Evaluation of ohmic heating for sterilization of berry-like fruit juice of mulberry (*Morus nigra*), bignay (*Antidesma bunius*), and jambolana (*Syzygium cumini*)

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Abstract. Increasing awareness on healthy lifestyles escalated the demand for health beneficial products which lead to the creation of minimally processed products using novel technologies. Ohmic heating considered as an emerging sterilization technology which adopt the principle of High-Temperature Short Time (HTST) in thermal sterilization technology. Among the indigenous species of berry-like fruit grown in Indonesia are mulberry (*Morus nigra*), bignay (*Antidesma bunius*), and jambolana (*Syzygium cumini*). This berry-like fruits possess great potential as raw materials for juice industries. In order to evaluate the applicability of ohmic technology for sterilization of juice and purees from these fruits, a stationary ohmic heating system has been built and tested on these three types of fruit juice. The electrical conductivities, heating rates, and system performance coefficients were measured. This study found that the electrical conductivities of all these fruit juices were ranging from 0.128 to 0.430 S.m⁻¹ which increased linearly with temperature. The heating rates were 0.57-0.66 °C/s and the SPC values were ranging from 0.64 - 0.81. This study concluded that ohmic heating is suitable for sterilization of these three types of fruit juices as it could provide a short heating time and a high coefficient of performance. However, the designed ohmic heating system seems to suit better for jambolana juice than for mulberry and bignay juice.

Keywords: ohmic heating, electrical conductivity, mulberry, bignay, jambolana

1. Introduction
Increasing demand for health-promoting products perceived as a great potential for a tropical country like Indonesia with its extensive diversity of exotic fruits. Several berry-like fruits such as mulberry (*Morus nigra*), bignay (*Antidesma bunius*), and jambolana (*Syzygium cumini*) are known as an indigenous species in Indonesia and are underutilized to its optimum potential. Several researchers have reported previously that these fruits possessed an excessive amount of bioactive compounds such as phenolic and anthocyanin which have high free-radical scavenging activities [1-3]. Besides, since these trees can grow well naturally in the wild with a high production yield [4], it can be highly advantageous to be cultivated by local farmers with limited resources.
Processing fruits into juices is considered an effective preservation method as it ensures food safety and extends the product shelf life, and can therefore allow a wider distribution range [5], [6]. Sterilization is a substantial aspect of juice processing as it provides the destruction of pathogenic and detrimental microorganisms and spores. Conventional thermal treatment is the most widely applied sterilization method by food industries. This conventional method relies on the heat transfer mechanism which may limit the uniformity of heating and resulting in either over-processing of the product near the heating source or cold spot in the center of the product, especially in bigger processing scales [7].

The growing interest towards alternative heating methods which can provide better heating uniformity has increased the potential used of ohmic heating as a substitute for conventional heating. Ohmic heating is an advanced thermal treatment where the heat is induced from inside the product without the presence of heat transfer by applying alternating electric current within the processed products. The underlying concept of ohmic heating is where electric current flows through a product with sufficient electrical conductivity, creating an agitation of molecule inside the product and proportionally increase the product temperature. The heating rate is directly influenced by electrical conductivity, voltage gradient strength, and product types [8-14]. Several studies have been conducted to evaluate the effectiveness of ohmic based technology in microbial and enzyme inactivation. Park and Kang [15] reported that at a moderate heating temperature (55-60 °C) ohmic heating provided a better bacterial reduction rate compared to conventional heating, specifically for acidic fruit juice such as apple juice. The voltage gradient applied during ohmic heating can initiate electroporation which damages the cell membrane. This effect combined with the stress from applied temperature increase the cell permeability and therefore causing faster cell disruption [7,15]. Applying a voltage gradient at low intensity also can significantly affect the inactivation of browning enzyme such as peroxidase and polyphenol oxidase [16,17]. Ohmic-treated orange juice has been reported to retain some important flavor compounds (decanal, limonene, octana, myrcene, and pinene) during storage and provided a longer sensory shelf life than conventional thermal heating [18].

The feasibility of ohmic heating highly depends on the product’s electrical conductivity as it represents the ability of a product to transmit electric charges and therefore it directly affects the heating rate during the process [8]. Electrical conductivity influenced by temperature, voltage gradient applied, and the product components such as ionic compound, fat content, and free water [12,13]. Information regarding the change in electrical conductivity of a product under ohmic heating is crucial in determining the processing setup and designing a scale-up system. Therefore, this study aimed to investigate the potential use of ohmic heating for sterilization of berry-like fruit juice from Indonesia based on the electrical conductivity, heating rate, and the coefficient of performance of the ohmic heating.

2. Materials and methods

2.1. Design of ohmic heating system

A static ohmic heating system was built for the laboratory scale experiment. The ohmic heating was constructed by a power supply system integrated with temperature control and data acquisition system which are connected to an ohmic heating chamber where the heating process takes place. The schematic illustration of the ohmic heating system was displayed in Figure 1 [19].
2.1.1. Integrated control system
The system input was an altering electric current (AC) which was supplied from the main power supply system and fed to the heating chamber throughout the electrodes. A data logger (CR1000X, Campbell Scientific, Logan, Utah, USA) was implemented to automatically record and store the values of the system inputs (voltage and current) and output (temperature) during the heating process with 1 second time interval. The flow of electric current to the electrodes were controlled using a 1/16 DIN Temperature Controller (CN9400, Omega Engineering, Norwalk, Connecticut, USA) based on the temperature of the product. The temperature was measured using a T-type Thermocouple (Omega Engineering, Norwalk, Connecticut, USA) that was positioned at the center of the ohmic heating chamber.

2.1.2. Ohmic heating chamber

The heating chamber body was made of Polytetrafluoroethylene (PTFE) material with a 16 cm length, 4 cm internal diameter, and 8.89 cm outside diameter. The maximum capacity of the heating chamber was ± 150 mL. Two food-grade stainless steel (SS304) electrodes were attached at both end of the ohmic heating chamber and secured with a cap made from the same material.
as that of the ohmic heating chamber body. The joint between the electrodes and the body of the heating chamber was locked with a 3½ inch ferrule connector clamp (SS304). The designed ohmic heating chamber is illustrated in Figure 2.

2.2. Fruit juice preparation
Bignay and jambolan fruits were bought from a traditional market in Makassar, South Sulawesi, Indonesia, while the mulberry fruit was harvested from Soppeng, South Sulawesi, Indonesia. All fruits were washed thoroughly using tap water before they were processed into juice. Juice from the fruits was obtained by using a commercial juicer (Philips HR1832) followed by additional filtration to remove the remaining pulp. The single strength juice was stored at -20°C until used. The pH and total soluble solid content of each juice were given in Table 1.

| Juice Types   | Total Soluble Solid (°Bx) | pH       |
|---------------|---------------------------|----------|
| Mulberry juice| 13.93 ± 0.05              | 4.05 ± 0.01|
| Bignay juice  | 14.67 ± 0.09              | 3.45 ± 0.03|
| Jambolan juice| 15.60 ± 0.02              | 3.45 ± 0.02|

2.3. System performance evaluation
The following parameters were applied to evaluate the designed ohmic heating system; the heating rate of the product, the electrical conductivity changes during heating, and the energy required by the system to conduct the heating process. The evaluation of ohmic heating performance was carried out by heating each type of juice at 110°C and holding time of 30 s. The average voltage gradient applied to the system was fluctuated in the range of 17.9 - 18.5 V cm⁻¹. The experiment was conducted in triplicate.

2.3.1. Electrical conductivity measurement
The electric current (I) and voltage (V) data recorded during the heating process were used to determine the resistivity value (R) of fruit juice based on the Ohm’s law (equation 1) [20]:

\[ R = \frac{V}{I} \]  

The electrical conductivities of fruit juice (\(\sigma, \text{S m}^{-1}\)) were determined using equation 2 [20].

\[ \sigma = \frac{L}{AR} \]  

where \(L\) is the distance between two electrodes (m), \(A\) is the reactor cross sectional area (m²), and \(R\) is the resistivity of the fruit juice (Ω).

2.3.2. Energy consumption measurement
The measurement of energy consumed by the system was conducted according to the method described in [21] with modifications. Parameters used to measure the energy consumption of the ohmic heating system were listed in Table 2. The total amount of energy supplied to the system was calculated based on the voltage, current, and time data (equation 3).

\[ E_g = \sum \Delta V t \]  

The cumulative energy consumption was determined using Simpson 3/8 mathematical approach described in equation 4 [22].

\[ \sum E_g = \frac{3h}{8} [E(t_0) + 3E(t_i) + 3E(t_0) + E(t_n)] \]
The theoretical energy necessary to heat the product until reaching the targeted temperature was determined based on the general heat equation (equation 5). The specific heat of each fruit juice was assumed according to the specific heat of blackberries.

$$Q = m \cdot c_p \cdot (T_f - T_i)$$  \hspace{1cm} (5)

| Parameters used in the energy consumption measurement | Value | Unit |
|-----------------------------------------------------|-------|------|
| Distance between electrodes                         | 12.1  | cm   |
| The diameter of the ohmic reactor                   | 4     | cm   |
| The density of fruit juice                          |       |      |
| Mulberry juice                                      | 908.7 | kg m$^{-3}$ |
| Bignay juice                                        | 894.6 | kg m$^{-3}$ |
| Jambolanana juice                                   | 1094.2| kg m$^{-3}$ |
| Volume of sample                                    | 150   | mL   |
| Specific heat of blackberries$^{[20]}$              | 1.926 | kJ kg$^{-1}$°C$^{-1}$ |

3. Results and discussions

3.1. Electrical conductivity and heating rate of fruit juice

Electrical conductivity is an important product property for ohmic heating since ohmic heating relies on the electric current to generate heat from inside the product. Optimum electrical conductivity values were ranging between 0.1-5 S m$^{-1}$ [13]. The electrical conductivities of the three berry-like fruit juice at 33-110°C were found to be optimum for ohmic heating, ranging from 0.144-0.430 S m$^{-1}$ for mulberry juice, 0.128-0.390 S m$^{-1}$ for bignay juice, and 0.137-0.363 S m$^{-1}$ for jambolana juice (Figure 3). Similar electrical conductivity ranges were found in the blueberry pulp (4-16% solid content) at the temperature of 30-82°C (0.79-3.86 mS cm$^{-1}$) [23], strawberry pulp undergoing ohmic heating at the voltage gradient of 40-80 V cm$^{-1}$ (0.001-0.004 S cm$^{-1}$) [24], pomegranate juice heated from 20-85°C with voltage gradient ranging from 30-55 V cm$^{-1}$ (0.209-1.013 S m$^{-1}$) [25], and watermelon juice at temperature range of 35-95°C and voltage gradient 10-23.33 V cm$^{-1}$ (0.23-1.23 S m$^{-1}$) [26].

| Juice Type          | Electrical conductivity | R$^2$ | Heating rate          | R$^2$ |
|---------------------|------------------------|-------|-----------------------|-------|
| Mulberry juice      | 0.0032T + 0.0388       | 0.998 | 0.6597t + 27.947      | 0.987 |
| Bignay juice        | 0.0034T + 0.0111       | 0.998 | 0.5652t + 29.150      | 0.992 |
| Jambolanana juice   | 0.0029T + 0.0128       | 0.999 | 0.5726t + 30.031      | 0.991 |

The temperature dependence of electrical conductivity followed the linear equation with R$^2 > 0.99$ as represented in Table 3. The electrical conductivity of fruit juice increased following the temperature elevation during heating. Increased in temperature caused membrane destruction inside the cells which leads to the structural change, released of ionic compound, and simultaneously increased the electrical conductivity [8,23,24]. The change in electrical conductivity was attributed by the reducing drag force of compounds that affected the ionic mobility inside the product [27]. Studies conducted to evaluate the influence of voltage gradient on product’s conductivity described that the voltage gradient significantly affected the electrical conductivity. Elevating the voltage gradient provided a greater amount of current that passed through the product and allowed a rapid movement of the ionic compounds and therefore increased the
electrical conductivity of the product at the given temperature [21,25,28]. Castro et al. (2004) analyzed the electrical conductivity of different strawberry products and obtained that electrical conductivities differ between each type of product. This study suggested that strawberry topping which provided 5-19% smaller electrical conductivity value compared to strawberry pulp required to be processed under different ohmic heating designs. In addition, electrical conductivity is also affected by sugar content and soluble solid where the electrical conductivity decreased following the increase in concentration and sugar content [27,29,30]. The different effects of the voltage gradient on various products which also depended on the product constituent and characteristics illustrated the importance of electrical conductivity determination to ensure an effective and efficient ohmic heating performance.

Figure 3. The electrical conductivity of berry-like fruit juice under ohmic heating

![Electrical Conductivity vs Temperature](image1.png)

Figure 4. Ohmic heating curves of three berry-like fruit juice

![Heating Curves](image2.png)

The heating rate of a product obtained by plotting the temperature and time required to reach the designated temperature followed by fitting a linear model on the previously obtained heating trend. The slope acquired from the graph attributed to the heating rate of the product (°C s⁻¹). The ohmic heating of the three berry-like fruit juice used in this study resulted in the following heating rate of 0.66, 0.57, and 0.57°C s⁻¹ for mulberry, bignay, and jambolana juice, respectively. The
heating rate of mulberry juice obtained in this study agreed with the results of a previous study which applied ohmic heating technology for concentration process of mulberry juice [31]. This study reported heating rates ranging from 0.221°C s⁻¹ to 0.885°C s⁻¹ at the voltage gradient of 15 – 30 V cm⁻¹ [31]. Comparable heating time was found in ohmic heating of grape juice (± 120 s) which was performed at a proportional voltage gradient of 20 V cm⁻¹ [32].

The heating rate during ohmic processing influenced by the products electrical conductivity [12]. High electrical conductivity provided rapid ion mobility and therefore increased the rate of heat generation inside the product and consequently shortened the heating time. For illustration, ohmic heating of tomato paste at 14 V cm⁻¹ resulted in a higher heating rate of 2.031 °C s⁻¹. The result implicated that the electrical conductivity of tomato paste was higher than the electrical conductivity of fruit juice found in this study [33]. At a given voltage gradient, the rate of heat generation was found to be proportional to the electrical conductivity changes during heating [12,21].

Based on the operating condition during ohmic heating, the voltage gradient represented as an important parameter affecting the heating rate of a product. Inducing a higher voltage gradient will result in a greater energy input to the product and provides a faster heating rate during the process [25], [28]. Ohmic heating performed at 30 V cm⁻¹ on pomegranate, lemon, and grapefruit juice resulted in a higher heating rate of 1.392, 1.462, and 1.124°C s⁻¹, respectively [25,28]. Strawberry pulp treated with ohmic heating at 70 V cm⁻¹ provided an even higher heating rate of 6.22 °C s⁻¹ [24]. The narrative above showed the importance of adjusting the system design and operational conditions of ohmic heating with the product characteristics, especially the electrical conductivity of the product.

3.2. System performance of Ohmic heating

The efficiency of the ohmic heating for sterilization of berry-like fruit juice was determined based on the system performance coefficient (SPC) which was outlined as the ratio between the theoretical energy required to heat the fruit juice to a specific temperature (heat required for heating) with the electrical energy supplied to the system. The SPC of the three fruit juice used in this study is illustrated in Figure 5.

The SPC was 0.64 for mulberry juice, 0.66 for bignay juice, and 0.81 for jambolana juice. The results indicated that 19 – 36% of the energy was used for other processes besides heating the sample. The term is known as the energy loss (E_{loss}) of the system. The E_{loss} can be caused by several factors, such as the heat released to the surrounding environment via natural convection, the energy absorbed by the body and electrodes of the ohmic heating chamber, and the energy used for other process during heating such as the chemical, physical, and electrochemical reaction [21,27,30]. Based on the SPC value obtained, the current design of the ohmic heating system displayed better suitability for jambolana juice. It was explained by the lower electrical conductivity of jambolana juice compared to the two other juice. The result is similar with the study reported by Icier and Ilcali [27] which indicated that electrical conductivity was negatively impacted the SPC of ohmic heating. Their study found that sour-cherry juice which possessed higher electrical conductivity than apple juice resulted in a higher energy loss and smaller SPC value. Although the SPC values of mulberry and bignay juice were relatively lower than that of the jambolana juice, the values were well in the range of 0.47 - 0.92 which were considered as the SPC value of liquid product processed by ohmic heating [25]. The SPC value obtained for mulberry juice in this study was in accordance to the SPC values reported by Darvishi et al. [33] for ohmic heating of mulberry juice, which ranged from 66.61 to 74.27%. The study also reported that ohmic heating performed up to 38 – 46% better than conventional heating as the result of the internal temperature rise during ohmic heating which prevented the E_{loss} from the conduction process.
Consistent with electrical conductivity and heating rate, the SPC of ohmic heating also depends on the voltage gradient, where higher SPC value was achieved at a lower voltage gradient [21,25]. The SPC value of apricot puree decreased from 1.0 to 0.49 following the application of higher voltage gradient from 20 to 70 V cm\(^{-1}\) [21]. Icier and Ilcali [27] stated that since the SPC value at lower voltage gradient was high (0.88 - 0.92), the energy loss was solely explained as the energy used to heat the reactor or test cell approximated to be between 2-8% of the total energy supplied to the system. At a higher voltage gradient, greater energy loss was obtained which implied that other processes occurred during ohmic heating which absorb part of the electrical energy that is supplied to the system. The possible reaction that occurs include electrochemical reaction resulted from the use of stainless steel electrodes to pass the electric current and conducted the ohmic heating process [34].

4. Conclusion
Ohmic heating process conducted on the juice of mulberry, bignay, and jambolana implied that the electrical conductivity of all the juice increased linearly following the rise in processing temperatures (\(R^2 > 0.99\)). The voltage gradient played as a key factor affecting the heating rate, electrical conductivity, and the performance of the ohmic heating system. The different effects of the voltage gradient on various products which also depended on the product constituent and characteristics illustrated the importance of electrical conductivity determination to ensure an effective and efficient ohmic heating performance. Based on the SPC value obtained, the current design of the ohmic heating system displayed better suitability for jambolana juice. The obtained electrical conductivity values indicated that the three types of fruit juice used in this study showed a great potential to be sterilized by ohmic heating as it provided a relatively controllable heating rate at lower voltage gradient and allowed more room for ohmic heating system modification.

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