



Effects of different ripening stages on the physiological, biochemical, and sensory properties of microwave-dried berangan banana (*Musa acuminata*)

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Abstract

Bananas are a climacteric fruit, which means that they continue to ripen after harvest. To increase the length of time that bananas may be stored, a variety of dried banana products are made utilizing the microwave drying method. However, it is unknown at what stage of banana ripening is most suited for microwave drying. The purpose of this study is to examine how various ripening stages affect the quality of microwave-dried bananas. *Musa acuminata* Colla cv. Berangan bananas in three different ripening stages (3, 5, and 7) were selected, and banana discs with a thickness of 5.0 ± 0.1 mm were microwave-dried using the settings optimized in this study (*i.e.*, 300 W, 10 s drying time with 50 s intermittent time). Physiological (colour, total soluble solids, titratable acidity, moisture content), biochemical (total carotenoid content, total polyphenol content, and total antioxidant content), and sensory acceptance were among the criteria used to evaluate the samples. Our results showed that the optimized drying parameters reduced the moisture content for all ripening stages of dried bananas within the safety moisture content level for dried food (5%). The dried bananas of the ripening stage 7 had the highest color change of 44.68, total soluble solid content to titratable acidity of 16.93, total antioxidant level of 2183.98 $\mu\text{g/g}$ DW, total polyphenol content of 5.92 mg GAE/g DW, and sensory acceptance level of 4.3. In summary, the best bananas for microwave-dried banana chips are those at a stage 7 ripening stage.

Keywords Banana · Microwave · Drying · Ripening · Physicochemical

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Introduction

Bananas (*Musa sp.*) have gained global attention and interest due to their sweet and flavorful taste. Bananas are multifunctional fruits as they are rich in carbohydrates, minerals, fiber, and vitamins [1]. Bananas also have high antioxidant activity due to high levels of phenolics, flavonoids, and tannins that can scavenge the free radicals and protect the cells from oxidative stress [2]. This can slow down the degenerative process and prevent related diseases, such as hypertension and cardiovascular disease [2].

According to the Food and Agriculture Organization, FAO [3], the world production of bananas has exceeded 100 million tonnes since 2009, while in 2020, the total world production of bananas reached 119.8 million tonnes. The Observatory of Economic Complexity (<https://oec.world/en/profile/bilateral-product/bananas/reporter/mys>) reported that Malaysia exported USD 10.3 million worth of bananas in 2020, making Malaysia the 53rd largest global exporter of bananas. The main destinations of bananas exported from Malaysia are Singapore,

Brunei, and the United States. In Malaysia, bananas cover more than 11% of the total area of fruit production and are considered the second premier fruit after durian.

Due to its climacteric nature, the banana is considered a perishable fruit with limited postharvest shelf life. In fact, almost 25–50% of banana postharvest loss occurs as a result of rapid ripening and physiological deterioration. High moisture content and a nutrient-rich environment also promote the growth and development of bacteria. Therefore, there are various preservative techniques available, such as using heat [4], salt [4], and chemicals [5]. Bananas are often processed into various products such as powders, chips, and fig. Among many of the preservative methods for fruits, drying is the most popular and widely utilized method in the processing field due to its relatively low cost [6]. Not only that, drying extends the shelf life by reducing the moisture content of the product to a safe level, which prevents the growth and development of bacteria as well as other microorganisms. The deterioration of the products is slowed down due to the reduction in moisture content [7].

Microwave drying is one of the popular drying techniques due to its low consumption and energy efficiency [8]. The electromagnetic wave heats the fruit samples via vibrating the molecules within the fruit slices causing the uniform heating of the whole fruit, eventually leading to acute deduction of the moisture content [9]. Intermittent drying is an alternative drying method to dry fruits and vegetables other than continuous convective drying. Microwave intermittent drying is a common microwave drying process that controls the heating time and microwave power, and alternates with certain tempering periods [8, 10]. This method shortens the drying time inside the dryer, reduces energy consumption, improves quality, and retains the heat-sensitive material within the dried products by inducing milder temperatures [11, 12].

Previous studies on drying banana slices have applied different processing parameters such as microwave power, intermittent time, and slice thickness [10]. According to the study, all the parameters mentioned above significantly impact the drying rate. However, there is a lack of research investigating how different ripening stages of bananas may affect the quality of microwave-dried bananas. Herein, this study aims to investigate the effects of different ripening stages (stage 3, 5, and 7) on the quality of dried Berangan bananas.

Materials and methods

Chemicals and instruments

Methanol and hexane were purchased from SYSTERM®, 2,2-diphenylpicrylhydrazyl (DPPH) was purchased from

EMD Millipore, ascorbic acid, Fiolin-Ciocalteu reagent, phenolphthalein, sodium carbonate, and gallic acid were purchased from R&M Chemicals, acetone was purchased from Fisher Chemical, ethanol was purchased from ChemAR, anhydrous sodium hydroxide was purchased from Merck. Other instruments and apparatus are colorimeter (Color Grab version 3.9.2© 2021 Loomatix Ltd.), digital refractometer (ATAGO PR-1), microwave (Samsung ME731-M), desiccator, oven (Mettler UL4001), spectrophotometer (Thermo Fisher), centrifuge (Beckman Coulter Allegra X-30R), homogenizer (Labfeng), rotary shaker (Jeio Tech S1900R), freezer (ESCO HP Series), water bath (Mettler), and electronic balance (Precisa 12VPC).

Preparation of banana sample

Berangan bananas (*Musa acuminata* Colla cv. Berangan) of three different ripening stages (stage 3, 5, and 7) were purchased from a local wet market, in Petaling Jaya, Malaysia on January 15 and February 15, 2024 and immediately transported to the Postharvest Laboratory, Universiti Malaya for cleaning and selection process. Berangan banana's ripening stages were determined based on the ripening chart from Majaliwa et al. [13], which classifies ripening based on peel colour: stage 3 banana starts to turn yellow but still has green areas; stage 5 banana peel is completely yellow; the entire peel of stage 7 banana turns brown or black. All bananas used in this study were free from observable diseases and mechanical injury. Bananas brought to the laboratory were used immediately for experiments. Fruits were peeled and sliced into discs of 5 mm thickness, with an average diameter of 3.0 ± 0.5 cm. A total of six fruits were used for each experiment and three technical repeats were carried out.

Optimization of microwave drying parameters

Determination of microwave power for drying

The samples were placed on baking paper and the initial mass of the samples was weighed. The samples were placed on the microwave plate in a circular layout and dried using 300 W of microwave drying power. The weight of the samples was recorded every 10 s until a constant weight (± 0.01 g) was achieved. The same procedure was repeated using 450, 600, and 800 W of microwave power.

Determination of drying time and intermittent time

The samples were dried using 300 W of microwave drying power. After 10 s of drying time, the drying was stopped for 50 s (intermittent time). The weight of the samples was recorded every 10 s of drying until a constant weight (± 0.01 g) was reached. The procedure was repeated using

20 s drying with 50 s intermittent time, 30 s drying with 50 s intermittent time, and 5 min drying without intermittent time. The average weight of the samples was calculated and a graph of weight against drying time was plotted.

Determination of total drying time

The ripening stages 3, 5, and 7 banana discs were dried for 10 s followed by 50 s of intermittent time using 300 W of microwave (Samsung ME731-M) drying power. The weight of the samples was recorded every 10 s until a constant weight (± 0.01 g) was reached. The average weights of the samples were calculated and recorded. A graph of weight against total drying time was plotted.

Physiological analysis

Preparation of the dried banana slices

The banana samples were placed on baking paper and the initial mass was weighed. Samples were dried for 10 s followed by 50 s of intermittent time using 300 W of microwave drying power until 220 s of total drying time. The procedures were repeated for stages 5 and 7 of Berangan banana samples using 210 s of total drying time (drying time for samples was determined based on the results obtained from the previous section).

Determination of color change between fresh and dried banana slices

Color parameters were measured using the Color Grab version 3.9.2© 2021 Loomatix Ltd. The colorimeter was positioned perpendicularly to the banana surface. Three different points (top, middle, and bottom) on each banana were measured to ensure uniformity. The values of lightness (L^*), red-green axis (a^*), and yellow-blue axis (b^*) before and after drying were recorded. The color change, ΔE was calculated using the formula (Eq. 1) [14]:

$$\Delta E = \left[(L_o - L)^2 + (a_o - a)^2 + (b_o - b)^2 \right]^{1/2} \quad (1)$$

where,

L_o initial lightness

a_o initial red-green axis.

b_o initial yellow-blue axis.

L final lightness.

a_o final red-green axis.

b_o final yellow-blue axis.

Determination of total soluble solid

The total soluble solids (TSS) of dried samples were analyzed according to Rongtong et al. [15]. A 1.3 g portion of dried sample was ground using a mortar and pestle, followed by the addition of 3 mL of distilled water. The total soluble solids (TSS) were determined using a digital refractometer (ATAGO PR-1) and expressed in °Brix.

Determination of titratable acidity

The titratable acidity (TA) of the sample was determined according to the protocol outlined by Shalini et al. [16], to detect the presence of primary organic acids such as malic acid and citric acid. Two grams of sample were ground using mortar and pestle, followed by the addition of 30 mL of distilled water to the ground sample. The mixture was filtered using a Muslin cloth, and 10 mL of the filtrate was pipetted into a conical flask. Two drops of 1% phenolphthalein solution were added to the mixture and titrated using 0.1 M sodium hydroxide in a burette until the color of the solution changed and lasted for at least 15 s. The volume of sodium hydroxide used was recorded. The TA was calculated by the formula (Eq. 2):

$$\% \text{ of TA} = \frac{0.1 \text{ M NaOH} \times \text{volume of NaOH (in litre)} \times 192.43}{\text{Weight of sample}} \times 100 \quad (2)$$

Determination of moisture content of the dried banana discs

The moisture content of the dried banana discs was determined according to the protocol outlined by AOAC [17]. The empty petri dish and the cover lid were dried in the oven (Memmert ULM4001) at 70 °C for 3 h. The empty petri dish and the cover lid were transferred to the desiccator to cool and were weighed. The dried samples were transferred into the petri dish and vacuum dried for 24 h at 70 °C. After drying was completed, the dish containing the sample with a partially covered lid was transferred to the desiccator to cool. The dish and its dried sample were reweighed. The moisture content of the dried banana was calculated by using the formula (Eq. 3):

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (3)$$

where W_1 is the weight (g) of the sample before drying while W_2 is the weight (g) of the sample after drying.

Biochemical analysis

Preparation of the banana sample for antioxidant analysis

Fresh and dried samples were ground into powder with liquid nitrogen using a mortar and pestle. The banana powder was stored in a −20 °C freezer until further analysis.

Determination of total carotenoid content

The total carotenoid content of the sample was determined according to the protocol outlined by Mat Saad et al. [18] with some modifications. A hexane: acetone: ethanol extraction buffer was prepared according to a 2:1:1 ratio. Then, 5 g of samples were weighed and added into 10 mL of extraction buffer. The mixture was homogenized for 1 min by using a homogenizer (Labfeng). The mixture was centrifuged at 6500 rpm for 10 min at 5 °C, and subsequently, the supernatant was collected. The absorbance of the supernatant was measured at 445 nm by using a spectrophotometer (Thermo Fisher). Total carotenoid content was calculated by using the equation (Eq. 4):

$$\text{Total carotenoid} \left(\frac{\text{mg}}{100\text{g}} \text{DW} \right) = \frac{A \times V(\text{mL}) \times 10^6}{A_{1\text{cm}}^{\%} \times 10^3 \times W} \quad (4)$$

where A is absorbance, V is the volume of extract, $A_{1\text{cm}}$ is the specific extinction coefficient of carotenoid in a selective solvent, *i.e.*, hexane (2592), and W is the weight of banana powder.

Determination of total antioxidant content

The extraction of fresh and dried bananas for antioxidant analysis was conducted according to the protocol outlined previously [19]. Ten grams of samples were transferred into a Falcon tube containing 10 mL of 80% methanol. The tubes containing the mixture were placed on the rotary shaker (Jeio Tech S1900R) at 150 rpm for 30 min at room temperature. The mixture was centrifuged at 6500 rpm for 15 min at 4 °C. The supernatant obtained was collected and used for subsequent antioxidant analysis. The determination of total antioxidant content was conducted according to the protocol outlined by Alothman et al. [20]. Briefly, the standard graph was prepared using different concentrations of ascorbic acid (20, 40, 60, 80, and 100 µg/mL). Subsequently, 0.5 mL of ascorbic acid solution with different concentrations was added to 1 mL of 0.1 mM DPPH solution in 80% methanol in a 2 mL micro-centrifuge. The mixtures were vortexed for 15 s. The mixtures were incubated in the water bath at 37 °C for 30 min in a dark place. The same procedure was repeated on banana samples. Absorbance was measured at 517 nm and the total antioxidant contents were expressed as ascorbic acid equivalent per 1 g sample (µg/g DW).

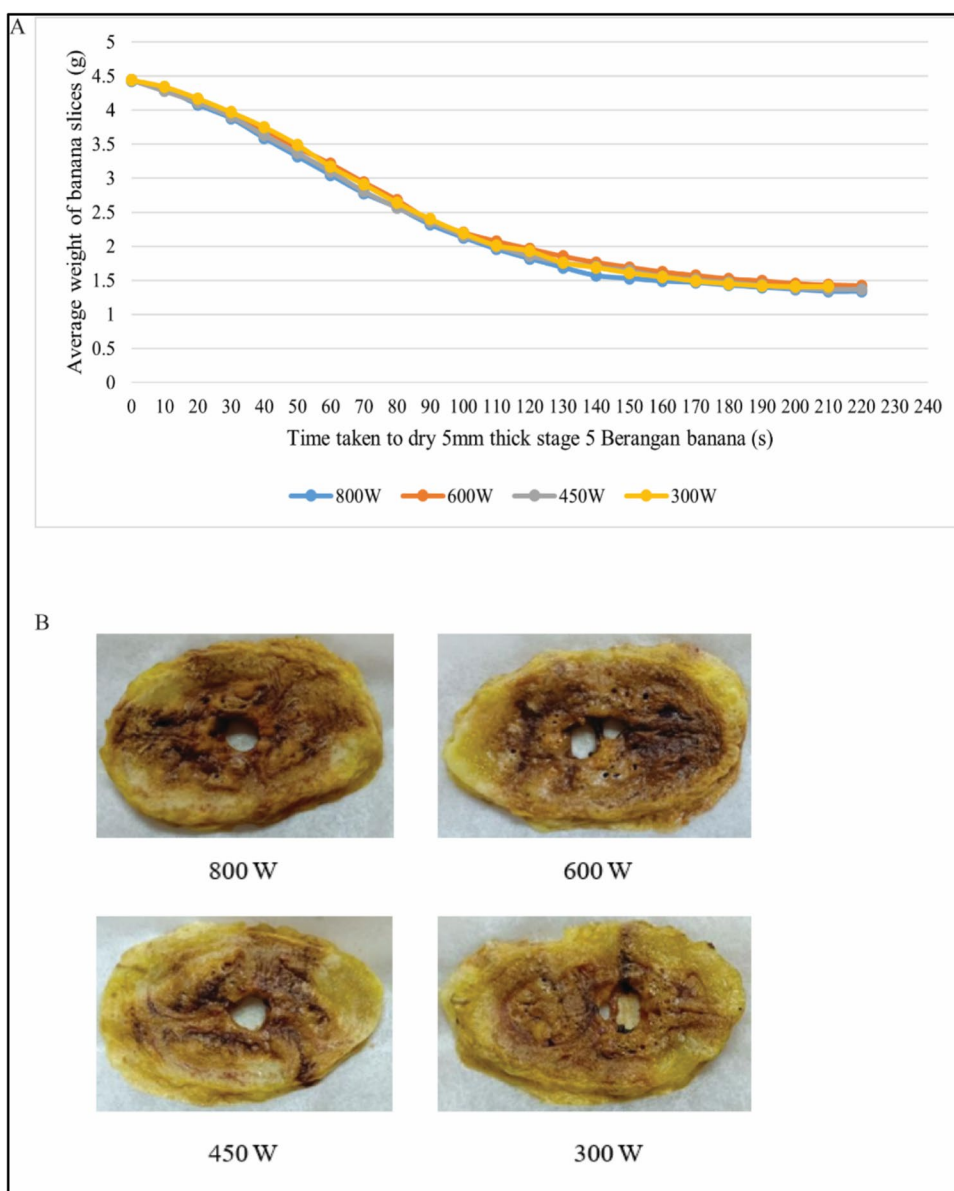
Determination of total polyphenol content

The extraction of fresh and dried bananas for antioxidant analysis was conducted according to the protocol outlined above. Then, the total polyphenol content was determined according to Singleton et al. [21]. Briefly, the standard graph was prepared using different concentrations of gallic acid (0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 mg/mL). Subsequently, 0.79 mL of distilled water and 0.01 mL of gallic acid (0.2–1.2 mg/mL), as well as 0.05 mL of Folin-Ciocalteu reagent, were added in a 1.5 mL Eppendorf tube. The mixture was mixed thoroughly. After 1 min, 0.15 mL of sodium carbonate (20 g/100 mL) was added. The mixture was allowed to stand at room temperature (25 °C) for 120 min in the dark. The same procedure was repeated on banana samples. The absorbances of gallic acid standards and samples at 750 nm were measured. The total polyphenol content (TPC) in the samples was determined and expressed in mg of gallic acid equivalent per g sample (mg GAE/g DW).

Sensory analysis

The samples were placed in three different containers labelled A, B, and C. Thirty non-professional responders were invited to test the dried samples. The responders were provided with crackers, pens, and sensory analysis forms. The responders were required to clean the palate by using crackers to start the sensory analysis and also before tasting a different sample.

Fig. 1 (A) Time taken to dry 5 mm thick banana slices at different microwave powers with 10 s drying time and 50 s intermittent time. (B) The appearance of banana dried using different microwave power



The responders were required to choose from 1, which was “extremely dislike” until 5, which was “extremely like” for different sensory parameters, such as appearance, taste, smell, and overall preference in the sensory analysis forms.

Statistical analysis All data are presented as the means $\pm$ standard deviation of triplicates. Data from physicochemical analysis and biochemical analysis were analyzed by one-way analysis of variance (ANOVA) using SPSS version 22 (IBM). The differences between means were compared by post-hoc Tukey’s Honestly Significant Difference Test at a 5% ($p < 0.05$) probability level.

Results and discussion

Microwave drying parameters

Determination of the microwave drying power

The effect of different microwave power (300, 450, 600, and 800 W) on the time required to dry 5 mm thick banana discs until constant weight is shown in Fig. 1A. The drying time needed to reach a constant weight at microwave powers of 800, 600, and 450 W was 220 s, slightly longer than at 300 W, which required only 210 s. This may be due to

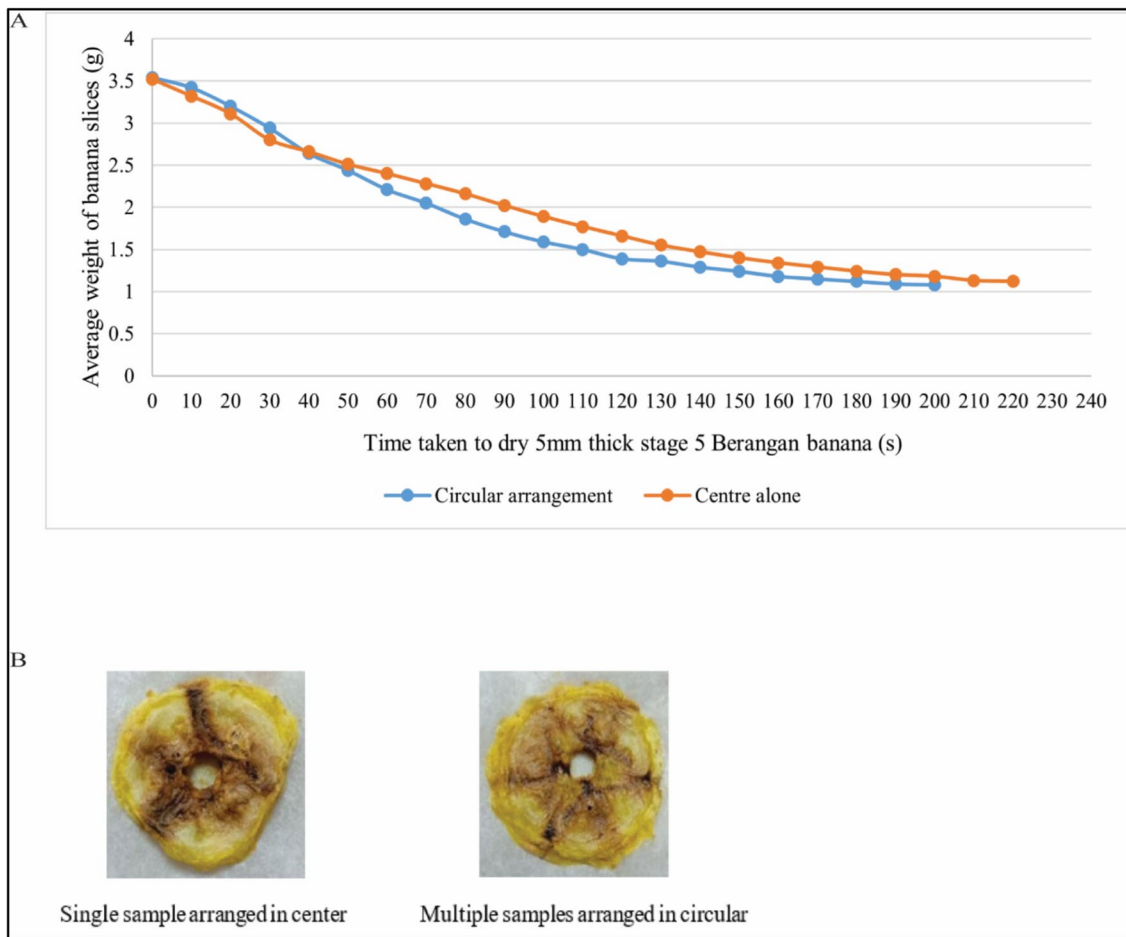


Fig. 2 (A) Time taken to dry 5 mm thick banana slices in different arrangements in the microwave with 10 s drying time and 50 s intermittent time. (B) The appearance of banana dried using different arrangements

excessive microwave power causing the outer layers to dry too quickly, leading to case hardening [22]. Additionally, a high microwave power level may reduce drying efficiency, ultimately resulting in a longer drying time. Furthermore, a high microwave power level may also reduce the drying efficiency, resulting in a longer drying time [23]. At higher power levels, increased heat generation raises the internal vapor pressure [24]. This buildup can prevent moisture from escaping efficiently, leading to moisture retention within the sample [25]. As a result, the drying process slows down, requiring additional time to reach a constant weight.

This result contradicts the previous research findings, which indicate that the higher the power of the microwave, the shorter the time required to reach the desired moisture content [10]. This deviation might be caused by the different heat conductivity of the materials used to dry the banana discs. In this experiment, the banana discs were arranged on a layer of baking paper and placed on the microwave plate, while in previous research by Dai et al. [10], the banana

slices were spread on a silicone rubber tray. Furthermore, the difference may be attributed to environmental factors such as humidity and temperature. These factors were reported to affect moisture loss or uptake by banana tissues Ferreira et al. [26]. Three stages of drying of banana discs, which included the accelerated, constant, and decelerated drying stages are shown in Fig. 1A. This phenomenon showed that diffusion of the moisture from the interior to the surface of banana slices during the drying process was the dominant physical mechanism [10]. However, the effect of higher microwave power on the appearance of the samples can be observed in Fig. 1B. The samples dried using 800 W showed a more blackened area compared to that of 600, 450, and 300 W. The higher the microwave power, the more heat was emitted by the microwave, resulting in a darker appearance.

Caramelization (browning reaction) is positively correlated to the temperature applied to drying food: the higher the microwave power, the greater the rate of sugar degradation and browning [27]. This was also supported by Guiné et al. [28], where the high temperature in the convective

drying led to an increase in the rate of browning reaction due to the formation of oxidized forms of phenolics. Based on the results, drying samples using 300 W of microwave power had the best appearance with the least browning and no burnt area on the surface. Therefore, the subsequent analyses used the microwave power of 300 W.

Determination of the sample arrangement

Arrangement of the banana discs in the microwave is essential for drying because it affects the efficiency of the drying method [9]. Banana discs could be arranged on the microwave plate at the centre alone or in a circular layout. Based on the results in Fig. 2A, drying samples using both types of arrangements resulted in the three aforementioned drying stages. The total drying time for a single sample placed at the center was longer compared to multiple samples arranged in a circular layout, requiring 220 and 200 s, respectively. Furthermore, the single arrangement resulted in a darker appearance compared to the multiple samples arrangement (Fig. 2B).

This might be a result of equal distribution of heat transfer when multiple samples were arranged in a circular layout. In contrast, all the heat emitted was absorbed by the single sample at the center [8]. This may have caused the overheating on the surface of the sample resulting in a darker sample surface compared to the previous sample arrangement. When the samples are arranged in a circular layout, the moisture within the banana can be distributed equally during the intermittent time before the surface receives excessive heat in the next drying process [29]. Moreover, there were more samples dried in the circular layout compared to the single arrangement which leads to higher efficiency of the drying process. In this regard, all samples were arranged in a circular pattern for the subsequent analyses.

Determination of drying time with 50 s intermittent time

Figure 3A shows the time taken for drying banana slices using different drying times (10, 20, and 30 s) with 50 s intermittent time to reach a constant weight. From the graph, the total drying time taken for the banana discs to reach constant weight by using 30 s of drying time was the longest and the 10 s of drying time was the shortest. This is because when the temperature inside the samples increases to a certain value during the prolonged drying time, parts of the microwave energy are lost [10]. Moreover, the moisture in the fruit is not equally distributed during the long drying time, hence the drying process is slowed down compared to the short drying time [29]. The 50 s intermittent time enabled the moisture from the inner part of the sample to diffuse to the surface and 10 s drying time was just enough

to evaporate the surface moisture without penetrating the samples.

Figure 3B shows the appearance of samples dried using the different drying times with intermittent time. The samples dried using 30 s drying time had more burnt area compared to that of 10 s and 20 s. The samples dried using 10 s drying time with 50 s intermittent time had the best appearance due to the presence of a ‘thermal-resistance layer’ since the evaporation occurred on the surface instead of deep inside the banana pulp [30]. The samples that were dried without any intermittent time had a large burnt area on the surface of the banana slices, while other parts were in wet condition due to the inability to distribute the moisture within the banana slice, thus leading to overheating [19]. Furthermore, the longer drying time elevated the temperature in the microwave resulting in higher caramelization [27]. In addition, a study conducted by Thamkaew et al. [31] showed that both convective (hot air) and microwave drying on pineapple resulted in notable color differences between fresh and dried samples with increasing temperatures. Thus, for the subsequent analyses we used 10 s of drying time with 50 s intermittent time.

Determination of total drying time for different ripening stages of banana

According to Fig. 4A, stage 3 samples required 220 s of drying time, while stage 5 and 7 samples required 210 s to reach constant weight. The difference in the total drying time might be due to the different moisture content in the different ripening stages of the banana. Watharkar et al. [32] reported that the moisture content of the banana pulp increased during ripening due to the respiratory breakdown of carbohydrates on the peel and pulp into soluble sugars. Furthermore, moisture is transferred from the peel into the pulp of the banana. As shown in Fig. 4B, stage 7 Berangan banana had the largest blackened area, followed by stages 5 and 3.

The findings of this study are consistent with those of Zhou et al. [33], which demonstrated that increasing banana ripeness leads to a reduction in drying time. This shorter drying time in riper bananas may be attributed to the presence of larger micropores, which likely enhance water diffusion and evaporation during the drying process. A similar trend has been observed in other fruits, such as Thompson seedless grapes and mulberries, where drying time decreases with increasing ripeness [34, 35]. Wang et al. [35] explained that as grapes ripen, their free water content increases significantly, while the bound water distribution decreases, leading to faster drying rates in riper samples. In the case of mulberries, the reduced drying time is attributed to changes in cell structure and pectin properties during ripening [34].

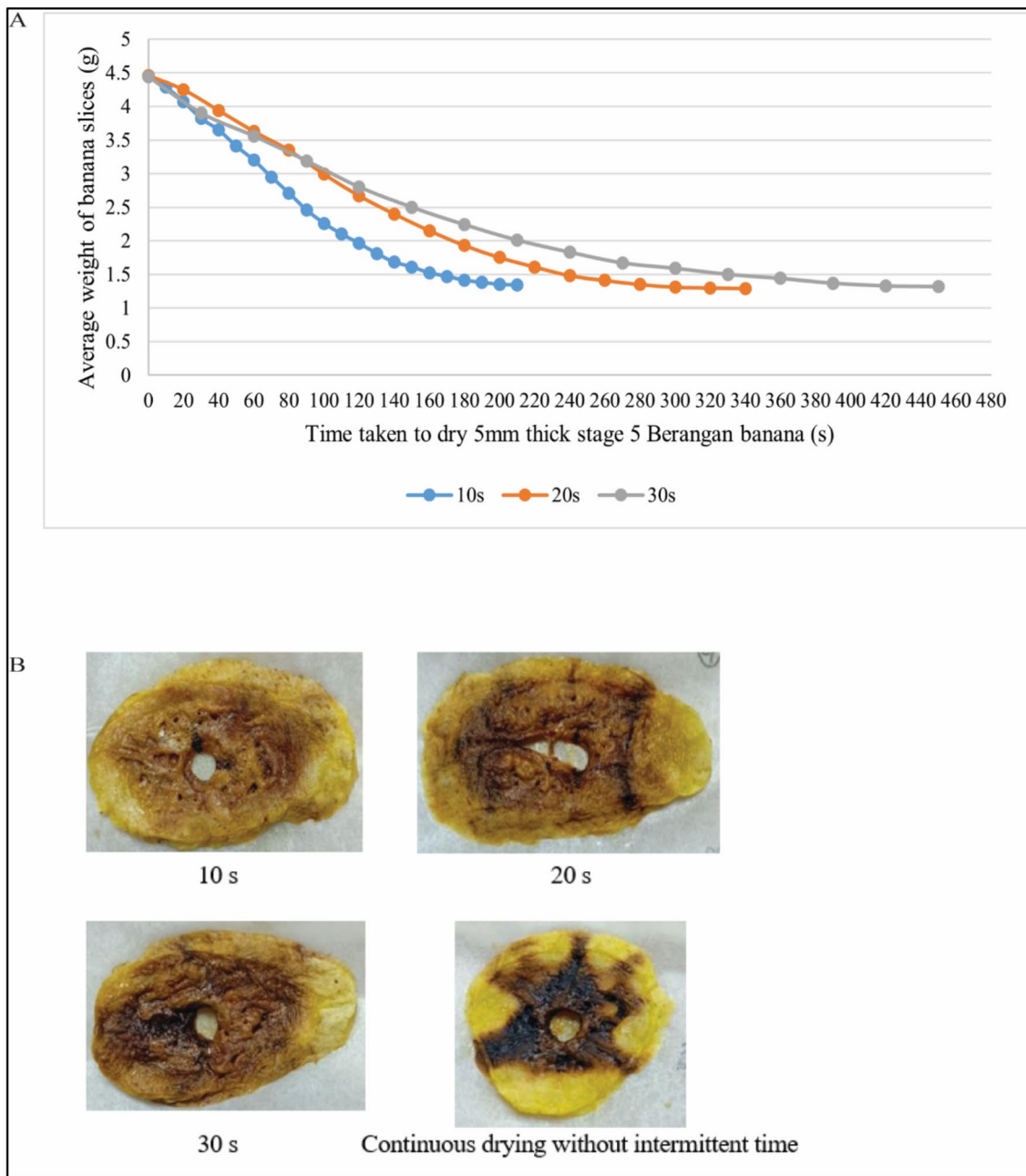


Fig. 3 (A) Effect of different drying time on the drying time required for 5 mm thick banana slices to reach constant weight. (B) Appearance of dried banana using different drying time and intermittent time

Physiological analysis

Color change

Color is an important physiological property of food that significantly influences consumer preference for dried fruit products. Microwave drying significantly affected the L^* values (lightness) of bananas across all ripening stages (Fig. 5A). Fresh banana samples had L^* values of 71.38 ± 5.6 , 71.22 ± 4.2 , and 71.72 ± 2.5 for Stages 3, 5, and 7, respectively.

After microwave drying, these values decreased to 47.00, 43.00, and 39.00, indicating noticeable darkening of the banana slices. The percentage reduction in L^* values ranged from approximately 34.1 to 45.1%. The a^* values of banana samples increased markedly after microwave drying, indicating a transition from a greenish hue in fresh samples to a reddish tone in dried ones (Fig. 5B). This change was particularly evident in Stage 7 (overripe) banana, where the a^* value changed from -1.8 ± 1.5 (fresh) to 14.4 ± 2.0 (dried). The b^* values, which reflect the yellow-blue chromatic component,

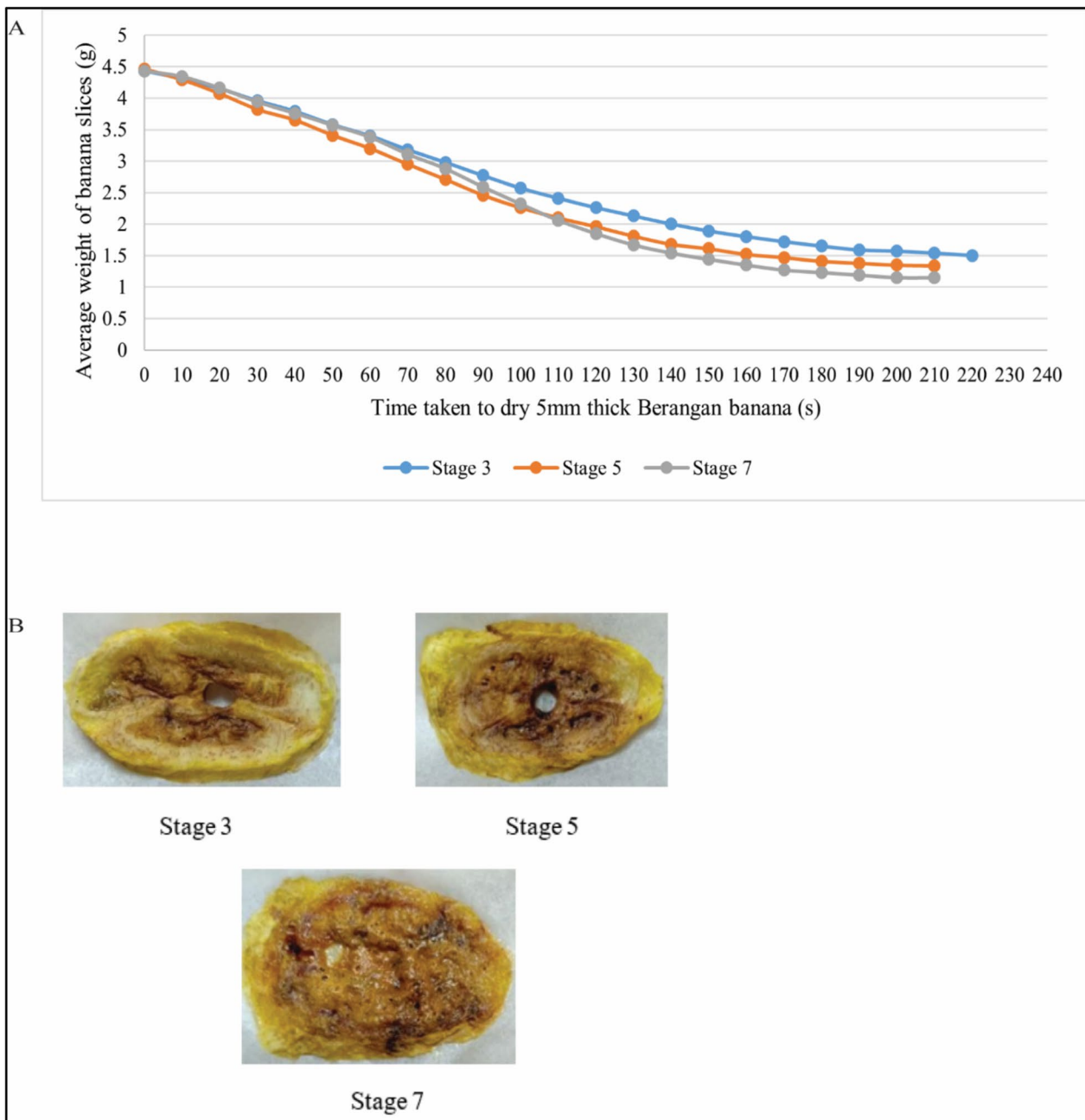


Fig. 4 (A) Total time taken to dry 5 mm thick banana slices of different ripening stages until constant weight with 10 s drying time 50 s intermittent time by using 300 W. (B) Appearance of dried samples using different ripening stages

also declined consistently after microwave drying across all stages of banana ripeness (Fig. 5C). Fresh samples displayed b^* values of 42.9 ± 5.5 (Stage 3), 47.5 ± 3.7 (Stage 5), and 49.6 ± 3.8 (Stage 7). After drying, these values dropped to 39.1 ± 7.4 , 45.1 ± 12.4 , and 40.6 ± 2.6 , respectively. The reduction indicates a loss in yellowness, which can be attributed to pigment degradation during the drying process.

To better quantify the overall colour change resulting from microwave drying, the total colour difference (ΔE)

was calculated based on the changes in L , a , and b^* values. As shown in Fig. 5D, the color change between fresh and dried samples was most pronounced in stage 7 bananas, with a value of 44.67 ± 6.85 . In comparison, stage 3 and 5 samples exhibited smaller color changes, with values of 30.48 ± 2.57 and 30.66 ± 1.13 , respectively. The difference in color change of different ripening stages of bananas may be attributed to the variation in sugar content. Zhou et al. [33] reported that the highest color change was observed in

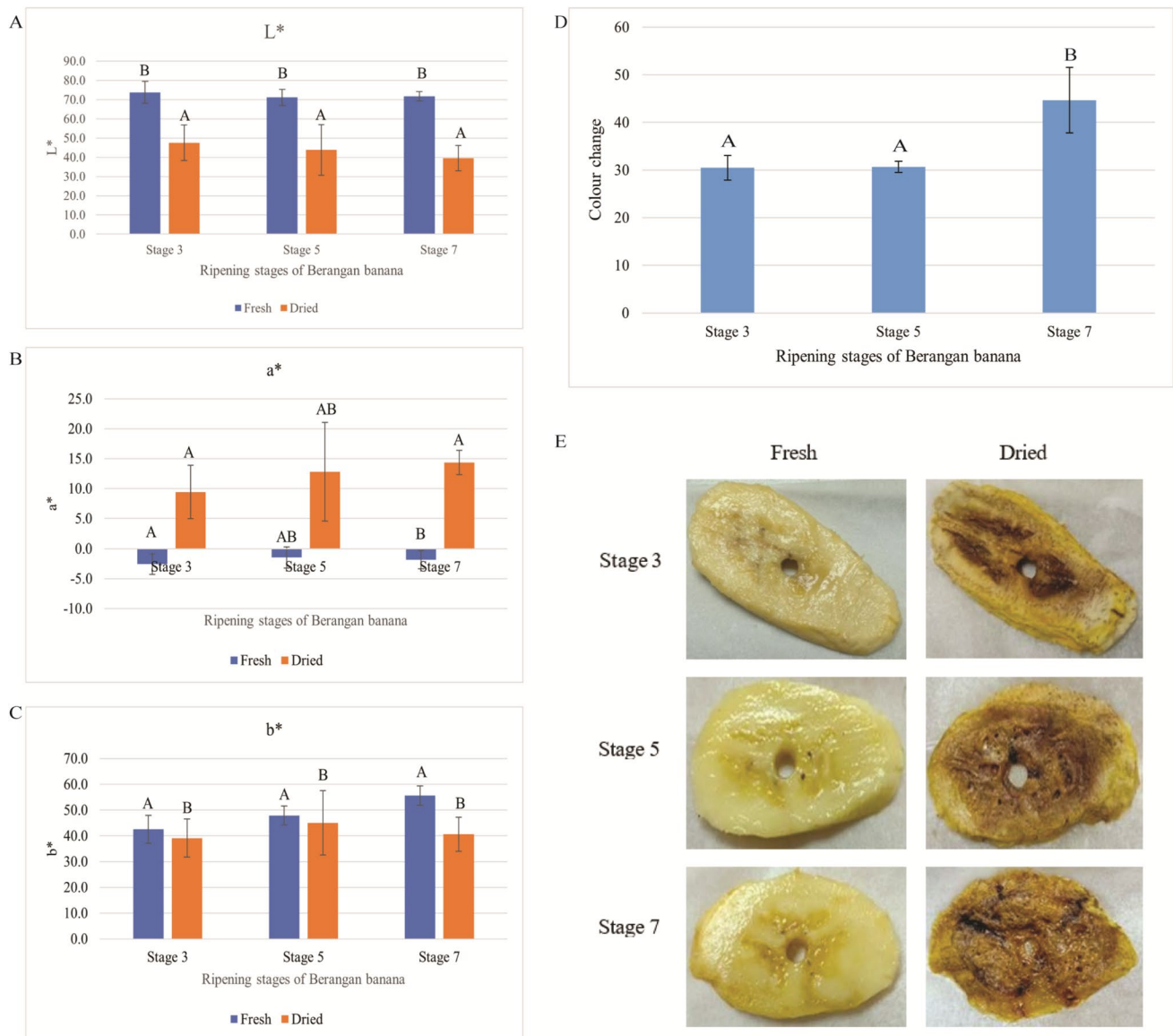


Fig. 5 (A) L^* value, (B) a^* value, (C) b^* value, and (D) color changes of dried bananas of three different ripening stages. Uppercase letters indicate significant differences among the three ripening stages of banana. (E) Appearances of fresh and dried samples at different ripening stages

overripe stage bananas compared to green ripe and full ripe stages even though the drying time was the shortest. This phenomenon might be caused by a high accumulation of sugar content in overripe bananas leading to an increased browning reaction (Maillard reaction). Therefore, the color change of fruit after drying is not solely dependent on the drying time but is also positively correlated with the sugar content especially reducing sugars.

Comparing the appearance of fresh and dried banana samples (Fig. 5E), darkening of the surface was observed in all three ripening stages of the banana. Among the three

ripening stages, the most intense darkening was noticed in stage 7 dried samples. According to Izli et al. [36], during microwave drying, the increase in temperature resulted in the reduction of L (lightness), a (redness/greenness), and b (yellowness/blueness) values. The most notable reduction was observed in L value due to the production of darker samples. Additionally, Nagvanshi and Goswami [37] reported a significant color change in 2 mm thick Cavendish banana slices after microwave drying. This change was likely due to the slices becoming more reddish-yellow, a result of browning and pigment degradation during the drying process.

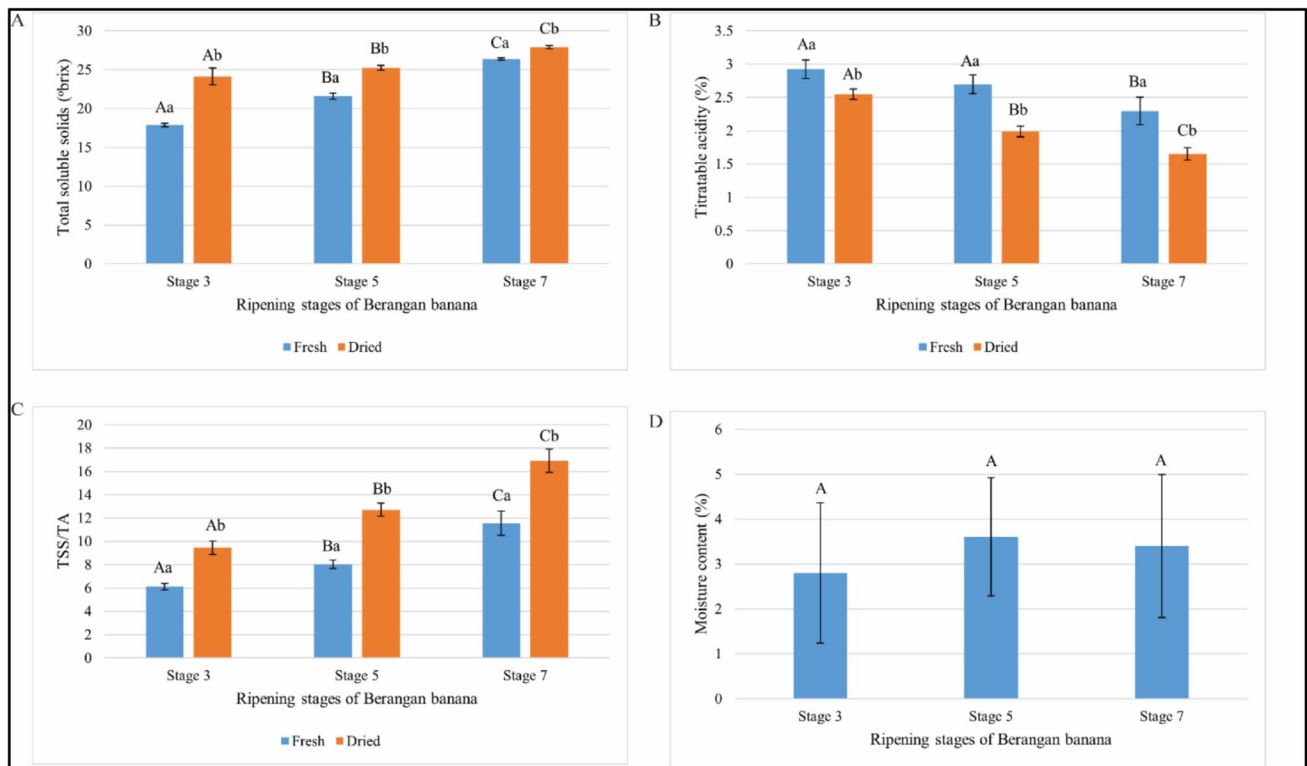


Fig. 6 (A) Total soluble solids, (B) titratable acidity, (C) ratio of total soluble solids over titratable acidity, and (D) moisture content of fresh and dried bananas of three different ripening stages. Uppercase

letters indicate significant differences among the three ripening stages of bananas, while lowercase letters represent significant differences between the fresh and dried bananas

Total soluble solids

Since sugar is the main soluble solids in fruits, total soluble solids (TSS) is a standard indication of sweetness in this study. The results showed that TSS in fresh Berangan bananas increased when the ripening stages of the banana increased (Fig. 6A). Among the fresh banana samples, stage 3 bananas had the lowest TSS, measuring 17.87 ± 0.23 °Brix. This value increased to 21.6 ± 0.37 °Brix at stage 5 and achieved the highest value at stage 7, with a TSS of 26.35 ± 0.14 °Brix. These results were similar to those reported by Newilah et al. [38], where TSS increased with the ripening stages for all the dessert banana varieties. In some dessert banana varieties such as Mas banana, the TSS of stage 5 banana almost doubled compared to stage 3 banana, and even tripled when it reached stage 7. In accordance, Pongprasert et al. [39] reported that the TSS of the Khai banana increased with the ripening stage and reached the highest at the fully ripe stage with a value of 23 °brix. In the early stages of ripening, the starch present in the sample has not yet been converted into sugars. The increase in TSS is a typical characteristic in ripening bananas due to the increased conversion of starch into sugar. The increasing

trend of TSS with banana ripening was also reported by Youryon and Supapvanich [40]. The TSS in the ‘Kluai Leb Mue Nang’ banana increased significantly from the mature green stage to the ripped and overripe stages. This may be due to the elevation of sucrose phosphate synthase, sucrose synthase, and invertase activities in the ripe banana samples.

Similar to fresh bananas, the TSS of the dried banana increased during banana ripening. TSS of the dried banana reached the highest in stage 7 at 27.88 ± 0.19 °brix, while the stage 5 banana contained 25.22 ± 0.30 °brix of TSS, and the lowest TSS was recorded in the dried stage 3 banana at 17.87 ± 1.10 °brix. The elevation of TSS after drying can be attributed to the increased concentration of sugar content as the total volume of the banana sample shrunk after drying [41]. Wei et al. [42] reported that the heating process can increase the soluble sugar content in sweet potatoes by degradation of starch by α -amylase and transforming into soluble sugars, especially maltose and sucrose. Hence, the enzymatic breakdown of long carbohydrate chains during the drying process leads to the formation of soluble sugars like sucrose, fructose, and glucose [43], which may result in the higher TSS values observed in dried bananas.

Titrateable acidity

According to Fig. 6B, the titrateable acidity (TA) of the fresh banana decreased as the banana ripened. Among the fresh banana samples, the highest TA was recorded in stage 3 banana at $2.92 \pm 0.14\%$, followed by $2.70 \pm 0.14\%$ in stage 5 banana, and stage 7 banana comprised the lowest TA at $2.30 \pm 0.21\%$. However, the results of this experiment differ from those reported in studies on other banana varieties. Newilah et al. [38] observed that most dessert bananas were shown to exhibit the lowest TA when unripe (stage 3), which increased to a peak as the bananas ripened, and then declined as they became overripe (stage 7). The increase in TA during ripening was attributed to the production of malic and citric acids [38]. Similarly, *Musa nana Lour* and '*Kluai leb mue nang*' banana fruits showed significantly higher TA in the ripe and overripe stage than in the mature green stage [32, 40]. The contradicted findings may be due to differences in the banana varieties and their geographic origins.

The TA of the dried bananas for all ripening stages was lower than fresh banana. The highest TA recorded in dried banana was in stage 3 at $2.55 \pm 0.08\%$, followed by stage 5 banana at $1.99 \pm 0.08\%$, and the lowest TA was recorded in stage 7 banana at $1.65 \pm 0.09\%$. Techane [44] reported similar findings with significantly higher TA of oven-dried and sun-dried mangoes at the unripe stage than at the fully ripe stages. The decline in acidity may result from the susceptibility of organic acids toward oxidative degradation influenced by the ripening environment. The reduction in acidity implies a decrease in sourness, potentially enhancing the perception of sweetness, as evidenced by the increase in TSS observed in this study.

Ratio of TSS and TA

The TSS/TA ratio is the standard indicator for food flavor and taste, especially for fruit products. Among the fresh banana samples, the highest TSS/TA ratio was recorded in stage 7 bananas at 11.56 ± 1.02 °brix/%, followed by stage 5 bananas at 8.03 ± 0.37 °brix/% (Fig. 6C). The lowest TSS/TA ratio was observed in stage 3 bananas, with a value of 6.12 ± 0.28 °brix/%. The flesh of unripe bananas contains higher starch content and lower soluble sugar levels (Li et al., 2018), which explains the lowest TSS/TA ratio observed in stage 3 bananas. As bananas ripen, insoluble starch is enzymatically converted into soluble sugars, accumulating in the ripe fruit [45]. This process results in the highest TSS/TA ratio in stage 7 bananas, contributing to their enhanced sweetness and overall taste [46]. Similarly, Adi et al. [47] observed that the TSS/TA ratio in ABB-type bananas increased nearly threefold, from 33.85 °brix/% at stage 1 to 87.68 °brix/% at stage 7, primarily due to the gradual rise in TSS during ripening.

Overall, microwave-dried bananas exhibited a higher TSS/TA ratio than fresh samples (Fig. 6C). Dried stage 3 samples showed the lowest TSS/TA ratio at 9.47 ± 0.58 °brix/%, followed by stage 5 dried samples at 12.71 ± 0.55 °brix/%, and the highest ratio was observed in stage 7 dried samples were dried at the value of 16.93 ± 1.01 °brix/%. The increase in the TSS/TA ratio in dried samples can be a result of an increase in sugar concentration in the banana as the total volume of the banana shrunk [41]. Wei et al. [42] proposed that the heat and enzymatic degradation of complex polysaccharides during the heating process resulted in the elevation of total sugar content in sweet potatoes. In our study, the TA value decreases at each ripening stage after microwave drying, which may be attributed to the thermal degradation of acids. As a result, the TSS/TA ratio increases in dried banana samples, making them taste sweeter and less sour compared to fresh bananas.

Moisture content

According to Fig. 6D, no significant differences in moisture content were observed in stage 7, 5, and 3 samples, with values of $3.61 \pm 1.32\%$, $3.40 \pm 1.59\%$, and $2.8 \pm 1.56\%$, respectively. The moisture content for all ripening stages of dried bananas falls within the safety moisture content level for dried food (5%) [48]. This is important because microbial activity can be significantly inhibited when the moisture content level is below 20%. Reducing the moisture content of dried fruit to a safe level retards microbial growth, as water is essential for the survival of microorganisms [7]. Similar findings were reported by Monteiro et al. [49] and Salunke et al. [50], who found moisture levels below 5% in microwave-dried banana samples.

Biochemical analysis

Total carotenoid content

The total carotenoid content increased with the ripening stage of the fresh banana samples (Fig. 7A). Fresh stage 3 bananas contained 0.31 ± 0.03 mg/100 g DW of carotenoids, which increased to 0.50 ± 0.02 mg/100 g DW in stage 5 samples, with the highest content observed in stage 7 samples at 0.62 ± 0.03 mg/100 g DW. Borges et al. [51] suggested that carotenoid content is influenced by ripening stages, primarily due to the composition of β -carotene, α -carotene, and lutein. They found that carotenoid levels typically increase from stage 2 to stage 5 before decreasing at stage 7 for most dessert bananas. While this trend contradicts the findings for fresh bananas in this study, the dried banana samples followed a similar pattern to those reported. The highest total carotenoid content in dried Berangan bananas was observed at stage 5, with a value of 1.54 ± 0.06 mg/100 g

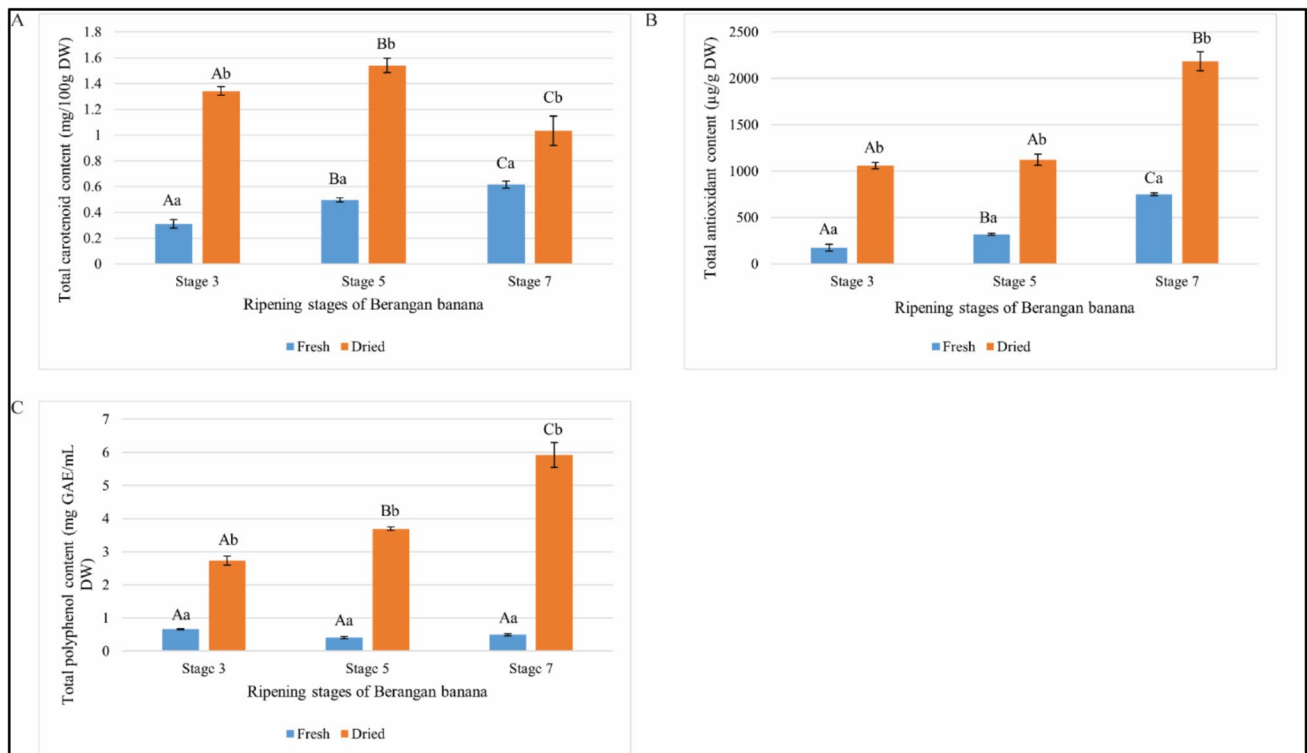


Fig. 7 (A) Total carotenoid content, (B) total antioxidant content, and (C) total polyphenol content of fresh and dried bananas of three different ripening stages. Uppercase letters indicate significant differ-

ences among the three ripening stages of bananas, while lowercase letters represent significant differences between the fresh and dried bananas

DW, followed by stage 3 samples at 1.34 ± 0.03 mg/100 g DW. The lowest carotenoid content was recorded in stage 7 dried bananas, with a value of 1.03 ± 0.11 mg/100 g DW.

As shown in Fig. 7A, the total carotenoid content increased in all three ripening stages of bananas after drying compared to their fresh counterparts. These findings align with those of Borges et al. [51], who reported a significant increase in carotenoid content in '*D'Angola*' plantains and '*Pelipita*' cooking bananas following microwave drying. This enhancement may be attributed to microwaving, which significantly improves the extractability of carotenoids [52]. Mehmood and Zeb [53] also suggested that heat treatment disrupts carotene-protein complexes within the food matrix, facilitating carotenoid release. Additionally, Lau et al. [54] emphasized the role of microwave power in retaining carotenoids by reducing exposure time to heat, thereby minimizing carotenoid degradation. This process not only preserves but also enhances the release of carotenoids, increasing the functional and nutritional value of bananas through thermal processing [51].

Total antioxidant content

Total antioxidant content usually varies with the ripening stage of fruits due to the different concentrations of

antioxidant compounds in the fruits [55]. According to Fig. 7B, stage 3 fresh samples had the lowest total antioxidant content with a value of 174.75 ± 37.69 µg/g DW, followed by 318.32 ± 10.85 µg/g DW in stage 5 fresh samples, and reached the highest at 751.68 ± 13.91 µg/g DW in stage 7 fresh samples. Similarly, Watharkar et al. [32] observed that overripe bananas (stage 8) exhibited the highest antioxidant capacity, with the percentage inhibition significantly greater than that of fully ripe and mature green bananas. This variation in antioxidant capacity during ripening may be attributed to changes in the concentration of antioxidant compounds, such as gallic acid, a dominant phenolic compound in bananas. In contrast, Youryon and Supapvanich [40] found that total antioxidant capacity was lowest in unripe *Kluai Leb Mue Nang* bananas, significantly increased in ripe fruit, and decreased again in overripe bananas. These differences in findings could be due to variations in banana species and their geographic origins.

Based on Fig. 7B, the total antioxidant content of the dried banana sample followed the trend of fresh banana, where the stage 3 dried banana had the lowest total antioxidant content, followed by the stage 5 dried sample, and the highest value recorded was in the stage 7 dried sample. From the results obtained, it is clear that the total antioxidant content increased after microwave drying. Thermal treatment

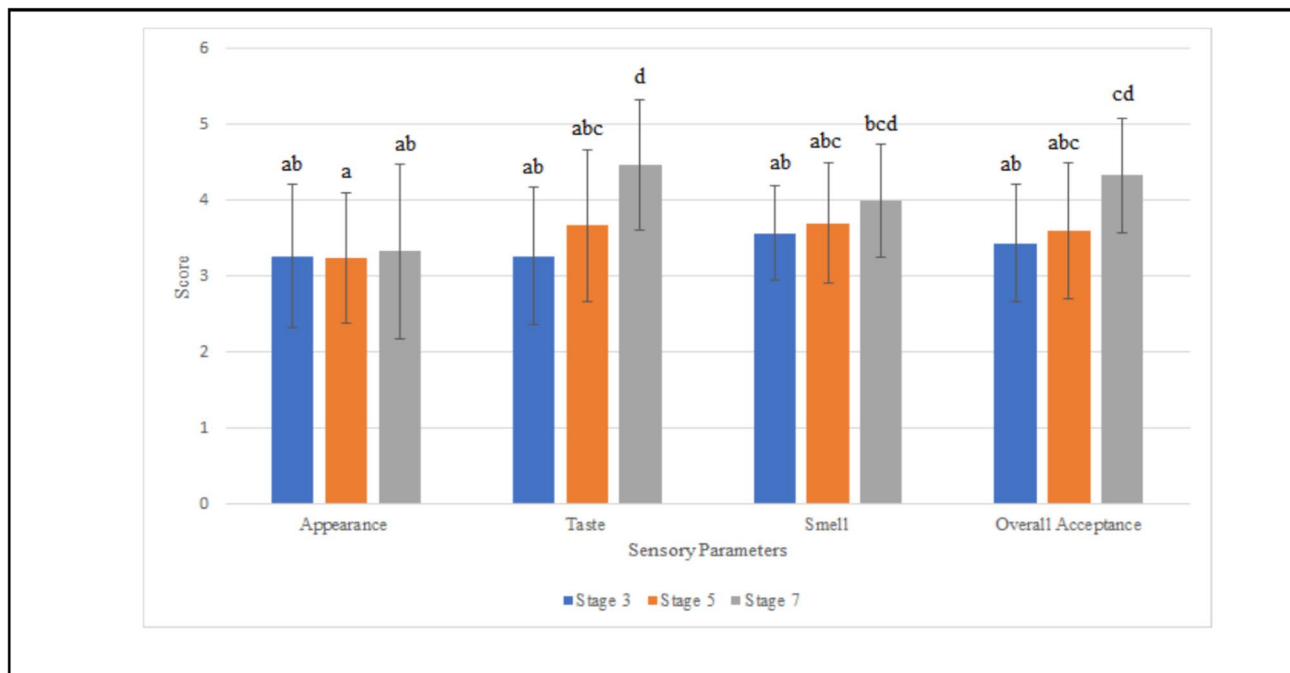


Fig. 8 Score of dried banana slices in terms of appearance, taste, smell, and overall preference. A total of 30 panelists were used for this sensory analysis

can activate and release the natural antioxidant compounds from the food matrix which could explain the increase in antioxidant content after microwave drying [56].

Total polyphenol content (TPC)

According to Fig. 7C, the total polyphenol content (TPC) of fresh samples showed no significant differences across the three different stages of banana. This result differed from that obtained by other studies which showed an increase of TPC during ripening. For instance, Youryon and Supapvanich [40] found the highest TPC in ripe ‘*Leb Mue Nang*’ bananas, attributed primarily to the presence of gallic acid. Similarly, Borges et al. [51] noted that the phenolic compound levels in ‘*Ney Poovan*’ bananas are influenced by ripening stages, with stage 5 (ripe) bananas exhibiting the highest values among all stages. Nevertheless, the differences in TPC during ripening may be due to the different varieties of bananas.

The results show that the TPC of all three banana samples increased significantly after microwave drying compared to fresh bananas. This finding aligns with Borges et al. [51], who reported a rise in TPC in banana samples following thermal treatment. The increase is attributed to the elevated temperatures, which enhance the recovery of bioactive compounds by releasing bound phenolics [57]. In contrast, fresh samples exhibited the lowest TPC values, highlighting the

improved extractability of phenolic compounds due to the breakdown of cell membranes during drying [58]. The lower phenolic content in fresh samples is likely due to the absence of cell rupture compared to the dried samples [57]. Microwave drying, in particular, resulted in substantially higher phenolic concentrations within a short processing time, offering both energy and time efficiency [29].

The highest TPC was recorded in the stage 7 dried banana samples, with a value of 5.92 ± 0.37 mg GAE/g DW, followed by the stage 5 samples at 3.69 ± 0.06 mg GAE/g DW, and the stage 3 samples at 2.73 ± 0.14 mg GAE/g DW. These findings align with previous studies reporting an increasing trend in TPC in various dried fruits as maturity progresses. For instance, Zhou et al. [33] found that TPC was significantly higher in overripe dried bananas compared to green-ripe samples. Similarly, Mahmood et al. [59] reported that total phenolic and flavonoid content were higher in fully ripened than unripe dried mulberry fruits. As illustrated in Fig. 7C, the highest TPC was observed in the stage 7 dried bananas, a trend consistent with the antioxidant content. This correlation may be explained by the strong relationship between antioxidant capacity and the levels of total polyphenols and flavonoids [60].

Sensory analysis

In this study, the sensory parameters evaluated include appearance, taste, smell, and overall preference. A total of

30 panelists were requested to evaluate the dried banana discs by using a hedonic scale from a score of 1 (extremely dislike) to 5 (extremely like). The average score for each sensory parameter is presented in Fig. 8. As shown in Fig. 8, the samples showed similar scores in terms of appearance. Appearance is a property of food products that affects the enjoyment and attraction of consumers towards dried fruit products [61]. Hence, a score of 3.2–3.3 in all samples suggests that while the appearance can be accepted, there is room for enhancing the appearance of the dried banana products.

Besides, taste was included as one of the parameters in the sensory analysis as taste is a sensory attribute to evaluate the food products [61]. The five basic taste qualities—sweet, sour, salty, bitter, and umami—are detected by specialized taste receptor cells on the taste buds [62]. When a substance reacts chemically with these receptors, signals are transmitted to the brain, allowing it to process and interpret the flavour [63]. The stage 7 samples showed the highest total score in taste with a score of 4.5, while the stage 3 and 5 dried bananas scored 3.3 and 3.7, respectively. This may be attributed to the stage 7 dried samples having the highest TSS/TA ratio compared to the stage 5 and 3 samples, which means that the banana slices consist of high levels of soluble solids, such as sugars, and less acid content. This improved the eating qualities of the dried banana with a sweeter flavor instead of a more sour taste.

Furthermore, all samples did not show any significant difference in score for smell with scores of 3.3, 3.7, and 4.0 for stage 3, stage 5, and stage 7, respectively. Aroma is developed in dried food because of the volatile substances present in the fruits. The olfactory tissues in the human nasal cavity perceive the volatile compounds [38]. Lastly, the scores for overall preference for the samples are 3.4, 4.0, and 4.3 for stage 3, stage 5, and stage 7, respectively. Overall, stage 7 samples had received the best score compared to stage 3 and 5, especially in terms of taste.

Conclusion

Overall, microwave drying successfully retained most physiochemical properties of Berangan banana samples of the three ripening stages including TSS, total antioxidant, total carotenoid, and total antioxidant content. Furthermore, the antioxidant, carotenoid, and phenolic content of the three ripening stages of microwave-dried bananas were significantly increased as compared to fresh bananas. All three ripening stages of the banana samples achieved safe moisture levels when dried by using an intermittent microwave drying technique. Overall, the dried bananas of the ripening stage 7 had the highest color change, TSS/TA, total antioxidant level, total

polyphenol content, and taste and sensory acceptance level, suggesting that the bananas with a ripening stage of 7 are the best choices for producing microwave-dried banana chips. For future research, pretreatment such as blanching, proximate analysis, and other biochemical studies should be carried out to preserve and retain the appearance and nutrients in the fruits. Additionally, a variety of drying techniques can be developed to enhance the fruit's quality and drying time.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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