Title: **Comparison of three types of drying (supercritical CO_2, air and freeze) on the quality of dried apple – Quality index approach**

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Abstract

The aim of this study was to develop a quality index and examine the effects of drying apples using three technologies (supercritical CO_2 drying, air drying and freeze drying) during a period of six months in ambient conditions. Based on nine quality parameters (textural, colour and sensory properties), a mathematical model for calculating a single total quality index (TQI) of dried apples packed in different types of packaging in normal and modified atmosphere has been introduced.

At the beginning of the study, apples dried in supercritical CO_2 had the best scores. After six months, samples dried in supercritical CO_2 and freeze dried apples, both packed in polyethylene coated aluminium with 100% N_2, scored similarly. The six month shelf-life research revealed that measurable changes occur during the second half of the shelf-life when it is possible to clearly distinguish differences in the overall quality index of different dried apple slices.

Key words: supercritical drying; air-drying; freeze-drying; total quality index; apples

1. Introduction

1.1 Food drying

One of the oldest fresh fruit preservation techniques is air-drying (Mujumdar, 2014). Adequate understanding of the heat/mass transfer mechanism and its correlation with drying parameters such as temperature, velocity and relative humidity of the air used for drying is required for ideal quality dried product (Unal & Sacilik, 2011). Dried foods should maintain qualities such as flavour, texture, convenience, and functionality and high nutritional content (M. Shafiur Rahman, 2005). This is supported by a review of literature showing that the majority of research analysed physical and mechanical properties (Sette, Salvatori, & Schebor, 2016), colour (Ceballos, Giraldo, & Orrego, 2012) texture profile analysis (Rizzolo et al., 2014) and sensory evaluation (Wojdyło et al., 2016). Besides physical quality characteristics, several authors focused on chemical changes of dried food including total antioxidant activity (Nindo, Sun, Wang, Tang, & Powers, 2003), the content of phenolics (Nayak, Berrios, Powers, Tang, & Ji, 2011) and organic acids (Dupas de Matos et al., 2017; Michalska, Wojdyło, Honke, Ciska, & Andlauer, 2018). As a result of inadequate drying of fresh fruit, various quality degradation processes occur that reduce shelf-life and can cause food spoilage and food safety risks (Bonazzi & Dumoulin, 2011).

Currently, the most widely used drying techniques are air-drying and freeze-drying. Raghavi, Moses, and Anandharamakrishnan (2018), in their latest review, assume that over 85% of industrial dryers are convective, with hot air or combustion gases used as heat transfer media. Use of elevated air-drying temperatures implies quality degradation of the fruit (Adiletta, Russo, Senadeera, & Di Matteo, 2016; Sette et al., 2016). Indeed, processing fruits at elevated temperatures carries a risk that visual appearance suffers and valuable and thermo-labile nutrients, such as vitamins or carotenoids, might be degraded, and consequently, the fruits will lose their nutritional and health benefits (Polydera, Stoforos, & Taoukis, 2005; Suvarnakuta, Devahastin, & Mujumdar, 2005). Freeze-drying ensures high quality dehydration of fruit but can produce porous, brittle, amorphous and hygroscopic structures (de Santana et al., 2015). Bonazzi and Dumoulin (2011) highlighted various aspects of dried product quality, such as appearance in terms of colour and shape, taste as well as rehydration or dissolving rate, stability over time and type of packaging.

Supercritical drying was recently introduced as an alternative process to conventional drying techniques and is assisted by the use of supercritical fluids, usually CO_2 (García-González, Camino-Rey, Alnaief, Zetzl, & Smirnova, 2012). In this process, supercritical CO_2 ($scCO_2$) is used to dry the product, but simultaneously an inactivation of micro-organisms is achieved due to the antimicrobial activity of the $scCO_2$. This type of drying is considered as an attractive preservation technology, meeting consumers' demands for a product with high nutritional and sensory qualities (Ferrentino, Balzan, & Spilimbergo, 2013). Its main advantages are the relatively low temperature that avoids the thermal effects of traditional heat preservation, retaining the food freshness, in combination with its decontaminating effect (Spilimbergo, Komes, Vojvodic, Levaj, & Ferrentino, 2013).

Modified atmosphere packaging (MAP) is often used to maintain characteristics of fruits and vegetables after harvest (Kader, Zagory, Kerbel, & Wang, 1989). This technology relies on modification of the atmosphere by the respiration of the commodity and the permeability of the packaging material (Dash, 2014). As a result of using MAP, food keeps its quality characteristics during the extended shelf-life (Farber, 1991).

1.2 Food quality

Food quality is considered as a complex concept measured using objective indices (Araujo et al., 2014). Constraints in developing a single total quality score are use of different units for measuring various quality parameters, and no consensus about the weight of each parameter (Finotti, Bersani, & Bersani, 2007). Various quality index methodologies were developed for different types of food such as extra-virgin olive oil (Finotti et al., 2007), farmed tambaqui (*Colossoma macropomum*) (Araújo, De Lima, Joele, & Lourenço, 2017) and mushrooms (Djekic et al., 2017b). M. Shafiur Rahman (2005) proposed a quality index model based on nutrition, safety and sensory attributes of dried food. However, quality models for innovative drying technologies such as supercritical drying processes have not been proposed.

Quality function deployment (QFD) is a tool developed to design quality aimed at satisfying the customer and transforming the customer's demands into quality targets (Akao, 1990; ReVelle, 2004). The very first step in applying QFD is to develop a house of quality (HOQ) and translate customer requirements to quality characteristics (Park, Ham, & Lee, 2012). Such a HOQ enables the weight importance of each quality characteristic to be calculated. Literature review reveals the use of QFD for chocolates (Viaene & Januszewska, 1999), extra virgin olive oil, (Bevilacqua, Ciarapica, & Marchetti, 2012), Bulgogi bovine meat, (Park et al., 2012) and organic products (Cardoso, Casarotto Filho, & Cauchick Miguel, 2015). No QFD application to any food drying technology has been reported.

The aim of this study was to develop a quality index and examine the effects of drying apples using three drying technologies (scCO_2 drying as novel technology compared with classical air drying and freeze drying) stored for six months in ambient conditions. For the purpose of this study, based on nine quality parameters, a mathematical model for calculating a single total quality index (TQI) of dried apples packed in different types of packaging in modified atmosphere has been introduced.

2. Material and methods

Two independent research trials were performed in order to develop the quality model. The first trial was designed to identify consumer preferences towards quality characteristics of dried apples. The second trial included the changes of selected quality characteristics of dried apple slices during six months of storage.

2.1 Field research

A survey on consumers' perception of quality of dried apples was conducted at the end of 2016. A total of 85 respondents from Belgrade, which has the biggest and most developed food markets in Serbia, were interviewed. The questionnaire consisted of two sections. The first section included general demographic information about the respondents. The second section gave the respondents the opportunity to rank eight sensory/quality characteristics of dried apples (skin colour, flesh colour, odour, overall flavour, sourness, sweetness, hardness, and crispiness) from 1 = the least important for the sensory quality to 8 = the most important for the sensory quality. These characteristics were chosen in line with the research of Tomic, Radivojevic, Milivojevic, Djekic, and Smigic (2016) and M. Shafiur Rahman (2005).

2.2 Drying of apple samples

Physiologically mature fruit of the ‘Elstar’ cultivar were harvested during the 2016 harvest season in a commercial orchard in the Netherlands and stored for around one month in normal atmosphere at 1 ± 0.5 °C and 90–95% relative humidity before processing. Apples of approximately uniform size and without obvious sunburn were cut into semi-circular slices ca. 50-55 mm in length and 2.2–2.5 mm thick (Defraeye, 2017), without removing the skin, and dried using three different drying methods. Air drying was performed using an Arcen air dryer type 7508 in a stagnant belt dryer (temperature 60 °C, drying time 8 h). Freeze drying was performed in a 20L SuperModulyo freeze dryer (pressure: 0.2 mbar during sublimation and 0.05 mbar during desorption: temperature of sublimation was maintained at -25 °C and gradually increased to 40 °C during desorption; drying time 24 h). Supercritical drying was performed in a patented pilot scale machine using $scCO_2$ (pressure 125 bar; temperature 50 ^{o}C; drying time 16 h), (FeyeCon, 2010).

2.3 Storage of dried apple

Dried apple slices were packed under air or modified atmosphere (100% nitrogen) using different packaging materials, as follows: single-layer polyethylene film (PE), multi-layer film consisting of ethylene-vinyl alcohol film placed between two polyethylene films (EVOH-PE), and multi-layer film consisting of aluminium film placed between two polyethylene films (Alu-PE). The packing combinations are shown in Table 1. Each package contained cca. 100 g of dried fruit. Packed dried apple slices were stored in dark at ambient temperature (≈22 °C) during 6 months and were sampled for analysis after 0 months (10 - 15 days after packing), 3 months and 6 months of storage.

2.4 Colour changes

To average big differences among slices within each type of sample, visual colour of 10 dried apples slices was measured on both cut surfaces of each slice using a colour analyser (RGB-1002, Lutron Electronic). Data were further expressed in CIELAB coordinates (L*, a* and b*). Total colour difference (ΔE) was determined by using equation 1 (Hunter & Harold, 1987):

$$\Delta\mathrm{E} = \sqrt{\left(^{*} - \ ^{*}\right) + \left(^{*} - \ ^{*}\right) + \left(^{*} - \ ^{*}\right)} \qquad /1/$$

Values for a_o, b_o, L_o were obtained from the apples dried in $scCO_2$ just after drying to analyse changes within the subset of scCO2 apples obtained using the novel technology as well as changes related to the common drying techniques, air and freeze drying.

Browning index (BI) of dried apples was calculated using equation 2 (Maskan, 2001; Oliveira, Sousa-Gallagher, Mahajan, & Teixeira, 2012).

$$= \frac{(\quad . \quad)}{.} \qquad \text{where} \qquad = \frac{^{*} \quad . \quad ^{*}}{. \quad ^{*} \quad ^{*} \quad . \quad ^{*}} \qquad /2/$$

2.5 Texture profile analyses

Texture profile analysis of the dried apples was conducted using a texture analyser (Brookfield CT3 Texture analyser). The trigger was set at 10 g. Dried apple slices were compressed with a sphere of 12.7 mm in diameter with a set deformation depth of 1.0 mm. The speed of the probe was 0.1 mm/s during the penetration. The left and right sides of each slice were used for measurements. Hardness (as peak loads of the compression cycles), cohesiveness (as ratio of energies expanded in compression) and springiness (rate at which a deformed slice returns to its original size and shape) as quality parameters were recorded and analysed. Measurements were performed under ambient conditions within 15 minutes after opening the packaging on eight dried apple slices in two replicates for each treatment.

2.6 Sensory analysis

Sensory quality rating was conducted by a trained 8-member panel consisting of researchers from the University of Belgrade who were experienced in fruit quality judging. Over a period of three weeks, five 2-hour training sessions were performed using dried apple slices prepared in the laboratory by air drying and $scCO_2$ drying, and three commercially available dried-apple snack products. The analysis was performed using a 5-level quality scoring method as follows: excellent quality (quality score > 4.5); very good quality (3.5 < score ≤ 4.5); good quality (2.5 < score ≤ 3.5); poor/unsatisfactory quality (1.5 < score ≤ 2.5); very poor quality (score ≤ 1.5). Four initially selected characteristics were evaluated: appearance, odour, oral texture, and flavour. Each of the five integer quality scores (1-5) was divided into quarters, to obtain a category scale with 20 alternative responses. The apple samples were labelled with random 3-digit codes and presented to the panellists monadically in random order, three undamaged pieces per assessor. In each case an additional separate apple sample, kept in a closed glass jar, was used for odour judging. No strict instructions were given to the assessors whether to swallow or expectorate individual bites. Low sodium bottled water was used for palate cleansing. All of the samples (Table 1) were evaluated by the panel in two replications after 0 months (10-15 days after packing), 3 months and 6 months of storage. The sensory tests were performed in sensory booths in the sensory testing laboratory at the University of Belgrade.

2.7 Statistical analysis

Objective colour and texture data were analysed by applying one-way ANOVA (with 'samples' as fixed factor) or two-way ANOVA models combining 'storage time' with 'drying methods' (only the γ samples included) or with 'packaging' (only $scCO_2$-dried samples included) as fixed factors, followed by Tukey's HSD *post-hoc* test. Sensory data were first subjected to 3-way ANOVA with 'samples' as fixed factor, and 'assessors' and 'replications' as random factors. The mixed model included main effects and all two-way interactions. Then, in order to assess the influence of drying methods, storage time, and packaging on sensory quality scores, two 4-way ANOVA models were applied (both with 'assessors' and 'replications' as random factors): one included only $scCO_2$-dried samples with 'storage time' and 'packaging' as fixed factors; the second one included only the γ samples (Table 1) with 'storage time' and 'drying methods' as fixed factors. Both mixed models took into account only the main effects and all two-way interactions. Tukey's HSD test was used to separate the mean sensory scores.

The ranking data based on consumers' attitudes towards sensory quality characteristics of dried apples were analysed using Friedman's test followed by the least significant difference *post-hoc* test (ISO, 2006). The level of statistical significance was set at 0.05. Statistical processing was performed using Microsoft Excel 2010 and SPSS Statistics 17.0.

2.8 Quality function deployment

The HOQ used in this paper (Fig. 1) consists of three elements: A: demanded quality (WHATs); B: quality characteristics (HOWs); C: relationship matrix (WHAT vs. HOW). This HOQ was modified according to Chan and Wu (2005), Park et al. (2012) and Djekic et al. (2017a). Consumer rankings of predetermined sensory attributes (skin colour, flesh colour, odour, overall flavour, sourness, sweetness, hardness, and crispiness), obtained within the field research, were used as inputs for defining the weight importance of defined quality characteristics. W_i is the weight importance of the ‘i’ demanded quality characteristics identified by the consumers. Relative weight is the percentage of the weight importance divided by the sum of all weight importance, equation 3.

$$= \frac{}{\sum} * 100\ [\%]$$

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The nine quality characteristics (HOWs) used in the matrix were the characteristics identified as colour parameters (ΔE and BI), sensory properties (appearance, odour, oral texture and flavour) and texture parameters (hardness, cohesiveness and springiness). Relationships between the WHATs and HOWs in order to identify weight importance were calculated using the following scale of relationships: 9 – very strong, 3 – strong, 1 – weak, and 0 – no relationship (Cardoso et al., 2015; Park et al., 2012). Absolute weight importance was calculated using equation 4:

$$= \sum \qquad *$$ /4/

where:

RW_i is the relative weight (WHATs) of 'i' demanded quality characteristic (n – number of demanded quality characteristics).

RS_{ij} is the relationship score (WHATs vs. HOWs) between demanded quality characteristic 'i' and product quality characteristics 'j' (m – number of product quality characteristics). Based on the absolute importance, the relative absolute weight importance (RAW) was finally calculated (Park et al., 2012).

2.9 Total quality index

The quality parameters were divided into three groups, in line with the work of Finotti et al. (2007). Parameters of the first kind are those with a target value. The following rule applies – 'the nearer to the target value the parameter is, the better the quality is', equation 5:

$$= \frac{2 * (\quad - \quad)}{-}$$

/5/

where:

QI – quality index for a parameter; x_i – measured value in the subset of values; T - target value; x_{max} – maximal value in the subset of values; x_{min} – minimal value in the subset of values. Four sensory attributes were included in this rule (target values = 5). Parameters of the second kind have the following rule: 'the smaller the value is, the better the quality is'. For this type of parameter, QI is calculated based on equation 6:

$$= \frac{\quad}{\quad}$$ /6/

where:

QI is the quality index for a specific quality parameter. Colour parameters were included in this group (ΔE and BI). Parameters of the third kind have the following rule: 'the higher its value, the better the quality is'. For this type of parameter, QI is calculated based on equation 7:

$$= \frac{\qquad}{\qquad} \qquad ; x_i \leq x_{max}$$ /7/

where:

QI is the quality index for a specific quality parameter. Texture quality parameters were included in this group.

Upon calculation of all QIs, we can assume that in the new Euclidean space R^m (m is the number of quality parameters) quality indexes are considered as vectors $QI = (QI_1, QI_2, . . . , QI_m) \in R^m$ (Horn & Johnson, 1985). The Euclidean norm of the vector, whose components are the indexes QI, multiplied by weighting factors (RAW) will represent the overall total quality index (TQI) equation 8 (Finotti et al., 2007).

$$= \overline{\qquad\qquad} *$$

/8/

As a conclusion, the rule of thumb is that the further from the origin the vector, the worse its TQI is, and the nearer to the origin the vector, the better the TQI (Finotti et al., 2007).

3. Results and discussion

3.1 Field research

The results of the survey on consumer attitudes towards the eight selected sensory quality characteristics of dried apples as a snack product are shown in Fig. 2. According to the consumers' opinion, 'flavour' was the attribute ranked as the most important for the sensory quality of the product in question, while 'crispiness' was the least important ($\alpha = 0.05$). The differences among the rest of the included characteristics (skin or flesh colour, odour, hardness, sweetness, and sourness), related to their influence on the sensory quality, were not statistically significant ($p > 0.05$), which implies that they are equally important to the consumers. This information was included within the 'demanded quality' element (WHATs) in QFD.

3.2 Colour changes

In this study, different drying technologies initially induced colour changes (Table 2). The colour of air dried and freeze dried apples were statistically different compared to the colour of apples dried in $scCO_2$ ($p<0.05$) in all three measurement periods. After six months, all dried apple slices (except A-γ) showed significant differences compared to the beginning of the study. Depending on the value of ΔE, when this value is below 2.0, trained observers would notice the difference, while when this values is over 3.5, a clear difference in colour is noticed even by average observers (Mokrzycki & Tatol, 2011). The largest colour differences were for A-γ dried apple slices. Colour changes can occur due to degradation of pigments or non-enzymatic Maillard browning (Dadali, Demirhan, & Özbek, 2007). Colour retention of dried fruits and vegetables can indicate retention of the pigments and nutrients such as carotenoids, flavonoids, phenols, chlorophyll and betalains (Devahastin & Niamnuy, 2010). Soliva-Fortuny, Grigelmo-Miguel, Odriozola-Serrano, Gorinstein, and Martín-Belloso (2001) showed that the faster the initial polyphenol oxidase activity decays, the less the colour changes on apples in MAP occur. When the colour of the dried product is considered as a quality indicator, the colour parameters can be used to optimise the drying process and minimise the degradation of important compounds (Aral & Beşe, 2016).

The browning index (BI) is used to characterise the overall changes in browning colour and is one of the most common indicators of browning in food products containing sugar (Quitão-Teixeira, Aguiló-Aguayo, Ramos, & Martín-Belloso, 2008). Browning of apples results from both enzymatic or non-enzymatic reactions and can differ depending on the apple cultivar (Putnik et al., 2017). The formation of browning in dried fruits is often associated with the non-enzymatic Maillard reaction (Baini & Langrish, 2009; Persic, Mikulic-Petkovsek, Slatnar, & Veberic, 2017). Assessing the formation of browning in dried food helps in the selection of an appropriate drying technique, which minimises the degradation of quality in terms of colour (Pathare, Opara, & Al-Said, 2013). Our results show the BI increased over time and was initially the largest for air dried apple slices compared to other dried apple slices ($p<0.05$). The colour changes in dried apple slices C-α, C-β and F-γ, reflected through the BI, were statistically significant ($p<0.05$) after six months of storage.

Two way ANOVA confirmed statistically significant interactions between different 'drying technologies' and 'storage time', both in colour differences and BI ($p<0.05$).

3.3 Sensory analysis

The results of sensory quality judging are shown in Table 3. Different ANOVA models applied to the quality scores of the evaluated sensory characteristics showed significant changes in sensory quality as affected by 'drying method', 'storage time' and 'packaging'. The most affected were the dried apple slices packed in PE/Air (C-α) and EVOH-PE/N_2 (C-β), followed by the air-dried apple (A-γ). At the end of the observed period, the quality scores of C-α and C-β dried apple slices were within the ranges of 'poor' and 'very poor' quality, while the A-γ dried apple slices retained their initial sensory quality to a greater extent than the former two. Air-drying of apple slices led to product characterised by pronounced shape deformation (incurved and twisted shapes), well preserved skin colour, yellowish-brown colour of flesh, as well as pronounced hardness, brittleness, and apple odour and flavour.

The effects of different types of packaging on the sensory quality of dried apple were assessed by observing only the three $scCO_2$-dried apple slices (Table 1). The effect of $scCO_2$ drying was reflected in partly deformed shape of the apple slices, the appearance of reddish/pinkish discolorations in flesh originating from the skin colour, the appearance of cracks on the flesh surface, moderate crispiness, good chewiness, and pleasant apple flavour. Supercritical fluids have been used in the food industry as extraction solvents, and actually, the drying process in $scCO_2$ drying is an extraction process in which water is not removed by vaporisation or sublimation but is dissolved in the $scCO_2$ (Bourdoux, Li, Rajkovic, Devlieghere, & Uyttendaele, 2016). Water is not the only matter that dissolves during this extraction process. The reddish/pinkish discoloration of flesh obviously occurs as a result of dissolving of the apple skin pigments in the supercritical fluid and their diffusion from skin into the flesh, where the scCO2 serves as a carrier. According to the ANOVA results, it seems that after a relatively short storage period for dry fruits (3 months), ‘type of packaging’ did not affect the evaluated sensory characteristics. A statistically significant decrease was found only in the texture quality of γ-packaged apples compared with apple slices in α and β packaging (Table 4). Decreases in quality of practical significance were observed only in C-α and C-β apple slices after 6 months of storage (the scores were within the ranges of ‘poor’ and ‘very poor’ quality). After six months of storage, C-α and C-β apple slices became darker yellow-brown to greyish-brown in colour, typical apple odour and flavour were lost and replaced by hay-like odour and empty dried-fruit flavour, crispiness had completely disappeared and they became more cohesive and flexible, more adhesive on first bite and chew, and also had increased chewiness. These intense changes in sensory characteristics could primarily be attributed to the changes in water activity (a_w) during the storage time, which promotes changes in both physical characteristics of the product matrix and the oxidation rate. In air-packed apple slices (C-α), oxidation changes could further be supported by the presence of oxygen. Starting from 0.19 on average after drying (Table 1), the a_w of the apple slices packed in both PE and EVOH-PE (C-α and C-β) significantly increased after 6 months of storage (p<0.01), in contrast to the Alu-PE packed apple slices in which the increase was not statistically significant at the same level of significance (data not shown). The final average a_w values for C-α and C-β apple slices were 0.46 and 0.48, respectively. Oxidation processes and browning can occur rapidly in dehydrated fruit products depending on the a_w (Lavelli & Corti, 2011). With the exception of lipid oxidation, an increase in a_w can enhance the rate of oxidation by increasing mobility of reactants and bringing existing catalysts into solution (M. Shafiur Rahman, 1995). Investigating the effect of drying and long-term storage on phytochemical contents of apple pomace, Lavelli and Corti (2011) found that air-drying at 60 °C was better than vacuum-drying at 40 °C in terms of anthocyanin and flavanol retention, which could be due to a longer exposure to unfavourable moisture levels during drying. They also found that stability of these antioxidants during storage was greatly affected by the a_w level that ranged from 0.11 to 0.75, reporting that the maximum stability was accomplished for all investigated apple phytochemicals at the lowest a_w level. C-α sample resulted in lower score values as compared to C-β after six months of storage, since some of the panellists noticed musty flavour and pointed in their comments traces of mould on some apple slices. The presence of musty sensory properties and moulds are probably correlated with each other. Packages had no traces of damage prior to opening and storage conditions were the same for all samples. Plastics are relatively permeable to small molecules such as gases and water vapour, ranging from excellent to low barrier values, which are important in the case of food products (Siracusa, 2012). Compared to e.g. polyvinylidene dicholiride and polyester, PE has the lowest water vapour transmission rate (Kropf, 2004). Aluminium foil is considered to be impermeable to light, water vapour and gases, while EVOH is a good barrier when embedded within waterproof layers, such as PE (Lamberti & Escher, 2007).

Taking only γ apple samples into account (the apple slices packed in Alu-PE/N_2, Table 1), the results showed that 'drying method' significantly affected appearance and texture over the observed storage time. The best-preserved sensory characteristics were found in the freeze-dried apple sample (F-γ). After six months of storage, all of the evaluated characteristics of F-γ apple slices retained their initial level of sensory quality ('excellent' or 'very good'). The F-γ apple sample was characterised by apple slices of regular shape (not deformed), pale yellow colour of flesh without red discolorations, typical apple flavour with pleasant sourness, crispiness (at some level even after six months of storage), low hardness, and also good chewiness. In comparing the effects of $scCO_2$ drying and freeze-drying, the results showed no statistically significant differences in quality scores between C-γ and F-γ apple slices (with the exception of 'appearance') over the period of storage. All of the quality scores of C-γ apple slices were in the range of 'very good' quality. Unlike F-γ, the C-γ apple slices were characterised by reddish/pinkish discolorations of flesh, shape deformations of apple slices (at low level), the presence of cracks on the flesh surface, as well as lower intensity of apple flavour. These results reveal the potential of supercritical drying, as an emerging drying technology. This type of drying can retain dried apple slices for at least six months with similar sensory quality level as obtained by freeze-drying, provided the product is packed in non-permeable materials under inert atmosphere, such as Alu-PE/ N_2. However, disadvantage may lie in the fact that $scCO_2$ affects the migration of pigments from the peel into the flesh during drying.

3.4 Texture profile analysis

Hardness of dried apples showed a gradual decrease for all samples over the storage period, with the greatest decreases found in C-β and F-γ (Table 4). Results of Kutyła-Olesiuk, Nowacka, Wesoły, and Ciosek (2013) confirm that drying methods influence mechanical properties of dried apples. This is mainly since water content has an impact on the loss of the fragility of dried products (Labuza et al., 2004).

Comparison of hardness of different dried apple slices during the same storage period showed no statistical differences ($p>0.05$). Taking the storage time as a factor, significant decreases in hardness were found in dried apple slices C-α, C-β and F-γ, mainly after the period of six months (Table 4). In addition, 2-way ANOVA showed no statistically significant interactions in hardness ($p > 0.05$), neither between 'storage time' and 'drying methods' as factors (only the γ apple slices included), nor between 'storage time' and 'packaging' as factors (only $scCO_2$-dried apple slices included). The reason the greatest decrease in hardness was found in C-α and C-β dried apple slices could be related to the significant changes in a_w observed in these samples after both 3 and 6 months of storage. After 3 months of storage, the a_w levels increased on average to 0.33 and 0.35, and after 6 months to 0.46 and 0.48 in C-α and C-β apple slices, respectively (starting from 0.19). In contrast, in the γ dried apple slices, the increase in a_w was not statistically significant ($p > 0.01$). A negative correlation between moisture content and hardness of dried fruit is expected, as was presented in the work of Ansari, Maftoon-Azad, Farahnaky, Hosseini, and Badii (2014), stating that this behaviour is related to the transition of the glassy dried fruit (tough to deform) into rubbery rehydrated fruit (easy to deform). Rahman and Al-Farsi (2005) and Seow and Thevamalar (1988) confirm hardness as a function of moisture content attributing this behaviour to this transition.

Cohesiveness was the texture characteristic that showed significant changes in values ($p<0.05$), taking into account both the period of storage and drying methods (Table 4). Also, two way ANOVA confirmed that there was a statistically significant interaction in cohesiveness between different drying technologies and storage time ($p<0.05$).

Freeze-drying of apple slices resulted in a lower level of the product springiness ($p<0.05$) as compared to scCO2-drying and air-drying methods (Table 4). However, at the end of the shelf-life, dried apple slices showed no statistically significant differences in springiness ($p>0.05$). Results show that during the shelf-life, C-γ and F-γ dried apple slices expressed statistically significant differences ($p<0.05$). Two way ANOVA confirmed that there was no statistically significant interaction in springiness ($p>0.05$) between different 'drying technologies' and 'storage time' as factors.

3.5 Quality function deployment

Upon completion of the field research and laboratory testing of dried apples during the six-month period, the next step was to complete the HOQ and establish the absolute and relative importance of each quality characteristic. Fig. 3 reports the relative and absolute importance of the quality characteristics for dried apples packed in modified atmosphere. The three most important characteristics are flavour with 21.5% of RAW, followed by total colour difference (20.1%) and odour (15.8%). These results prioritise customer requirements, which would help in tailoring quality characteristics of the dried apple slices. On the other hand, cohesiveness is among the characteristics that have a low impact on the overall quality of the dried products.

3.6 Total quality index

Fig. 4 shows the final TQI scores of the dried apples. At the beginning of the study, apples dried in $scCO_2$ (regardless of the packaging) had the best TQI scores. After three months similar results were obtained for apple slices dried in scCO2 and freeze dried apples (scores between 0.39-0.44). Air dried apple slices had the worst score at three months. However, after six months, C-α and C-β dried apple slices expressed the worst scores while C-γ and F-γ had similar scores.

This method of calculating a unique TQI is capable of comparing and evaluating apples dried in different drying technologies and packed in different MAPs in a quantitative way. It is sensitive to any displacement of QI from their optimal and/or target values (Finotti et al., 2007). Also, this model can enable a large-scale comparison of various products packed in MAPs and was found a reliable, precise, and simple tool for monitoring TQI during shelf-life (Djekic et al., 2017b).

4. Conclusion

This research indicates the potential of QFD and the case of a novel TQI in analysing the shelf-life of dried apples using different drying technologies. QFD enabled the merging of consumer research on the most important sensory attributes of dried apples, and made it possible to transfer these demanded quality characteristics to measurable product characteristics. As an outcome, QFD calculated the importance of quality characteristics typical for dried apples and identified the most important attributes that play a significant role in consumer preference. This study established a mathematical index of TQI in order to evaluate the total quality of apples dried using three different drying technologies during their shelf-life. This model enables the evaluation and comparison of different drying techniques.

Results revealed two phases in quality deterioration of dried apples during six months of storage. TQI showed that measurable changes occur during the second half of the observed period, when it is possible to clearly distinguish differences in the overall TQI. Although at the end of the examined period C-γ and F-γ dried apple samples had similar scores, further research should deploy investigation of additional quality parameters. The limitation of this research is the fact that various microbiological and chemical parameters have not been included and that one variety of apple fruit was used.

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Table 1. Dried apple samples used in the research

Drying method	Initial water activity[1]	Packaging material[2]	Atmosphere	Sample abbreviation
$scCO_2$-drying	0.19 ± 0.00	PE	Air	C-α
		EVOH-PE	100% Nitrogen	C-β
		Alu-PE	100% Nitrogen	C-γ
Air-drying	0.18 ± 0.01	Alu-PE	100% Nitrogen	A-γ
Freeze-drying	0.14 ± 0.00	Alu-PE	100% Nitrogen	F-γ

[1] Mean ± standard deviation (n = 3), immediately after drying.

[2] PE=polyethylene; EVOH-PE=ethylene vinyl alcohol/polyethylene copolymer; Alu-PE = polyethylene coated aluminum.

Table 2. The effects of different atmospheres and storage time on the colour properties of dried apples

	Dried apple samples[1, 2]				
	C-α	C-β	C-γ	A-γ	F-γ
Total colour difference (ΔE)					
0 months	4.17 ± 2.08$^{a, A}$	5.94 ± 3.17$^{a, A}$	4.06 ± 1.55$^{a, A}$	21.11 ± 9.09$^{a, C}$	11.37 ± 1.23$^{a, B}$
3 months	7.76 ± 5.70$^{ab, A}$	11.04 ± 8.85$^{a, A}$	7.83 ± 6.16$^{a, A}$	24.37 ± 7.16$^{a, B}$	8.39 ± 2.01$^{a, A}$
6 months	12.65 ± 7.37$^{b, A}$	17.30 ± 5.60$^{b, AB}$	14.88 ± 9.13$^{b, A}$	28.02 ± 9.24$^{a, C}$	22.53 ± 6.51$^{b, BC}$
Browning index (BI)					
0 months	34.31 ± 4.27$^{a, A}$	39.13 ± 12.55$^{a, A}$	33.44 ± 6.53$^{a, A}$	77.94 ± 18.19$^{a, B}$	35.55 ± 5.49$^{ab, A}$
3 months	36.18 ± 6.03$^{a, A}$	39.22 ± 6.92$^{a, A}$	35.15 ± 6.32$^{a, A}$	76.84 ± 13.73$^{a, B}$	31.96 ± 2.81$^{a, A}$
6 months	50.78 ± 17.66$^{b, A}$	48.37 ± 5.22$^{b, AB}$	36.42 ± 4.72$^{a, C}$	82.47 ± 17.78$^{a, D}$	38.27 ± 7.42$^{b, BC}$

[1] Sample abbreviations are given in Table 1.

[2] Values are the arithmetic mean ± standard deviation (N = 10 samples on both cut surfaces). Values marked with the same small letter within the same column are not statistically different (α = 0.05). Values marked with the same capital letter within the same row are not stat. different (α = 0.05).

Table 3. Effects of different storage conditions on changes in sensory quality characteristics of dried apples during six months of storage.

	Dried apple samples$^{1, 2}$				
	C-α	C-β	C-γ	A-γ	F-γ
Appearance					
0 months	3.9±0.6$^{a, B}$	4.1±0.5$^{a, B}$	4.1±0.7$^{a, B}$	3.0±0.8$^{a, C}$	4.8±0.2$^{a, A}$
3 months	4.3±0.5$^{a, B}$	4.3±0.5$^{a, B}$	4.2±0.6$^{a, B}$	3.2±1.1$^{a, C}$	4.9±0.2$^{a, A}$
6 months	1.3±1.3$^{b, D}$	1.7±1.2$^{b, CD}$	3.5±0.7$^{b, B}$	2.1±1.2$^{b, C}$	4.6±0.4$^{b, A}$
Odour					
0 months	3.8±0.6$^{a, A}$	4.0±0.5$^{a, A}$	4.0±0.6$^{a, A}$	4.3±0.8$^{a, A}$	4.1±0.7$^{a, A}$
3 months	3.9±0.8$^{a, A}$	4.3±0.7$^{a, A}$	3.8±1.0$^{a, A}$	4.1±1.0$^{a, A}$	4.5±0.4$^{a, A}$
6 months	2.0±1.0$^{b, B}$	2.3±0.9$^{b, B}$	3.6±0.9$^{a, A}$	3.4±1.1$^{a, A}$	3.6±0.9$^{b, A}$
Texture					
0 months	4.1±0.5$^{a, A}$	4.1±0.6$^{a, A}$	4.5±0.5$^{a, A}$	4.4±0.6$^{a, A}$	4.5±0.4$^{b, A}$
3 months	3.8±0.6$^{a, C}$	4.0±0.5$^{a, C}$	4.7±0.4$^{a, AB}$	4.4±0.6$^{a, B}$	4.8±0.3$^{a, A}$
6 months	1.2±0.6$^{b, C}$	1.6±1.0$^{b, C}$	4.1±0.7$^{b, A}$	3.3±1.2$^{b, B}$	4.1±0.6$^{c, A}$
Flavour					
0 months	4.4±0.4$^{a, A}$	4.5±0.4$^{a, A}$	4.4±0.4$^{a, A}$	4.6±0.4$^{a, A}$	4.7±0.3$^{a, A}$
3 months	4.2±0.8$^{a, A}$	4.2±0.8$^{a, A}$	4.4±0.5$^{a, A}$	4.7±0.4$^{a, A}$	4.6±0.5$^{a, A}$
6 months	0.9±0.9$^{b, C}$	2.3±1.1$^{b, B}$	3.9±0.9$^{b, A}$	4.1±1.3$^{b, A}$	4.0±0.8$^{b, A}$

[1] Sample abbreviations are given in Table 1.

[2] Values are the arithmetic mean ± standard deviation (N = 16 = 8 assessors x 2 replications). Values marked with the same small letter within the same column are not statistically different (α = 0.05). Values marked with the same capital letter within the same row are not stat. different (α = 0.05).

Table 4. The effects of different atmospheres and storage time on the textural properties of dried apples

	Dried apple samples[1, 2]				
	C-α	C-β	C-γ	A-γ	F-γ
Hardness [g]					
0 months	302.4 ± 98.8$^{a, A}$	270.9 ± 77.5$^{a, A}$	266.6 ± 267.5$^{a, A}$	264.2 ± 138.3$^{a, A}$	175.8 ± 70.0$^{a, A}$
3 months	208.7 ± 35.2$^{ab, A}$	172.8 ± 64.7$^{b, A}$	177.5 ± 221.6$^{a, A}$	239.3 ± 196.8$^{a, A}$	174.8 ± 75.2$^{a, A}$
6 months	165.1 ± 166.4$^{b, A}$	80.1 ± 88.5$^{c, A}$	158.5 ± 183.3$^{a, A}$	178.7 ± 153.3$^{a, A}$	96.6 ± 48.3$^{b, A}$
Cohesiveness					
0 months	0.63 ± 0.15$^{ab, B}$	0.70 ± 0.13$^{a, A}$	0.62 ± 0.15$^{a, AB}$	0.59 ± 0.23$^{a, AB}$	0.47 ± 0.25$^{a, B}$
3 months	0.78 ± 0.36$^{a, AB}$	0.62 ± 0.28$^{a, AB}$	0.77 ± 0.3$^{a, AB}$	0.49 ± 0.21$^{a, A}$	0.84 ± 0.04$^{b, B}$
6 months	0.42 ± 0.05$^{b, A}$	0.62 ± 0.20$^{a, AB}$	0.80 ± 0.51$^{a, B}$	0.72 ± 0.21$^{a, AB}$	0.67 ± 0.45$^{ab, AB}$
Springiness [mm]					
0 months	0.73 ± 0.04$^{a, A}$	0.78 ± 0.03$^{a, A}$	0.77 ± 0.04$^{a, A}$	0.73 ± 0.11$^{a, A}$	0.61 ± 0.04$^{ab, B}$
3 months	0.74 ± 0.08$^{a, AB}$	0.77 ± 0.05$^{a, A}$	0.71 ± 0.05$^{b, ABC}$	0.57 ± 0.38$^{a, BC}$	0.54 ± 0.05$^{a, C}$
6 months	0.75 ± 0.09$^{a, A}$	0.75 ± 0.17$^{a, A}$	0.76 ± 0.03$^{a, A}$	0.89 ± 0.39$^{a, A}$	0.69 ± 0.16$^{b, A}$

[1] Sample abbreviations are given in Table 1.

[2] Values are the arithmetic mean ± standard deviation (N = 8 samples in 2 replications). Values marked with the same small letter within the same column are not statistically different (α = 0.05). Values marked with the same capital letter within the same row are not stat. different (α = 0.05).

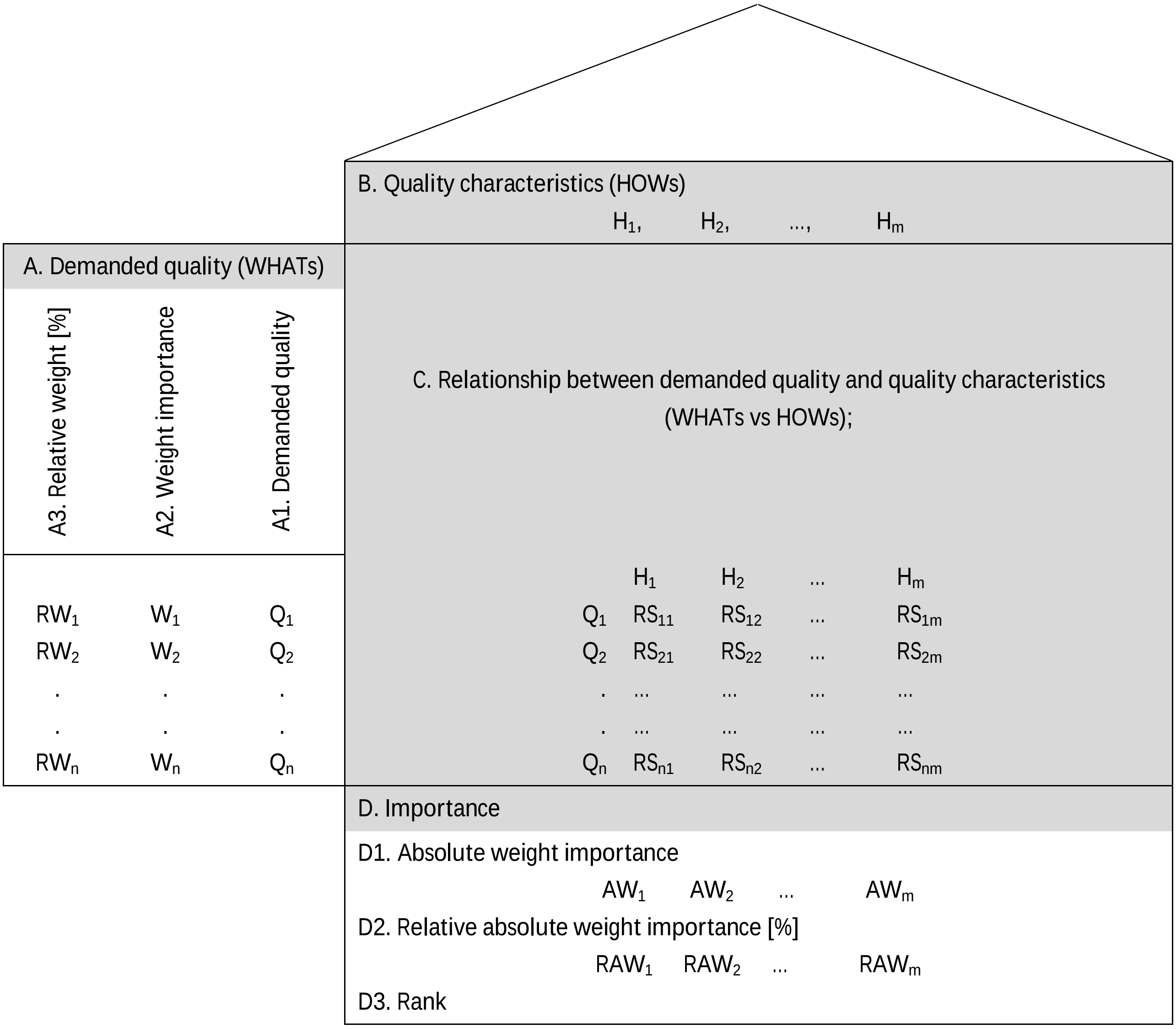

Figure 1. House of quality (HOQ)

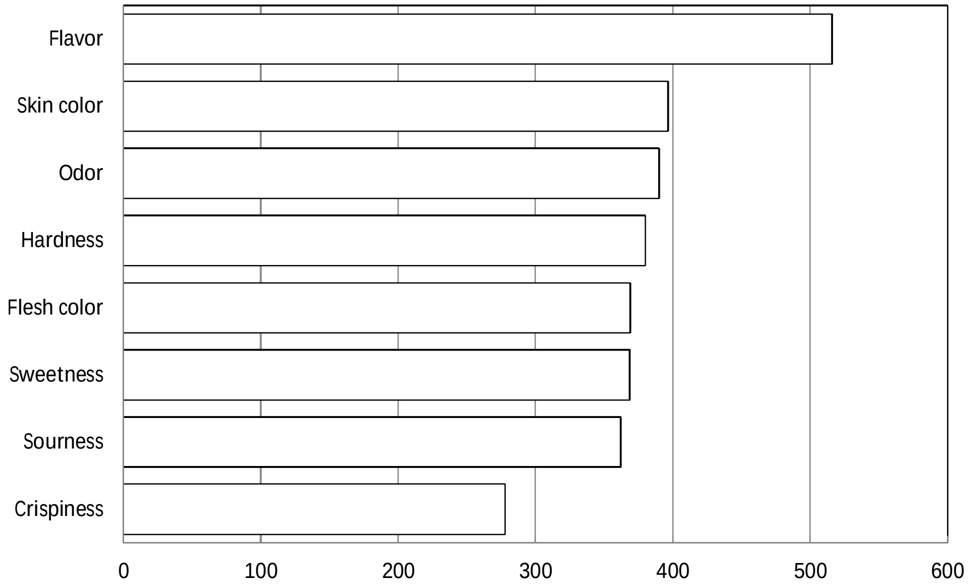

Figure 2. Consumer attitudes towards sensory quality characteristics of dried apples

Legend: Values are the rank sums (N = 85). The characteristics were ranked from 1='the least important' to 8='the most important'.

Weight			Color		Sensory parameters				Other		
Relative weight [%]	Weight importance	Quality characteristics (HOWs) Demanded quality (WHATs)	Total color difference (ΔE)	Browning Index	Appearance	Odor	Oral texture	Flavor	Hardness	Cohesiveness	Springiness
19.44%	**7**	Skin color	●	⭘	⭘						
11.11%	**4**	Flesh color	●	⭘	⭘						
16.67%	**6**	Odor				●		⭘			
22.22%	**8**	Flavor				⭘		●			
5.56%	**2**	Sourness						⭘			
8.33%	**3**	Sweetness						⭘			
13.89%	**5**	Hardness					●		●	⭘	⭘
2.78%	**1**	Crispiness					●	○	●	⭘	⭘
Absolute weight importance			2.75	0.92	0.92	2.17	1.50	2.94	1.50	0.50	0.50
Relative absolute weight importance [%]			20.1%	6.7%	6.7%	15.8%	11.0%	21.5%	11.0%	3.7%	3.7%

Figure 3. House of quality for dried apples packed in MAP

Legend: ● ‘strong relationship’ = 9, ⭘ ‘moderate’ = 3, ○ ‘weak relationship’ = 1 and blank = ‘non-existent’ or ‘zero’

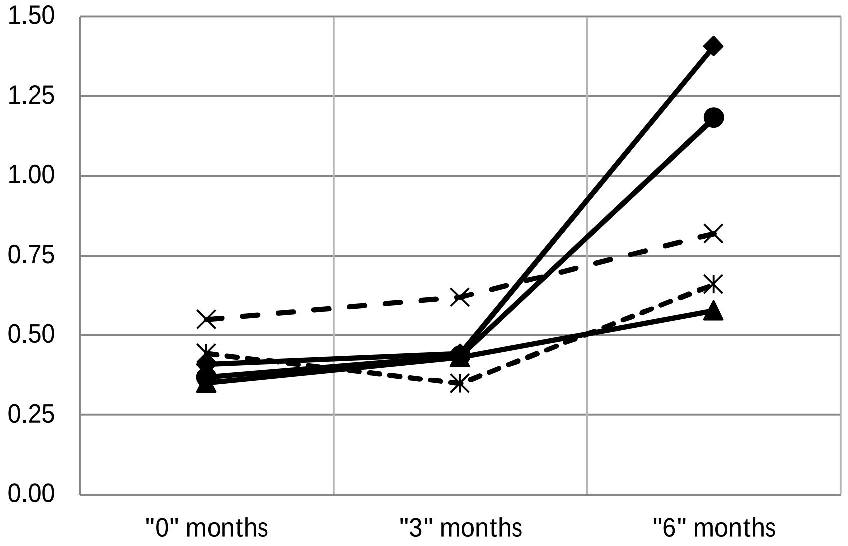

Figure 4 – Total quality index of dried apples packed in modified atmosphere during shelf-life

Legend: CO_2 dried packed in PE with air (◆ C-α); CO_2 dried packed in EVOH-PE with 100% N_2 (● C-β); CO_2 dried packed in AluPE with 100% N_2 (▲ C-γ); Air dried packed in AluPE with 100% N_2 (× A-γ); Freeze dried packed in AluPE with 100% N_2 (✱ F-γ)

Rule of the thumb: the lower the value, the better the total quality index