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Comparative study on microwave and tray drying of beef: Effect of partial salt replacement on drying kinetics and structural characteristics

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Abstract

Beef cuts were dried by tray drying (TD), microwave drying (MD), and TD+MD. Salting as pre-treatment was carried out with NaCl or NaCl+KCl salts to evaluate the effect of sodium reduction. The beef was divided into nine groups: three were subjected to TD, MD, and TD+MD; for the other six groups, dry salting was applied with 100% NaCl or 50% NaCl + 50% KCl, followed by MD, TD, or TD+MD. Processing times of TD, MD, and TD+MD were about 660, 250, and 300 min, and effective diffusivities (D_{eff}) were 1.33 × 10^{-8}, 3.88 × 10^{-8}, and 3.57 × 10^{-8} m^2/s, respectively. Compared with TD, the MD procedure resulted in significantly harder texture and lower rehydration ratio ($p < 0.05$). SEM images of dried beef indicated fractures and disruption after TD, while a compact structure was obtained with MD. Both salt types contributed a softer texture in rehydrated MD, but KCl did not change the hardness values of dried meat. MD could have great potential for drying meat by reducing drying time, and KCl could be applied as a substitute for NaCl without adversely affecting the structural quality.

Introduction

Meat is an important source of valuable nutrients such as iron, selenium, magnesium, zinc, vitamin B, and essential amino acids. This valuable foodstuff is highly perishable because it is vulnerable to microbiological growth, enzymatic, and chemical reactions due to its composition, particularly high moisture and fat contents. Since ancient times, drying has been widely used as a food preservation method to extend shelf life. This energy-intensive water removal process leads to changes in quality attributes of the product such as texture, water retention capacity, nutritional value, flavour, and colour (Rahman *et al.*, 2005; Feng *et al*., 2012).

Although several traditional and innovative food drying methods exist, conventional tray drying is the most popular technique in industrial applications. In this technique, fresh or cured meats are placed on metal trays, allowing air circulation and drying to take place at temperatures around 75 - 80°C for nearly 18 h depending on the product characteristics (Rahman *et al.*, 2005). Tray drying (TD) is a very effective method where the water removal from the surface is convection-dependent in the early stages of the process. Considering the three main stages of drying which are constant, first falling, and second falling rate, this early stage corresponds to the constant rate period. After this stage, water removal from inside the product becomes more difficult because a phase change takes longer; therefore, a significant amount of energy is required, and the heat transfer efficacy decreases (Feng *et al*., 2012). Due to the extended drying time and thus undesirable physical and chemical changes in the quality of the ultimate products, novel drying techniques providing better quality, such as ultrasound, pulsed vacuum, and microwave drying have been proposed to assist or replace conventional TD.

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The purpose of these alternatives is to reduce the drying time due to rapid moisture removal leading to retention of the overall quality of the final product. Among these novel techniques, microwave drying (MD) has gained growing interest in the food industry since it causes a swift decrease in moisture content, enhances energy efficiency, and yields improved product quality, including better flavour and colour retention, as well as greater porosity (Feng *et al*., 2012). Contrary to TD, which transfers exterior heat from the surface into the food, in MD, an elevated temperature internal vapour pressure facilitates water removal. The contact-free heating behaviour of microwaves directly targets water molecules, and due to volumetric heat generation, the drying rate increases, surface heating is prevented, and rapid, homogeneous, and therefore efficient drying is achieved (Feng *et al*., 2012; Michalak *et al*., 2020). Due to some drawbacks of MD, particularly non-uniform heating and high mass transfer rate which results in puffing and disintegration of the product, it is not typically used as a stand-alone technique. For these reasons, it is used to assist or enhance other drying methods (Amer *et al.*, 2019). Combination of MD and TD provides a balanced approach that offers the benefits of both methods in terms of product quality, drying efficiency, energy use, processing time, uniform drying, and cost savings.

Combinations of MD and TD have been widely employed to overcome those problems with some degree of success to enhance the quality of several food products (Jia *et al.*, 2019). When this is the case, applying microwaves in the later stages of drying is recommended, since rapid heating and evaporation lead to a highly porous dried product. Thus, TD is the initial stage, and when the product reaches a certain moisture level, MD can be applied as the final stage to provide shorter drying time and reduced shrinkage (Feng *et al*., 2012).

Most industrial dried meat products are subjected to dry salting as a complementary process before the main drying process (Kaban *et al.*, 2020). Salting is a common step when preparing dried meat products such as pastırma (a traditional Turkish dried beef product), charque (a traditional Brazilian dried beef product), and jerky (dried cured beef product) (Kim *et al.*, 2021). As a pre-drying step, dry salting is achieved by covering food with crystalline salt (sodium chloride), which facilitates dehydration through the mass transfer of water from the food matrix into the surroundings and solutes into the food (Chiralt and Fito, 2003). Salting is used to assist the drying process by reducing moisture in a short time before the application of other drying techniques such as tray, freeze, and vacuum drying. It also contributes to inhibiting the growth of spoilage microorganisms and pathogens, and improving the functional properties of meat proteins. Nevertheless, epidemiological studies demonstrated that high dietary sodium intake leads to an elevated risk of high blood pressure, and thus cardiovascular diseases (Antonios and MacGregor, 1997). As recommended by the World Health Organization, daily salt (NaCl) intake must be reduced below 5 g/day, which is the most rational method in reducing health risks due to salt consumption. Since processed meats are the primary products responsible for high salt intake in the diet of consumers in developed countries (Verma *et al*., 2012), the American Heart Association recommends consuming less processed meat to decrease sodium intake, thus minimising the risk of cardiovascular diseases (Eckel *et al.*, 2014). This has prompted researchers to reduce NaCl in meat products as one of the solutions to deal with the related health risks. As the adverse health impact of salt arises from the "Na" element, researchers have focused on reducing or replacing NaCl in the product formulation by substituting it with other chloride salts such as KCl, CaCl, and MgCl, or non-chloride salts such as phosphates. It was previously observed that reducing NaCl content *via* 50% substitution with KCl did not impact the salting kinetics (Aliño *et al*., 2009), as the same amount of water removal can be achieved using K^+ ions. Moreover, several studies indicated that KCl is the most common option for NaCl substitution among other salt types ($MgCl_2$ and $CaCl_2$), since $MgCl_2$ was found to cause bitter taste and $CaCl_2$ did not exhibit favourable physicochemical properties in meat formulations. KCl and NaCl have similar physicochemical properties, thus providing advantages in terms of the sensorial and textural quality of dried beef (Horita *et al*., 2011; da Silva Araujo *et al.,* 2021).

Based on this background, one of the objectives of the present work was to determine the kinetic behaviour of beef during various drying techniques (MD, TD, and TD+MD). Moreover, the present work also aimed to evaluate (i) the effects of partial replacement of sodium with potassium chloride during microwave and/or tray drying combinations on drying kinetics, and (ii) the product quality of low sodium dried meat products to meet consumer demand for healthier products.

Materials and methods

Drying techniques

Semimembranosus muscles of beef were purchased 48 h post-mortem in different months, for three replications, from a local supermarket in Ankara, Turkey. They were used as raw material. The beef samples were transferred to a laboratory in refrigerated containers, cut into small pieces (3 × 2 × 2 cm) with a cutting template, and stored at -80°C until drying was conducted.

The beef cuts were held at 4°C overnight to thaw before the drying process, afterwards, they were divided into nine groups, three of which were subjected to tray drying (TD), microwave drying (MD), and microwave-assisted TD (TD+MD). TD was performed in a laboratory tray drier (Eksis, TK-lab model, Turkey) at 80°C with 0.5 m/s air velocity inside the cabin. MD was conducted in a microwave (Dizge Analitik Inc., Turkey) at power of 350 Watts and frequency of 2450 MHz. In the TD+MD group, the beef samples were first subjected to TD for 90 min until approximately 40% moisture loss was achieved, followed by MD. Dry-salting was applied by placing a salt layer between the beef cuts with the respective salts, *i.e.*, NaCl or a combination of 50% NaCl + 50% KCl salts, with a salt to meat ratio of 1:1 (w/w) for 120 min, followed by either TD, MD, or TD+MD. For each treatment, each replication of the triplicate samples was analysed for moisture ratio to evaluate the drying kinetics and estimate the effective diffusion coefficient, as well as for the rehydration ratio and the textural (hardness) and structural (scanning electron microscope images) changes in different dried beef cuts. Exposure time to salting, *i.e.*, 120 min, was decided after preliminary trials based on the rate of moisture loss. Drying procedures lasted until the equilibrium moisture content was reached. The group combinations of different drying techniques are presented in Table 1, and drying times are given in Table 2.

Table 1. Different drying techniques applied to beef.

Group	NaCl	KCl	Tray drying (TD)	Microwave drying (MD)
TD	-	-	+	-
MD	-	-	-	+
TD+MD	-	-	+	+
NaCl+TD	+	-	+	-
NaCl+MD	+	-	-	+
NaCl+TD+MD	+	-	+	+
NaCl/KCl+TD	+	+	+	-
NaCl/KCl+MD	+	+	-	+
NaCl/KCl+TD+MD	+	+	+	+

TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying.

Table 2. Drying times and effective diffusion coefficients of different drying techniques.

Group	Drying time (min)	D_{eff}
TD	660	1.33×10^{-8}
MD	250	3.88×10^{-8}
TD+MD	300	3.57×10^{-8}
NaCl+TD	580	1.33×10^{-8}
NaCl+MD	240	3.16×10^{-8}
NaCl+TD+MD	240	3.26×10^{-8}
NaCl/KCl+TD	580	1.02×10^{-8}
NaCl/KCl+MD	240	2.04×10^{-8}
NaCl/KCl+TD+MD	240	1.95×10^{-8}

TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying.

Drying kinetics

Moisture content was determined at certain time intervals (15 min for TD, and 5 min for MD) based on weight loss during the drying process. Moisture ratio (MR) was calculated using Eq.1:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad \text{(Eq. 1)}$$

where, M_t = moisture content at time t, M_e = equilibrium moisture content, and M_0 = initial moisture content.

Effective diffusion coefficient

Effective moisture diffusivity was calculated using Eq. 2:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[-(2n+1)^2 \frac{\pi^2 D_{eff}\, t}{4L^2}\right] \quad \text{(Eq. 2)}$$

where, MR = moisture ratio (dimensionless), M_t, M_e, and M_0 = moisture contents at time t, the equilibrium moisture content, and initial moisture content, respectively, all expressed on dry basis (g water/g dry solids). D_{eff} = effective diffusion coefficient (m^2/s), L = half thickness of the beef (m), t = drying time (s), and n = number of terms in the Fourier series.

For long drying times, only the first term in the series was used, and MR became:

$$MR = \frac{8}{\pi^2} \exp\left[\frac{-\pi^2 D_{eff} t}{4L^2}\right] \quad \text{(Eq. 3)}$$

If the natural logarithmic transforms of MR values were plotted as a function of time with the use of the slope of the straight line, D_{eff} was expressed using Eq. 4, where k = slope of the line.

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad \text{(Eq. 4)}$$

Structural characteristics of dried beef cuts

Texture (hardness)

A penetration test was performed using the texture analyser (Stable Microsystems TA.XT TEE32, UK) to determine the maximum peak force (hardness, N) with a 2 mm cylindrical probe. In the penetration test, the test speed was 0.5 mm/s and the penetration distance through the meat surface was 2 mm. Average data from six measurements were used for each of the three replications. Hardness value was measured both for dried and rehydrated meat samples.

Rehydration ratio

The rehydration ratio was determined according to Nathakaranakule *et al.* (2007) with slight modifications. Individual dried meat pieces were immersed in distilled water in a beaker, and held at 90°C for 60 min in a water bath, followed by removing excessive moisture with tissue paper, and then measuring the weight of the rehydrated meat. Rehydration ratio was expressed as the percentage of weight gain of dry meat using Eq. 5:

$$\%\ \text{Rehydation} = \frac{M_r - M_d}{M_d}\, x\ 100 \quad \text{(Eq. 5)}$$

where, M_r = weight of rehydrated meat (g) and M_d = weight of dry meat (g). Average data from four measurements per group were used.

Shrinkage

The shrinkage of dried beef was estimated using toluene following the classical volumetric replacement method (Nathakaranakule *et al.*, 2007). The percentage volume reduction compared to the initial volume was calculated using Eq. 6:

$$\%\ \text{Shrinkage} = \frac{V_1 - V_2}{V_1}\, x\ 100 \quad \text{(Eq. 6)}$$

where, V_1 = first volume of fresh meat (m^3), and V_2 = volume of dried meat (m^3). Average data from four measurements per group were used.

Scanning electron microscope (SEM)

Dried beef was cut into small pieces, placed on holders with aluminium cement, and coated with gold under vacuum (0.5 mbar) using a sputter-coating/glow discharge (EMITECH K550X Attachment, Quorum Technologies Ltd., East Grinstead, UK,). The specimens were examined and photographed using a scanning electron microscope (SEM, ZEISS, EVO 40, Baden-Württemberg, Germany). SEM images were taken from the surface of the dried beef cuts, parallel to the myofibrils, and were performed at 300× magnification.

Statistical analysis

The drying procedure was performed with three replications using beef purchased in different months for each replication. Data for hardness, rehydration ratio, and shrinkage obtained from the three replications were subjected to statistical analyses using the SPSS statistical computer software package (SPSS version 22). A general linear model was employed where drying methods (TD, MD, and TD+MD), salting pre-treatment (not salted, NaCl, and NaCl/KCl), and their interactions were considered as fixed factors, and replicates as random factor. Duncan's Multiple Comparison test was applied for *post hoc* comparison of the means at 5% significance level when the fixed factors were significant ($p < 0.05$).

Results and discussion

Drying kinetics

Drying curves for beef dried with different methods are given in Figure 1. The moisture ratio (MR) of samples ($g_{water}/g_{dry\ matter}$) decreased exponentially in all drying cases, which was in agreement with previous studies which applied several drying techniques to different meat materials such as pork, beef, chicken, and fish (Laopoolkit and Suwannaporn, 2011; Hii *et al.*, 2014; Ling *et al.*, 2020). The constant rate period, where the drying rate is constant, was not observed in any of the drying techniques due to the rapid moisture removal from the surface with high temperature. There was a rapid decrease in MR over time with all applied techniques for the initial period of drying (first falling rate period, 0 - 90 min). However, the rate of moisture reduction decreased as drying proceeded, which was an indication of transition to the second falling rate period (90 min - end of drying). Kumar *et al*. (2019) indicated similar behaviour of drying curves during convective drying of chicken meat at several drying temperatures (60, 70, and 80°C). In the initial stages of drying, a rapid decrease in moisture content was observed due to the fast mass transfer mechanism. Evaporation is the main physical phenomenon for water removal from the surface of the product. In the further stages of drying, the diffusion of water from the surface decreases exponentially due to the difficulty in transporting the evaporating water through the material because of protein denaturation. When MD, TD, and TD+MD were compared without salt pre-treatment, the effect of the drying method was clearly observed on the drying curves. As demonstrated in Figures 1a and 1b, the slope of the MR curve for MD was greater than the slope of the MR curve for TD, which indicated a difference in drying rate since MD caused a more rapid decrease in MR than TD. During MD, the rapid and volumetric heat distribution and increased internal vapour pressure led to a shortened drying time. On the other hand, low heat and mass transfer efficiencies in addition to a greater energy demand for phase change in TD gave rise to long drying periods (Feng *et al.*, 2012). In the present work, during MD of beef cuts, a significantly lower drying time (250 min) was observed in comparison to TD (660 min). When these two methods were combined (TD+MD), the drying time was 300 min (Table 2).

Salting pre-treatment with NaCl and/or KCl affected the drying procedure depending on the drying methods. In TD, a slight decrease in moisture reduction rate was observed only during the first falling rate period due to salting. The decrease in MR of pre-salted NaCl+TD and NaCl/KCl+TD dried beef during the second falling rate period (after 90 min) was very similar to TD (Figure 1a). For both NaCl+TD and NaCl/KCl+TD, there was a shorter drying time to reach the equilibrium moisture content (580 min) when compared to TD. In other words, the salting pre-treatment decreased the drying time by 80 min when NaCl and/or KCl were applied before the drying process. Moreover, as shown in Figure 1b, a substantial effect of salting on moisture reduction was identified in MD where the slopes of the curves for the salted groups (NaCl+MD and NaCl/KCl+MD) were different from the unsalted MD group. Pre-salting before MD slowed down the moisture decrease in the early stages of drying, and as drying proceeded, the curves for the three groups showed similar tendencies for moisture reduction (Figure 1b). In the end, a slight effect of both NaCl alone and in combination with KCl on drying time (240 min) was observed (reduction of drying time by 10 min) in comparison to MD without pre-salting treatment (250 min) (Table 2). von Gersdorff *et al.* (2021) also reported a slight influence of pre-salting on the drying kinetics of sliced beef treated with 0.5 and 1% NaCl during tray drying at 70°C. Bampi *et al.* (2016; 2019) reported similar behaviour for brine salted beef cuts using partial replacement of NaCl with KCl, which did not lead to a significant difference in drying kinetics.

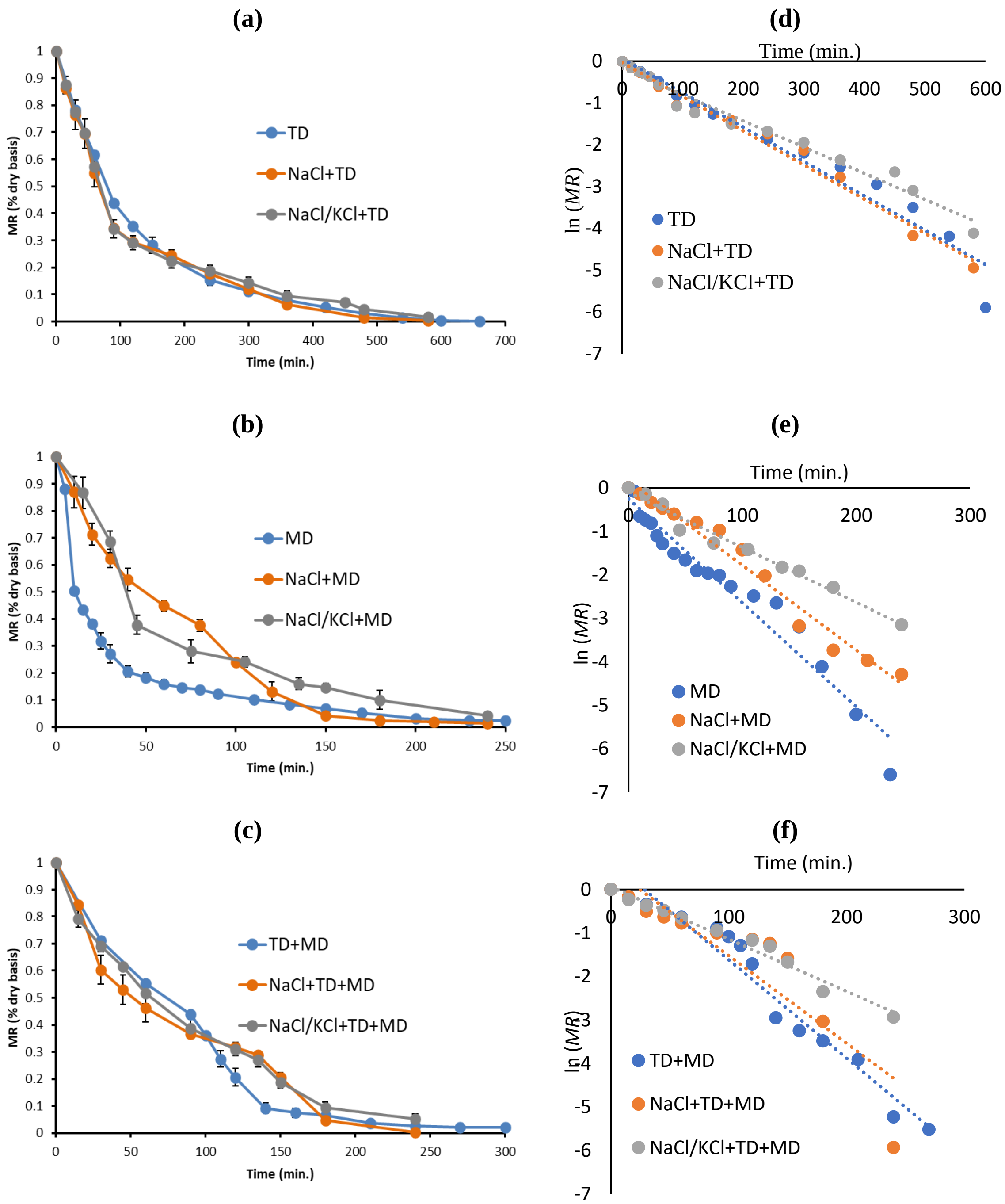

Figure 1. Variation in moisture ratio (MR) with drying time (**a**, **b**, and **c**) and variation in ln (MR) with drying time (**d**, **e**, and **f**) for meat samples dried with nine different techniques. MR: moisture ratio; TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying. Error bars indicate standard errors (n = 3).

In TD+MD, TD was applied for the initial 90 min followed by MD until the equilibrium moisture content was reached. The MR decreased exponentially during TD, and after 90 min MD application, caused a more rapid decrease in MR (Figure 1c). For salted groups, TD application (90 min) followed by MD demonstrated similar behaviour for both salt types and the moisture reduction rate was slowed with MD. The aim of salting as a pre-treatment before drying is to achieve microbiological safety and facilitate the drying process. It seemed that for MD, salting did not effectively reduce the drying time. At the same time, replacement of NaCl with KCl did not result in a change in the drying time. The mechanism of heat generation in MD was based on the repeated change in electromagnetic field polarity that resulted in the rotation of the dipole water molecules. The mobility of water molecules is the main reason for heat generation with microwaves since it causes friction (Verma *et al.*, 2020). In the present work, salting pre-treatment might have caused myofibrils to bind with water molecules (von Gersdorff *et al.*, 2021), and reducing the mobility of water, thus preventing water molecules from rotating in an electromagnetic field with MD.

Effective diffusion coefficient

Moisture diffusion in solid foods during drying is a complex process, and the term effective moisture diffusivity (D_{eff}) is used to describe the drying behaviours of foods (Erbay and İçier, 2010). The D_{eff} values during drying of beef cuts were calculated from the slope of the ln (MR) *versus* drying time graph. The change in ln (MR) against the drying time of beef dried with different techniques is illustrated in Figures 1d, 1e, and 1f. D_{eff} values of meats for all applied drying techniques were between 1.02×10^{-8} and 3.88×10^{-8} m^2/s (Table 2), which were in the range reported in the literature for different meat types (between 10^{-12} to 10^{-5} m^2/s) by Panagiotou *et al*. (2004).

When drying methods were compared regardless of salting pre-treatment, the D_{eff} increasing effect of MD was observed. Higher D_{eff} values were obtained for MD (3.88×10^{-8} m^2/s) and TD+MD (3.57×10^{-8} m^2/s) than for TD (1.33×10^{-8} m^2/s). This was due to the rapid heating behaviour of microwaves that increased the moisture diffusion rate. Furthermore, the drying temperature was higher with MD where the maximum core temperature was measured as 95°C than TD, which was operated at 80°C. Several studies revealed a similar relationship between temperature and D_{eff}, as elevated drying temperatures resulted in greater D_{eff} values (Gou *et al.*, 2003; Corrêa *et al.*, 2019; Sridhar and Charles, 2020).

In the groups with salting pre-treatment, the D_{eff} values for NaCl+TD, NaCl+MD, and NaCl+TD+MD were 1.33×10^{-8}, 3.16×10^{-8}, and 3.26×10^{-8} m^2/s, respectively. Partial replacement of NaCl with KCl in salting pre-treatment resulted in lower D_{eff} values for all drying techniques of 1.02×10^{-8}, 2.04×10^{-8}, and 1.95×10^{-8} m^2/s for NaCl/KCl+TD, NaCl/KCl+MD, and NaCl/KCl+TD+MD, respectively. As seen in Figure 1, salting, in general, caused a lower slope of the ln (MR) curve, and this effect was particularly notable when KCl was used to replace salt (Figure 1). Similarly, Gou *et al.* (2003) reported a decrease in D_{eff} in pork ham treated with several NaCl solutions with increasing salt concentrations. In another study, Sa-Adchom *et al.* (2011) noted lower D_{eff} for seasoned pork when compared to unseasoned pork, and attributed this to a possible obstructive effect of salting on mass transfer kinetics during drying. In the present work, the diffusion rate of water in the presence of KCl was lower since K^+ ions which entered the interior parts of the meat with high diffusion rate bound more water into the meat compared to Na^+ ions, resulting in a greater hindering effect on water evaporation during drying. Zhang *et al.* (2020) found a fast diffusion speed of K^+ ions compared with the Na^+ ions due to the smaller radius of Na^+ ions. The ion radius determines the diffusion rate of the relevant ions with a large ionic radius causing lower charge density and weak electrostatic effect; thus, ions can easily enter the meat (Bampi *et al.*, 2016; Zhang *et al.*, 2020). The hydration number is also a factor affecting the diffusion rate of the molecule. The ions possessing higher hydration numbers bind more water; thus, solvent molecules readily hinder the hydrated ions, resulting in a lower diffusion rate of the molecule which prevents it from diffusing to an environment with low ionic power (Bampi *et al.*, 2019). Na^+ ions possess higher hydration number than K^+ ions, and therefore, cause a lower diffusion rate (Bampi *et al.*, 2019; Zhang *et al.*, 2020).

Structural characteristics of dried beef cuts

Texture (hardness)

In the present work, the textural property of dried beef was reported in terms of hardness based on the penetration test. The results of penetration tests for both dried and rehydrated beef cuts are represented in Figure 2. Hardness in the force-time curve is the value of the maximum force required to penetrate food, represents the first bite during chewing, and is a major textural attribute for meat and meat products (Deng *et al.*, 2014).

Hardness values of dried meat for TD, MD, and TD+MD were 45.86, 100.68, and 79.32 N, respectively. All MD dried beef samples possessed higher ($p < 0.05$) hardness values compared to samples with the TD alone. This was in agreement with a previous study conducted on the drying of meats where MD resulted in a harder texture of the products (Özcan and Bozkurt, 2015). The textural quality of processed meats could be affected by the denaturation level of myofibrillar proteins. In the present work, TD was applied at a constant temperature (80°C) while the core temperature of beef was 95°C with MD. This higher temperature during drying might have increased the denaturation ratio of proteins, which promoted cross-linkage, resulting in shrinkage due to formation of a rigid structure. It was noted that every 10°C increase in temperature brings about 600 times more denaturation of proteins (Deng *et al.*, 2014; Hii *et al.*, 2014; Duma-Kocan *et al*., 2019). The hardness value of dried meat samples can be affected by processing time as well as processing temperature, while processing temperature has more effect on hardness (Chen *et al*., 2009). The hardness values determined in the dried beef samples in the present work revealed that early protein denaturation and higher processing temperature in MD had a greater effect on hardness than longer processing time in TD. The interaction of drying methods (TD, MD, and TD+MD) and salting pre-treatment (unsalted, NaCl, and NaCl/KCl) was not significant in terms of hardness value ($p > 0.05$). Furthermore, there was no significant difference in hardness values between the NaCl and NaCl/KCl applications ($p > 0.05$).

Hardness value was also evaluated for rehydrated beef cuts as the textural properties have crucial importance for overall product quality, in particular, when dried meat is used in the formulation of ready-to-eat meals. Rehydrated beef samples exhibited lower hardness values ($p < 0.05$) compared with dried samples (Figure 2). Similarly, Wang *et al*. (2013a) noted that water intake with rehydration resulted in swelling, thus causing lower hardness values when compared to dried fish. Rehydrated TD, MD, and TD+MD samples possessed hardness values of 6.89, 29.24, and 13.92 N, respectively, which differed significantly from each other ($p < 0.05$). The interaction between the drying method and salting pre-treatment was significant ($p < 0.05$) for the hardness value of rehydrated meat. The hardness value of MD (29.24 N) was significantly reduced by salting pre-treatment ($p < 0.05$) to 13.25 N in NaCl+MD and 14.17 N in NaCl/KCl+MD groups. It is worth mentioning that salting pre-treatment did not have a significant effect on the hardness values of TD samples ($p > 0.05$); however, it caused a softer texture in the MD group ($p < 0.05$). This is important for the industrial use of microwave technology in the drying of meats, since it will be possible to reduce the negative effect of microwaves on texture by salting pre-treatment. A previous study indicated that softer texture was achieved with salting of dried meats because of less compaction of the gaps within the myofibrillar structure due to the salt filling between the fibrils (Contreras Ruiz, 2020). When the hardness values of salted beef samples were compared with each other, no significant change was observed due to various drying techniques and the replacement of NaCl with KCl ($p > 0.05$).

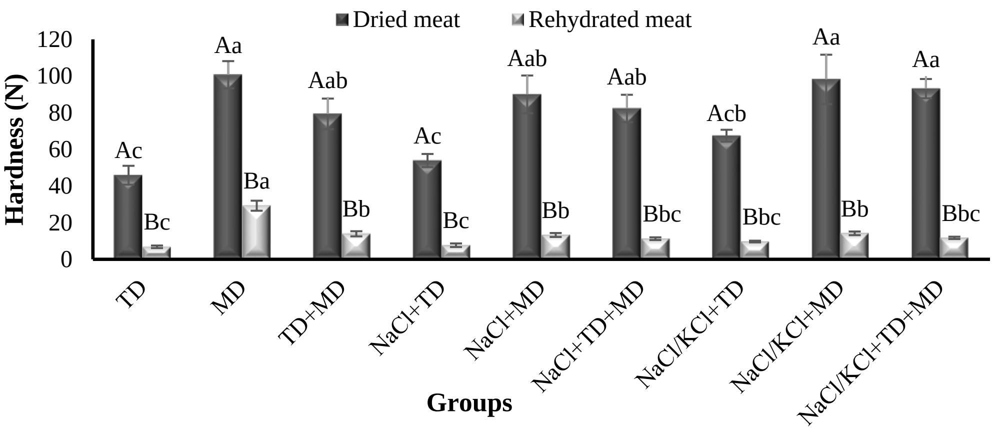

Figure 2. Hardness values for dried and rehydrated meat from nine different drying techniques. TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying. Error bars indicate standard errors ($n = 3$). Bars with different lowercase letters refer to statistically significant differences between the nine groups separately for both dried and rehydrated beef ($p < 0.05$). (Bars with different uppercase letters refer to statistically significant differences between the dried and rehydrated meats within the same group ($p < 0.05$).

Rehydration ratio

Another important quality parameter for dried foods, rehydration ratio (RR), is an indication of the physical and chemical changes as a result of drying and treatment before dehydration. These changes occur particularly due to the breakdown of myofibrils, which is associated with structural damage during the dehydration procedures (Jia *et al.*, 2019). Except for dry smoked meats that are commonly consumed as snack foods, in general, dried meats are rehydrated before consumption. Furthermore, when incorporating dried meats in ready-to-eat meals, rehydration ability is an important quality indicator. In the present work, the RR for TD, MD, and TD+MD groups were 46.78, 34.55, and 42.02%, respectively (Figure 3). The TD group had the highest ($p < 0.05$) RR value, which was not statistically different from the TD+MD group ($p > 0.05$). The rigid structure of microwave dried meat due to the higher temperatures reached with this technique may be the reason for lower RR when compared to the TD technique. Hii *et al.* (2014) investigated the rehydration capacity of chicken breast meat at different drying temperatures (60, 70, and 80°C) using a tray dryer, and reported that increasing temperatures caused more rigidity and lower rehydration capacity in meats. Matashige and Akahoshi (2002) indicated that surface hardness with thermal denaturation decreased the rehydration of dried meats. Similarly, several studies found that increasing drying temperature resulted in decreased RR in meats (Rahman *et al.*, 2005; Sa-Adchom *et al.*, 2011). Furthermore, the compact structure of fibres in microwave dried meat was the reason for the decrease in the ability to regain moisture while immersed in water during the RR test. In TD samples, due to the open fractures in myofibrils, water could enter the structure more easily, yielding higher RR. Hardness values supported these findings (Figure 2), as lower RR was observed in dried meats with higher hardness values. Similar results were noted by Wang *et al.* (2013b), where lower hardness values were observed for dried fish with higher RR.

The interaction between drying methods and salting pre-treatment was significant ($p < 0.05$) for RR. Salted groups possessed lower RR among all groups ($p < 0.05$). Similarly, Swasdisevi *et al*. (2006) reported that the salting process reduced the rehydration ratio when pork slices were dried at different temperatures with superheated steam drying. Regarding the salt type, the replacement of NaCl with KCl did not affect the RR ratio ($p > 0.05$). When salting was conducted by immersing in saline solution before drying, the RR values increased with salting as noted by Laopoolkit and Suwannaporn (2011). In the present work, dry salting was utilised instead of immersion in saline solution; therefore, stronger and firmer muscle fibril structure and lower rehydration ratio was developed by salting.

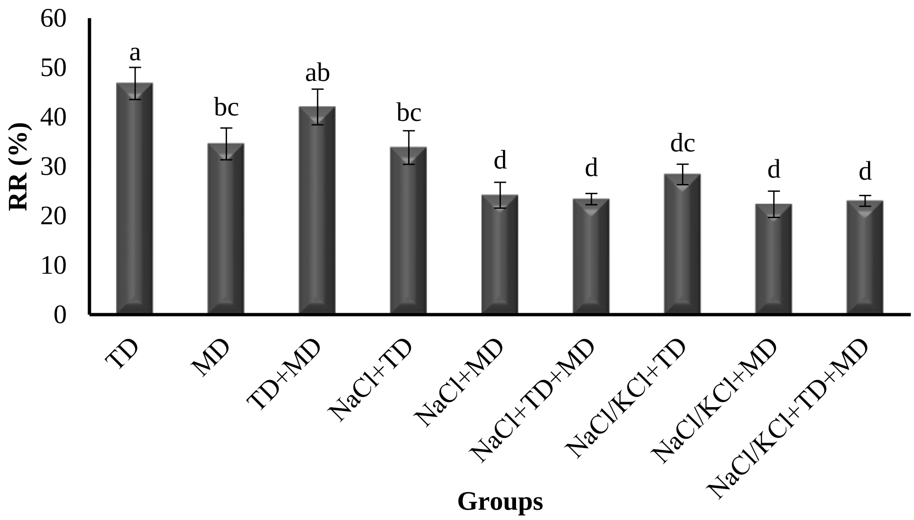

Figure 3. Rehydration ratio (RR) for dried meats from nine different drying techniques. RR: rehydration ratio; TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying. Error bars indicate standard errors ($n = 3$). Bars with different lowercase letters refer to statistically significant differences between the nine groups of dried and rehydrated beef ($p < 0.05$).

Shrinkage

One of the physical changes that occur during the drying process is shrinkage, which might be a natural result of the removal of water from the structure with the effect of heat (Laopoolkit and Suwannaporn, 2011). When meat proteins are exposed to heat and the temperature rises above 56°C, the collagen proteins shrink by 1/3 of their original length, and by half if a temperature above 61°C is reached (Nathakaranakule *et al.*, 2007). Based on the shrinkage results of the present work, drying methods did not affect the shrinkage rate significantly (p > 0.05), which was in the range of 68 - 71%. Since the final moisture content of the samples was very close to each other, there was no significant difference in shrinkage among the groups. The negative relationship between shrinkage and moisture content was previously demonstrated by Clemente *et al.* (2011). Similar results were reported in the study by Hii *et al.* (2014), where chicken meats were dried at different temperatures (60, 70, and 80°C) in a tray dryer, and the shrinkage values of the meats were found to be very close to each other at the end of the drying process when the equilibrium moisture content was reached. These findings demonstrated that both MD and dry salting could be employed without causing excessive shrinkage in industrial dried meats.

Scanning electron microscope (SEM) analysis

One of the most significant effects of the drying process on meat products is the change in the microstructure of muscle myofibrils, which determines the physical quality features of dried meat products (Pankyamma *et al.*, 2019). SEM images of dried meats provide information about structural changes in myofibrils with drying and salting. Microstructural changes in dried beef are displayed in SEM micrographs (Figure 4). Parallel fibre bundles were observed in all groups. The muscle fibres appeared smooth, well organised, and flat, similar to each other for all MD samples, including salted ones. While MD resulted in compact muscle fibres, fragmentation and gap formation between muscle fibres were observed in TD. Furthermore, damage and muscle breakdown were observed in the micrographs of fibres from the TD group, possessing slight spacing between the bundles. However, microwave-dried muscle fibres were unbroken and more compact in comparison to TD. In the SEM images of the TD+MD group, an unbroken muscle structure with slight damage was observed in comparison to the TD group. The broken and porous structure of the samples treated with TD might have been the result of the longer exposure to heat compared to MD.

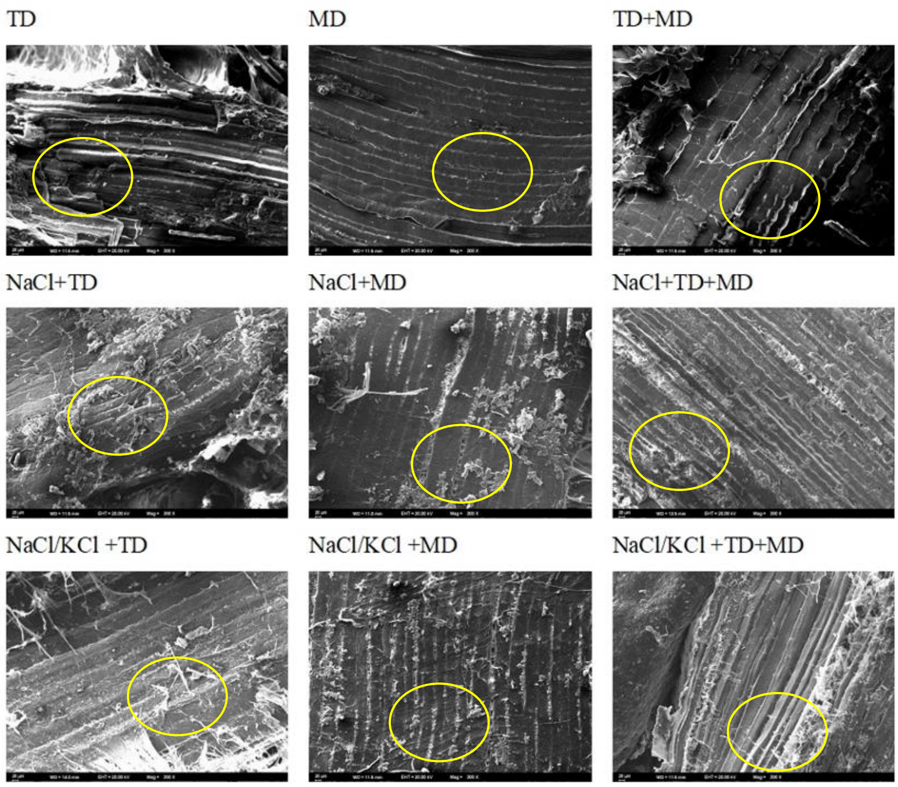

Figure 4. Representative SEM images of dried meats from nine different drying techniques. TD: tray drying; MD: microwave drying; and TD+MD: tray drying followed by microwave drying.

Salt crystals and slight spacing among muscle fibres were observed in the micrographs of salted meat compared to unsalted samples. In agreement with these results, Bampi *et al*. (2019) reported slight gaps between muscle fibre bundles in SEM micrographs of salted beef samples immersed in saline solution before drying. The meats subjected to salting pre-treatment with KCl/NaCl and NaCl revealed similar images in terms of muscle structure. Similarly, Zhang *et al.* (2020) demonstrated the effects of salt substitutes on the microstructure of salted pork where the size and distribution of muscle bundles looked similar in samples salted with both NaCl or KCl.

SEM images provide valuable information about the rehydration characteristics and texture of dried meats. The open structure of myofibrils can allow water to enter the structure during rehydration and results in an increase in RR and a decrease in hardness. In the present work, SEM images supported the findings of RR and hardness values in dried beef samples. TD resulted in higher RR in comparison to MD as a result of easier water intake into the structure due to the fractures developed during TD. Moreover, TD provided a porous structure leading to lower hardness values in comparison to MD. Porous structure could be the result of many factors such as drying temperature, drying time, and cooking method, *etc*., and the degree of porosity is related to the water intake during rehydration. Furthermore, as previously indicated, the alteration in muscle structure is generally related to protein breakdown where a higher amount of muscle fibres is broken by longer exposure to heat (Li *et al*., 2019). Therefore, more reductions in the dimension of myofibrils and collagen were observed with longer exposure to heat in TD, which exhibited shrinkage of myofibrils. Based on the SEM images of cooked yak meat samples, Li *et al.* (2019) reported that more muscle damage and breakdown due to the long exposure to heat were observed in conventional cooking when compared with microwave cooking. They associated this result with higher shear force value, indicating that microwave-cooked meat demonstrated higher tenderness than conventional-cooked meat. Pankyamma *et al.* (2019) pointed out a relationship between texture and muscle shrinkage in squid shreds as compact ordered muscle fibres had harder texture, which was in agreement with the present work. Several studies revealed a similar relationship between rehydration capacity and microstructure of dried food products as higher rehydration rates were observed in more porous products (Aksoy *et al*., 2019).

Conclusion

The present work evaluated the possible use of microwave drying as an alternative to conventional tray drying to enhance the drying of beef in terms of time and efficiency, and to reduce NaCl content by partial replacement with KCl during dry salting pre-treatment. Using microwaves noticeably shortened the drying time by increasing the water diffusion rate in comparison to TD. Salting pre-treatment was effective in reducing the drying time for TD. Similar drying periods were observed in all pre-salted groups dried using MD, either alone or in combination with TD, indicating that in reality, the salting effect on drying time is negligible for MD groups. Moreover, the substitution of NaCl with KCl did not result in a change in the drying time. Considering the dried beef structure, MD yielded harder products with lower rehydration capacity and more compact microstructure than TD. These findings could serve as a starting point for further adoption of microwave techniques for industrial drying of salted meat. Salting pre-treatment with reduced NaCl content by partially replacement with KCl is worthy of utilisation, and would meet consumer demand for healthier low-sodium meat products.

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