B_x = 15$$

$$C = 2.4639T + 3023.5 \qquad (10)$$
$$R^2 = 0.9448 \quad , \quad B_x = 20$$

Table 3: Comparing the means of lime juice thermal conductivity (W/m. °C) in different levels of soluble solid content and temperature Different letters indicate significant difference between means at p ≤0.05.

	Temperature(°C)								
Soluble solid (%)	28.6	35.4	40.5	47.6	56.1	63.3	72.3	83.2	90
15	0.52±0.01[ef]	0.54±0.01[e]	0.56±0.02[d]	0.57±0.02[cd]	0.59±0.02[bc]	0.63±0.03[ab]	0.65±0.03[a]	0.68±0.03[a]	0.69±0.03[a]
20	0.46±0.02[gh]	0.48±0.02[fg]	0.52±0.01[ef]	0.53±0.01[e]	0.55±0.02[de]	0.58±0.02[bc]	0.59±0.02[bc]	0.62±0.03[ab]	0.65±0.03[a]
25	0.41±0.02[hi]	0.43±0.01[hi]	0.45±0.02[gh]	0.48±0.02[fg]	0.51±0.01[ef]	0.53±0.01[e]	0.55±0.02[de]	0.58±0.02[bc]	0.59±0.02[bc]
30	0.34±0.02[j]	0.35±0.02[j]	0.38±0.02[j]	0.41±0.02[hi]	0.45±0.02[gh]	0.49±0.02[fg]	0.52±0.01[ef]	0.52±0.01[ef]	0.54±0.01[e]

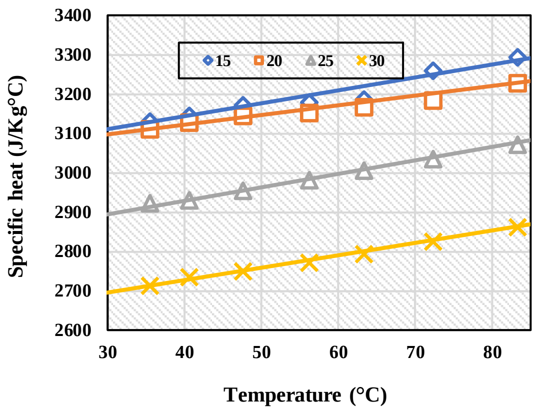

Fig. 5: Specific heat variations in different temperatures and different soluble solid contents.

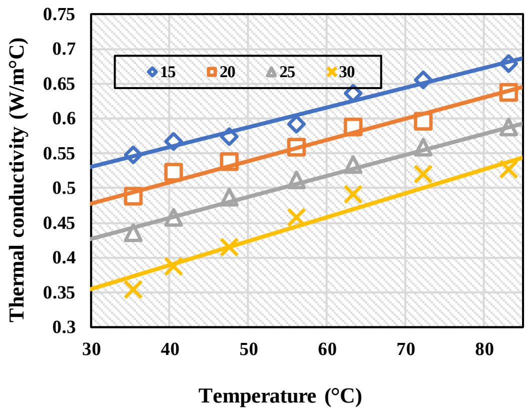

Fig. 6: Thermal conductivity coefficient variations in different soluble solid content and temperature.

$$C = 3.4297T + 2791.3 \quad (11)$$
$$R^2 = 0.9931 \quad , \quad B_x = 25$$

$$C = 3.1553T + 2600.9 \quad (12)$$
$$R^2 = 0.9907 \quad , \quad B_x = 30$$

Furthermore, equation 13 shows the density variation of lime juice in different soluble solid contents and temperatures using multivariable regression.

$$C = (3.5018 - 0.0287B_x - 0.0031T) \times 10^3 \quad (13)$$
$$R^2 = 0.9325$$

Aghbashloo et al. (2008) conducted a study on the thermal properties of barberry. They found out that increasing the water content from 19.3 to 74.3 % and the thermal levels from 50 to 70 °C can result in a linear increase of the specific heat of barberry from 1.9653 to 3.2811 J/kg °C [6]. Shrivastava and Datta (1999) carried out a study on the thermal properties of the mushroom. They revealed that by increasing the water content and the temperature, the specific heat of the mushroom was increased from 1.7158 to 3.9498 J/kg °C [16].

Considering Table 3, the different levels of the soluble solid content and temperature had a significant impact on the value of the thermal conductivity coefficient of the samples ($p \leq 0.05$). By increasing the temperature from 28 to 90 °C and increasing the soluble solid content from 15 to 30 %, the value of specific heat was increased and decreased, respectively. This is due to the fact that by increasing temperature, the molecular motion, and as a result, the thermal charge that passed through the matter was increased. Consequently, the heat transfer rate and thermal conductivity coefficient are increased. On the other hand, the thermal conductivity coefficient of water was higher than the solid matter inside lime juice, therefore, by decreasing the water content and increasing the soluble solid content of lime juice, the thermal conductivity coefficient of lime juice was decreased.

In Fig. 6, the experimental curves indicated the changes in the thermal conductivity coefficient of lime juice in the different soluble solid contents and different temperatures. Besides, the linear equations of 14 to 17 indicated a high correlation between the impact of temperature in various levels of solid matter on the thermal conductivity coefficient of lime juice.

$$k = 0.0028T + 0.4454 \quad (14)$$
$$R^2 = 0.9862 \quad , \quad B_x = 15$$

$$k = 0.003T + 0.3862 \quad (15)$$
$$R^2 = 0.9818 \quad , \quad B_x = 20$$

$$k = 0.003T + 0.3365 \quad (16)$$
$$R^2 = 0.9864 \quad , \quad B_x = 25$$

$$k = 0.0034T + 0.2518 \quad (17)$$
$$R^2 = 0.9555 \quad , \quad B_x = 30$$

Equation 18 indicated the changes in thermal conductivity coefficient of lime juice in the different soluble solid contents and temperatures.

$$k = 0.5932 - 0.106B_x \quad - 0.0031T \quad (18)$$
$$R^2 = 0.9828$$

Aghbashloo et al. (2008) revealed that by increasing the temperature from -6 to 20 °C and the water content from 4.4 to 25.5 %, the thermal conductivity coefficient of wheat was increased from 0.1382 to 0.167 [6]. *Singh* and *Goswami*, (2000) expressed that by increasing the temperature from -50 to 50 °C and increasing the water content from 1.8 to 20.5 %, the values of the thermal conductivity coefficient of cumin increased as a quadratic function from 0.223 to 0.046 [17]. *Heidari Dalfard et al.* (2015) examined the thermophysical properties of malt extract. Accordingly, the thermal conductivity coefficient of malt extract was increased by reduction of the soluble solid content from 80 to 60 % and it was increased from 0.1196 to 0.347 by increasing the temperature from 25 to 90 °C [18]. Results of study and research on specific heat and thermal conductivity Root grapes show a significant correlation between the results obtained from this research and the results of others who do on other products. Specific heat and thermal conductivity with increasing humidity at the levels mentioned in the article in the order of 1.6523 kJ/kg°C to 3.3253 kJ/kg°C and from 0.1252 W/m°C to 0.4202 W/m°C changes. Thermal properties are a very useful resource in designing, equipping, and optimizing devices that somehow, deal with heat (like dryers). It also Information on how to use processing and dry equipment making the product effective [19]. According to Table 4, the different levels of the soluble solid content and temperature had a significant impact on the value of the thermal diffusivity coefficient of the samples ($p \leq 0.05$). By increasing the soluble solid content from 15 to 30 %, the thermal diffusivity coefficient of the samples was decreased, which is mostly due to the increase in the density of the samples. On the other hand, by increasing the temperature from 28 to 90 °C, the thermal diffusivity coefficient of the samples was increased. The variations of the thermal diffusivity coefficient of lime juice in different levels of solid content and temperature are demonstrated in Table 4.

In Fig. 7, the experimental curves indicate the changes in the thermal diffusivity coefficient of lime juice in the different soluble solid contents and different temperatures. Besides the linear equations of 19 to 22 manifested the relationship between the thermal diffusivity coefficient of Jahrom lime juice with temperature and the different levels of solid content.

It is noteworthy that, the linear equations of 19 to 22 manifested the relationship between the thermal diffusivity coefficient of Jahrom lime juice with temperature and the different levels of solid content.

$$\alpha = 0.0065T + 1.5051 \quad (19)$$
$$R^2 = 0.9912 \quad , \quad B_s = 15$$

$$\alpha = 0.0064T + 1.3006 \quad (20)$$
$$R^2 = 0.9888 \quad , \quad B_s = 20$$

$$\alpha = 0.0075T + 0.0838 \quad (21)$$
$$R^2 = 0.9732 \quad , \quad B_s = 25$$

$$\alpha = 0.0087T + 0.826 \quad (22)$$
$$R^2 = 0.9906 \quad , \quad B_s = 20$$

Equation 23 indicated the changes in the thermal diffusivity coefficient of lime juice in the different soluble solid contents and temperatures.

$$\alpha = 1.9973 - 0.0364B_x - 0.0073 \quad (23)$$
$$R^2 = 0.9876$$

Telis-Romero et al. (1998) investigated into the thermophysical properties of orange juice in the temperature range of 0.5 to 62 °C and different levels of soluble solid content (27 to 66 %). Accordingly, an increase in the temperature can lead to an increase in the thermal diffusivity coefficient and an increase in the soluble solid content can lead to a decrease in the thermal diffusivity coefficient of the samples [20]. *Pranjal et al.* (2014) showed that density and Newtonian viscosity

Table 4: Comparing the means of lime juice thermal diffusivity coefficient (m^2/s) in different levels of soluble solid content and temperature Different letters indicate significant difference between means at $p \leq 0.05$.

	Temperature(°C)								
Soluble solid (%)	28.6	35.4	40.5	47.6	56.1	63.3	72.3	83.2	90
15	1.71±0.02^{ef}	1.72±0.02^{ef}	1.77±0.02^{d}	1.80±0.03^{cd}	1.85±0.02^{bc}	1.90±0.03^{b}	1.96±0.04^{ab}	2.05±0.05^{a}	2.10±0.05^{a}
20	1.50±0.03^{jk}	1.52±0.03^{jk}	1.56±0.03^{ij}	1.59±0.02^{hi}	1.66±0.02^{fg}	1.69±0.02^{fg}	1.76±0.02^{de}	1.82±0.02^{cd}	1.90±0.03^{b}
25	1.34±0.03^{lm}	1.35±0.02^{l}	1.37±0.03^{l}	1.39±0.02^{l}	1.48±0.02^{k}	1.54±0.02^{j}	1.65±0.02^{gh}	1.71±0.02^{ef}	1.76±0.02^{de}
30	1.12±0.03^{o}	1.13±0.03^{o}	1.18±0.03^{no}	1.22±0.02^{n}	1.29±0.03^{m}	1.36±0.02^{l}	1.47±0.03^{k}	1.54±0.02^{j}	1.61±0.02^{hi}

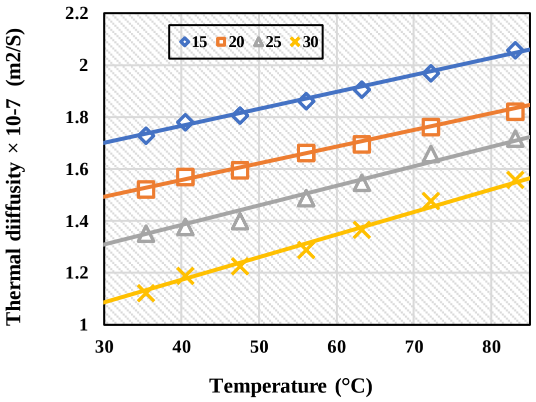

Fig. 7: Thermal diffusivity coefficient variations in different soluble solid content and temperature.

of enzyme-clarified sapota juice decreased significantly (p<0.05) from 1266.27 to 1042.24 kg/m^3 and 39.553 to 5.221 mPa s with increase in moisture content (38.01 to 88.64% wet basis) as well as water activity levels (0.839 to 0.987), respectively. The thermal conductivity increased significantly (p<0.05) from 0.3989 to 0.5703 W/mK with increase in moisture content and water activity. The specific heat and thermal diffusivity increased markedly with moisture content as well as water activity. Empirical mathematical models were established relating to thermophysical properties of enzyme clarified sapota juice with moisture content/water activity. Results indicated that a high significant (p<0.0001) correlation between thermophysical properties with moisture content/water activity of enzyme clarified sapota juice was observed. A significant (p<0.0001) positive correlation between thermal properties and moisture content/water activity was observed; whereas a significant negative (p<0.00001) correlation was observed between physical properties and moisture content/water activity [21]. Didar, (2020) Investigated the Effect of Different Factors on Thermal Conductivity and Specific Heat of Pumpkin Puree, the result showed that, the specific heat and thermal conductivity are the two main thermal properties of food products. In this research, the thermal properties of pumpkin purée in five levels of moisture (25, 30, 35, 40 and 45 percent), five temperature levels (25, 35, 45, 50 and 55ºC), different percentages of salt (0, 0.5, 1, 1.5 and 2%) and different percentages of sugar (0, 10, 15, 20 and 25%) were investigated. The experiments showed that temperature and moisture caused increases in specific heat and thermal conductivity in pumpkin puree whereas the addition of salt and sugar caused reductions in both specific heat and thermal conductivity of pumpkin puree. In order to predict the effect of moisture, temperature, salt and sugar content on thermal properties of pumpkin puree, regression modes are used. Coefficient of Determination (R2) of specific heat capacity for temperature, moisture content, salt content and sugar content were 0.920, 0.941, 0.949 and 0.961, respectively. Coefficient of Determination (R2) of thermal conductivity for temperature, moisture content, salt content and sugar content were 0.851, 0.962, 0.956 and 0.979, respectively [22].

CONCLUSIONS

To design and construct a machine required for processing agricultural products such as drying, there should be a precise and accurate understanding of the thermophysical properties of these products in order to analyze the biological behaviors of these biological matters. In the present research, the impact of temperature and the soluble solid content were examined on four thermophysical properties such as density, specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient. According to the results, by increasing the soluble solid content, the specific heat (from 3321 to 2897 J/kg°C), thermal conductivity coefficient (from 0.69

to 0.54 W/m°C), and thermal diffusivity coefficient (from 2.10×10^{-7} to 1.61×10^{-7} m^2/s) were decreased but the density of lime juice was increased (from 1013 to 1057 Kg/m^3). On the other hand, by increasing the temperature, the specific heat, thermal conductivity coefficient, and thermal diffusivity coefficient were increased but the density was decreased. The coefficient of determination of linear models of density 0.94, specific heat 0.93, thermal conductivity and thermal diffusivity 0.98. Besides, the linear two-variable regression has a good fit for examining the thermophysical properties of lime juice by changing the soluble solid content and temperature.]

Nomenclature

%	Percentage
°C	Degrees of centigrade
K	Degree of kelvin
ppm	Part per million
k	Thermal conductivity coefficient of the respective liquid, W/m°C
q	Heat flux, W
T_1 and T_2	Temperature of both sides of liquid layer, °C
r_1 and r_2	Radius of cylinders, mm
L	Length of two cylinders, 210 mL
α	Thermal diffusivity coefficient, m^2/s
C	Specific heat, J/kg°C
C_w	Volumetric heat capacity, J/m^3°C
B_x	Soluble solid content, %
T	Temperature, °C
ρ	Density, kg/m^3

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