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# Quality of plant-based food materials and its prediction during intermittent drying

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**ABSTRACT**
In most drying processes, several physical, chemical and nutritional modifications take place in food products. Innovative drying techniques such as intermittent drying can enhance the quality of dehydrated products effectively and efficiently. Intermittent drying is a technique where drying conditions are changed through varying the drying air temperature, humidity, velocity, pressure, or even mode of heat input. This drying technique has been successfully applied to overcome the problems of conventional drying systems such as longer time consumption, case hardening, lower energy efficiency and poor-quality attributes. However, as the effect of intermittent drying on food quality is not yet well understood, a comprehensive study of quality change during intermittent drying is crucial. The main aim of this paper is to present a thorough review of the potential effect of intermittent drying methods on physical, chemical, nutritional, and stability characteristics of plant-based food material. It is found that application of intermittency using different drying systems has a significant effect on product quality and its stability. In addition, a comprehensive review on existing models of physio/biochemical kinetics for food drying is presented. Finally, the paper is concluded with the discussion of the current challenges and future directions of intermittent drying for producing high-quality dried food products.

**KEYWORDS**
Intermittent drying; quality; review; nutritional changes; physical changes; microbiological changes; kinetic modeling



## Introduction

Drying of agricultural products demands special attention, as these are considered important sources of bioactive compounds and minerals essential for mankind (Karim and Hawlader 2005). Losses of fruits and vegetables in are estimated to be about a third of the total global production (Kumar, Karim, and Joardder 2014). The need to reduce post-harvest losses is of vital importance and drying is one of the best ways to reduce these losses. Moreover, there has been a growing demand for healthy processed foods. Nowadays, people are overburdened with a never-ending succession of works, at the expense of time for preparing and enjoying a healthy and delicious meal. High quality dried food can offer a greater variety of foods in a package which contains a better health-promoting contents with distinctive flavor and texture to suit anyone's taste without seasonal restriction. Therefore, high quality dried foods are gaining the commercial importance.

Food materials, specifically plant-based food materials, are diverse in composition and heterogeneous in structure, making it difficult to interpret quality changes during drying (Khan et al. 2017a). Improvement in the quality of dehydrated food product can expand the consumer market that leads to advances in food processing industries. To improve the quality of dried products, a clear understanding of the fundamentals of various drying processes is important (Khan and Karim 2017b). Researchers have proposed some advanced drying methods, for examples: freeze-drying, dielectric drying, infrared drying, microwave drying, ultrasonic assisted drying and combination of different drying techniques, that may enhance dehydrated food quality. In most drying processes, it is widely reported that substantial changes in physical, chemical, and nutritional quality occur inside the food materials (Joardder, Kumar, and Karim 2017a; Omolola, Jideani, and Kapila 2015; Orphanides et al. 2016; Vega-Mercado, Marcela Góngora-Nieto, and Barbosa-Cánovas 2001; Vega−Gálvez et al. 2010; Zhang et al. 2015). Various drying methods have been studied for plant-based food materials, and each approach has its advantages and disadvantages (Abbasi Souraki, 2008; Gao et al. 2012). Low product quality and high-energy consumption are the main problems for existing conventional drying systems. Continuous heat supply results in quality degradation during drying. This may be due to the high temperature and longtime exposure to the extreme drying environments. Moreover, continuous drying makes the texture of the sample tougher and harder. During hot air drying, the loss of functionality in cell membranes causes significant changes in sensory and nutritional quality (Torreggiani, 1993). This contributes to poor drying performance and higher overall operating costs (Lee, Jangam, and Mujumdar 2012; Nawirska et al. 2009).

In this context, several studies reported that intermittent drying is one of the new innovative approaches to overcome

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the limitations of existing conventional drying systems. This method can promote the organoleptic and nutrient properties of the dried products (Jangam, 2011).

Intermittent drying is a new technique that can reduce energy consumption and improve the product quality. Intermittency can be obtained by varying the drying conditions, such as the drying temperature (Chong and Law 2011; Chua, Mujumdar, et al. 2000; Ho et al. 2002), heat supply (Afzal, 2003; Chua and Chou 2005; Esturk, 2012; Junqueira, Corrêa, and Ernesto 2017; Soysal, Arslan, and Keskin 2009a), airflow rate, pressure of drying chamber (Xie, Mujumdar, et al. 2017), and relative humidity (Pimpaporn, Devahastin, and Chiewchan 2007) by regularly or irregularly turning on and off heat source, or changing the amplitude of the aforementioned drying parameters. Intermittent drying techniques can also involve integrating and regulating different drying methods such as convective drying, microwave drying, vacuum drying, infrared drying or dielectric heating in time-varying fashion (Fernandes et al. 2011).

Intermittency with varying heat supply can be obtained through the application of hot air periodically with any other drying method such as microwave and infrared. When the hot air supplied at a regular interval with a microwave drying or vice versa, it is called intermittent microwave convective drying (IMCD) (Kumar, Karim, and Joardder 2014). The intermittent energy supply is also used in some heat intensive drying methods, which are commonly believed as unfavorable treatments to food quality, such as radio frequency, infrared drying or superheated steam drying.

Furthermore, attainment of intermittency can be possible by changing air velocity at different stages of drying. This strategy was recorded as a useful technique during the initial warming up stage and constant drying period to remove free moisture accumulated near the surface of samples (Reyes et al. 2002). Likewise, intermittency can be obtained by varying the pressure in the drying environment. In this method, three different categories of pressure are considered: vacuum pressure, atmospheric pressure, and high-pressure.

The application of these different intermittent drying to food processing has shown an immense potential to reduce browning effects, mitigate hydro-thermo-mechanical stresses generated inside sample, and minimize chemical reactions leading to health-beneficial component losses and adverse physical quality modifications (Chou et al. 2000; Chua, Mujumdar, et al. 2000; Jumah et al. 2007; Thomkapanich, Suvarnakuta, and Devahastin 2007). It is proved to be a promising alternative for drying of thermolabile plant-based food materials, due to the milder processing conditions it induces. During active drying period, moisture from the surface is evaporated and in the tempering period temperature and moisture redistribution take place. Moisture is transported from inner part to the surface in the tempering period. This repeated rewetting of the surface saves the sample from overheating and quality deterioration and also enhance the drying rate in the next active cycle. Morover, some moisture evaporation still takes place utilizing the sensible heat of the sample stored during the active drying period. Overheating is also avoided as energy is wisely utilized by controlling the heat input to the sample and therefore keep the temperature within the safe level of food quality.

Adequate understanding of changes in quality during intermittent drying is crucial to predict and optimize the drying conditions and achieve a better quality product. However, the literature that considers the effect of intermittency on food quality and its prediction is scattered and limited. The objective of this review paper is to present an overview of the effects of time-variation of different drying methods under controlled conditions on dried plant-based food quality. It will be explained how dehydrated plant-based foods are affected by different intermittent drying practices in term of nutritional, chemical, physical quality attributes and increased product safety. Current food quality modeling techniques that can be applied in intermittent drying to improve food quality and reduce unnecessary experimentation will be evaluated. The review will conclude with a consideration of current challenges and the scope for further research on intermittent drying.

## Effects of intermittent drying on product quality

Previous research has mainly focused on lengthening storage life and reducing energy consumption, while compromising its health-related quality. Recently, several studies have been directed toward producing high-quality dehydrated foods in term of nutritional, chemical, and physical characteristics by taking advantage of intermittent drying technologies and enhancing and optimizing existing drying methods (Sablani, 2006), which are discussed below.

### *Nutritional quality*

Health-promoting ingredients are usually tightly bound to the food matrix intracellular and/or intercellular spaces (Aguilera, 2005). The heat treatment process makes the bioactive compounds more accessible by breaking the cellular food structure and disintegrating cell clusters (Aguilera, 2005; De Roos, 2003). During thermal processing of food material, heat energy weakens the cell membranes by increases the solubility and depolymerization of pectin (Greve at el., 1994), a main component of the cell wall. The softening of the food microstructure leads to denaturing of protein-bound nutrient complexes, modification of swollen starch granules, and/or the solubility of pectin may increase the bioactivity through conversion into more dynamic molecular structures (Parada and Aguilera 2007). Moreover, the thermal process weakens the cell wall barrier for better for physical and enzymatic digestion, and it is thereby a beneficial approach for releasing nutrients from the food matrix (Joardder, Kumar, and Karim 2017a). However, over an extended period of drying, many physical, and biochemical reactions can be induced, resulting in disruption of plant cell membranes. This disruption is mainly associated with rupture of the cell membrane, and release of the compounds inside the cell. Once these health-promoting compounds are exposed to the adverse drying environment, the nutrients, which are usually stable within the original fruit matrix, are extremely vulnerable to deterioration caused by various engineering factors such as heat, oxygen, and enzymes (Faulks and Southon 2005; Van Schie and Young 2000). Therefore, in many cases there is a significant reduction in nutrient content of processed food as a result of separation of the cell membranes of food tissues, disintegration of the protein matrix structures, which enhance the degradative chemical reactions in the drying environment (Aguilera and Lillford 2008). Because of their thermolabile characteristics, most nutrients deteriorate noticeably during the thermal dehydration process (Joardder, et al. 2015; Sablani, 2006). In addition to oxidative and hydrolysis reactions, a number of chemical interactions, such as carbonyl and amino compound reactions, can take place during dehydration and storage, bringing about non-enzymatic browning phenomena, followed by the reduction of nutritional values.

In general, in conventional drying systems, a constant rate of drying medium is supplied to dry the product. Continuous application of heat energy facilitates biochemical reactions that lead to the reduction of the nutritional quality. Due to continuous supply heat energy, the atoms and molecules of bioactive components move around faster which increases the frequency of collision until sufficient energy to start the chemical reaction. The rate of biological reaction approximately doubles for every 10°C increase in temperature (Sablani 2006; Barsa, Normand, and Peleg 2012; Defraeye 2016). Prolonged exposure to drying environment can accelerate the degradative reaction, e.g. vitamin C, polyphenol oxidation, protein hydrolysis and beta-carotene isomerization, which eventually reduce the health promoting and antioxidant activity of bioactive ingredients in plant-based food materials. Lower Beta-carotene retention was reported in continuous hot air drying, vibrated fluidized and continuous microwave convective drying of carrot (Kowalski, Szadzińska, and Łechtańska 2013; Pan et al. 1999; Arikan et al. 2012), vibrated fluid bed drying of squash (Pan et al. 1999), microwave convective drying of tomatoes (Demiray, Tulek, and Yilmaz 2013; Zhao et al. 2014). The other heat sensitive nutrient components, e.g. vitamin C and total polyphenol were also significantly reduced by continuous hot air microwave drying of green pepper (Szadzińska et al. 2014) superheated low-pressure steam drying of banana (Thomkapanich, Suvarnakuta, and Devahastin 2007). Nonetheless, intermittent application of heat energy can reduce the negative alternation of oxidative and hydrolytic enzymes and microorganisms without appreciably damage heat health-related biochemical ingredients. This is may be due to the short, pulsed duration of heat energy supply during intermittent drying. Having lower activation energy, the health-promoting components are often less temperature sensitive than the destructive enzymes and microorganisms. Therefore, applying high temperature in a short time in intermittent drying can inactivate those sources of harm without appreciably damaging heat-sensitive biochemical ingredients. The treatment's pulsed duration is too short to result in significant biochemical deterioration. Moreover, during the conventional drying, prolonged exposure of the sample surface in the drying chamber ultimately deteriorates the quality of the dried product. This is may be due to thermal, hydric stresses, and other degradation reactions. Some reactions during drying can provide appealing color and flavor while others under extended duration can cause undesirable physical and nutritional characteristics (Joardder, Kumar, and Karim 2017a).

Chua, Chou, et al. (2000) employed various patterns for periodic temperature changes to dry guava samples to yield higher vitamin C retention compared to the conventional hot-air drying method. A 20% higher retention of vitamin C was achieved without significant increase in drying time. Chong, et al. (2014) compared variable temperature heat-pump drying with microwave vacuum heat-pump drying, constant convective heat-pump drying and microwave vacuum convective drying. The best result was achieved by microwave vacuum heat-pump drying, and the step-up temperature heat-pump drying retained a high amount of total phenolic content. Cyclic temperature heat-pump drying can retain antioxidant levels better than the continuous convective microwave drying method.

The benefit of intermittent drying in retaining ascorbic content was attained by low-pressure superheated-steam (LPSSD) drying. This argument was claimed in a comparison between intermittent drying and vacuum drying (Thomkapanich, Suvarnakuta, and Devahastin 2007), especially in a lower temperature mode and with a longer relaxation period. However, the interrelationship between temperature and tempering time was not investigated nor whether this combination can lead to the optimal drying condition or not, as each drying method was tested independently. Zhao et al. (2014) conducted a study on carrot drying where they periodically applied microwave energy to assist hot air convective drying in improving the drying performance and dried food quality. Unlike other time-varying drying methods in which the pulsed cycle was repeated during the total course of drying, Zhao, et al. (2014) divided the drying process into two stages, in which different drying methods were applied at different amplitudes, and the IMCD results were compared to other combined drying techniques. Their results indicated that IMCD had high industrial potential to produce the best quality in terms of color, rehydration capacity, and retention of carotenoids, while requiring short drying time. However, the method was mainly based on response surface methodology, meaning it was merely mathematically and experimentally based.

Chong et al. (2014) conducted a complex combination and comparison of dried apple in term of physical appearance, antioxidant activity, and phenolic content under different drying methods. They found that that heat-pump vacuum microwave was the most efficient drying method (in comparison with hot air – dehumidified air drying, heat-pump drying and hot air vacuum microwave drying) in retaining total polyphenol retention and antioxidant activity. Nevertheless, their conclusion was not generalizable as the processing conditions in each combination differed from the other's works. The intermittent hot air drying was compared with other hybrid drying methods that usually favor the retention of color and total polyphenol contents, making this method inferior to the others. However, the advantage of intermittent hot air drying can be found here: the cyclic temperature drying mode provided better quality than heat pump drying. Aghilinategh et al. (2015) analyzed the effect of convective, continuous microwave with intermittent microwave-convective drying on physical properties and total polyphenol. They found that higher microwave level and air velocity could provide high phenolic retention, but an increase in hot-air temperature and power ratio in IMCD had a negative impact on this phytochemical. They explained that intensive heating due to high temperature and lengthy microwave radiation caused severe breakage of the cell compartment, which releases the deleterious enzymes and accelerates the oxidation reaction to destroy the compound rapidly.

Pan, Zhao, and Hu (1998) examined the drying effect on some quality parameters of squash slices using vibrofluidized bed drying. By applying the intermittent technique, the retention of beta-carotene and drying performance were enhanced. The retention of beta-carotene was also investigated in intermittent vibrofluidized bed drying of carrot in another research of Pan et al. (1999). They indicated that the degradation of beta-carotene during intermittently vibrofluidized bed drying was efficiently reduced in the tempering period while others postulated it reversely (Thomkapanich, Suvarnakuta, and Devahastin 2007). The nonstationary pressure during superheated-steam drying performed by Thomkapanich, Suvarnakuta, and Devahastin (2007) revealed that the degree of ascorbic acid retention was lower than convective drying compared to intermittent temperature drying. Therefore, its application was not suitable to dehydrate the thermolabile and easily oxidized products.

The benefit of tempering in preserving caffeine and sugar content of yerba maté was examined by Holowaty, Ramallo, and Schmalko (2012). While the difference of sugar content was insignificantly observed, the loss of caffeine content was 20% less in intermittent drying than in continuous drying. This is maybe because the caffeine is more sensitive and volatile when exposed to higher temperatures than sugar. Therefore, further investigation is necessary to explore whether intermittent drying has any impact on the sugar content of food items (Kumar, Karim, and Joardder 2014). Table 1 provides an overview of the existing literature that addresses the retention of nutrient components during intermittent drying and compares the quality changes between conventional and intermittent drying.

## Chemical quality

Many chemical phenomena in plant-based food products, including lipid oxidation, enzyme activity and modification of flavor, may occur during drying. Many investigators have employed intermittent heating schemes in their research, resulting in significantly increased in lipid oxidation of food products as discussed below and summarized in Table 2.

Lipids in foods serve several essential functions including aroma, flavor, color and texture, and mouthfeel. The oxidation process of lipids generates products that can adversely affect these quality attributes. Rancidity and off-flavors often happen in fatty foods when they have low moisture content. Lipid oxidation is also responsible for the degradation of fat-soluble health-promoting compounds and pigments, especially in dehydrated foods. The nature of fatty acid is a major issue that affects the lipid oxidation rate. Lipid oxidation is a significant problem with food which contains a high amount of oil and unsaturated fatty acids. Limited research has been found to investigate the benefit of intermittent technique in improving quality of fatty food. Fu et al. (2016) studied the effect of intermittent oven drying on lipid oxidation of walnuts. They demonstrated that walnuts have lowest lipid oxidation values when subjected to the intermittent oven drying process. Moreover, they also argued that the amount of linoleic acid in walnut be better retained in intermittent drying than those dried in the conventional oven.

Volatile flavor components are considerably affected by the process conditions over the course of drying. An et al. (2016) investigated the effect of the microwave, hot-air convective, infrared, and pulsed microwave-convective, and freeze-drying on the major volatile compounds of ginger. They found that the amount of sesquiterpenes ($C_{15}H_{24}$) compound significantly increased while monoterpenes ($C_{10}H_{16}$) decreased considerably. The authors concluded that the intermittent microwave-convective drying process retained lower volatile compounds compared to the other drying processes. This is maybe because the penetration of microwave energy accelerates the disruption of the cell membranes that ultimately releases the volatile compounds faster. Moreover, An et al. (2016) also pointed out that intermittent microwave convective drying is not recommended for ginger due to major reductions in volatile compounds. However, this negative result can be due to the improper application of hot air temperature, power density and power ratio of microwave heating during drying ginger.

The quality of fresh fruits and vegetables rapidly decline during storage, mainly caused by disease infection and severe water transpiration. Plant-based food tissue cells are equipped with antioxidant defense systems, which usually include some antioxidant enzymes such as chloramphenicol acetyltransferase (CAT), polyphenol oxidase (Tuberoso et al. 2010) and peroxidase (POD). The enzymes help to eliminate oxidative damage in senescence and regeneration of ascorbate and glutathione metabolites. Few studies have revealed the effects of nonstationary heat treatment on antioxidant compounds during storage. Zhang et al. (2014) studied the effect of intermittent heating on antioxidant enzymes in cucumber, namely CAT and POD activity. CAT and POD activity was significantly higher for intermittent heat treatment than continuous heat treatment, enhancing their activity and reinforcing the capacity of scavenging peroxide. The intermittent heat treatment improved the ability to protect cells from oxidative injury, providing better sensory quality for intermittent heat treatment of cucumbers. Zhu et al. (2010) demonstrated that simultaneous infrared dry-blanching with nonstationary heating can be used to producing high-quality plant-based food when they conducted on apple slices on residual PPO and POD. The activity of PPO was also found lower in intermittent infrared drying at the same temperature range than in hot air convective drying of banana and the inactivation process by intermittent infrared drying occurred at a significant higher rate during drying (Milly et al. 2013).

## Physical quality

Intermittent drying is an innovative method to reduce the destructive effects of continuous stationary drying processes such as food quality deterioration due to the water removal that results in the substantial changes in physical and structural properties of products (Bernstein and Noreña 2014; Setiady et al. 2009; Telis, Telis-Romero, and Gabas 2005). Most of the fresh plant-based foods are about 80–90% of water (Khan et al. 2016; Khan et al. 2017b).

**Table 1.** Summary of nutrient quality changes observed in different intermittent drying studies.

| Study | Materials | Drying method | Drying conditions | Conclusion about product quality changes |
|---|---|---|---|---|
| 11 Pan et al. (1999) | 21 Carrots | 31 Vibrated fluid bed | 41 Vibration frequency from 0 to 20 Hz, air 1–2m/s, temperature 100–130°C | 51 Better retained (by 18.5%) Beta-carotene and slightly higher rehydration rate compared to continuous drying. |
| Pan et al. (1999) | Squash | Vibro-fluidized bed dryer | 61 Vibration frequency 16 Hz. The initial bed height is 70 mm, air velocity about 0.76 m/s, the temperature of inlet air is 80,100, 110 and 130°C | 71 Tempering-intermittent drying can reduce degradation of beta-carotene by 25.7% and shorten the drying time in Vibro-fluidized bed drying. Rehydration capacity was not much different compared to continuous drying. |
| Chua et al. (2000) | Guavas | Two-stage heat pump dryer | **81** Periodical temperature change in square-wave and cosine-wave, temperature variations from 35°C | Higher retention (up to 20%) of vitamin C compared to isothermal conditions. |
| 91 Ho et al. (2001) | Potatoes | 101 Two-stage heat pump dryer | 111 Temperature 30 and 35°C, intermittency 1/4 and 1/2 | 121 Highest vitamin C retention at higher temperature (35°C) and intermittency (1/2), however, browning rate is increased. |
| Chua et al. (2005) | Carrot, apple | Microwave compared with infrared drying | 131 Microwave heating (MW): 100, 300, 500 W with intermittency 1/9 and 1/5; Infrared (IR) with heat flux of 0.23 W/m$^2$ and intermittency 1/2, 3/5 and 1/4; | 141 Intermittent MW drying can significantly reduce color change compared with convective or intermittent infrared drying. |
| Thomkapanich (2007) | Banana | Low-pressure superheated steam(LPSS) and vacuum drying | 151 Temperatures of 70, 80, and 90°C, vacuum pressure 7 kPa at a continuous and different combination of intermittency 2/3, 1/2, 1/3, and 1/4. | 161 A higher level of vitamin C retention, especially at PR = 10 min on / 10 min off in LPSS, and PR = 10 min on / 20 min off in vacuum drying. The product colours in intermittent pressure drying were poorer than in continuous drying. Product texture, the shrinkage was not significantly different. |
| Soysal, Ayhan et al. (2009) | Red pepper | Microwave convective | MV density 597.20 and 697.87 W, PR: on 30 s / off 30 s; on 30 s / off 45 s; on 30 s / off 60 s, and 30 s on / 90 s off. Convective drying at 35, 55, 60, 65 and 75°C | 171 Better sensory quality, color, texture and appealing appearance, than continuous microwave–convective drying and commercial drying. |
| Soysal, Arslan, et al. (2009) | Oregano | Microwave convective | 181 597.20 W, 25°C, 40°C, 45°C, and 50°C with PR: 15 s on / 30 s off; 15 s on / 45 s off; and 15 s on / 60 s off | 191 No significant change in essential oil content, but unacceptable colour. |
| Ramallo et al. (2010) | Yerba maté | Convective pilot dryer | 201 Air temperature at 60, 80 and 100°C and relaxing duration 0, 15 and 30 minutes | **211** Tempering time negatively influenced caffeine concentration, which reduced by up to 10%. |
| Zhu et al. (2010) | Apple | Infrared dry-blanching and intermittent heating | 221 Temperature 70, 75, and 80°C with intermittent heating | 231 No severe surface discoloration, faster inactivation of enzymes, when prolonging the heating time with the intermittent heating mode. |
| Balakrishnan et al. (2011) | Cardamom | Spouted bed | 241 30-minute tempering at drying setup conditions | 251 Increase oleoresin retention by 10 – 15% |
| Ong et al. (2012) | Salak fruit | Heat pump, hot air convective, freeze drying | 261 HP1: 26°C, 27%, 5.4 m/s; HP2: 37°C, 17%, 5.4 m/s; HP2 with or without blanching at 50, 60, 70°C; freeze-drying at −30, −50°C.<br>271 Intermittent HP2HP2: 37°C, 17% humidity, 5.4 m/s – 1.0 m/s air velocity, at 1 h interval; Step-up HP1HP2: 26°C (180 min) – 37°C (the rest time), 17% humidity, 5.4 m/s air velocity.<br>281 Hot air 40, 50, 70, 90°C at 1.0 m/s air velocity | 291 Except for HP2, step-up HP1HP2 and intermittent HP2HP2, it retains higher ascorbic acid.<br>301 Intermittent samples obtained higher retention of total phenolic content than other drying strategies. |
| Kowalski and Szadzinska (2013) | Carrot | 311 Convective drying | 321 Various intermittent cooling/heating scheme, hot air temperature of 70°C | 331 Compared to stationary conditions, beta-carotene retention in regular temperature change schemes was 18.5% higher. In addition, it is better preserved than irregular changes in hot air temperature drying. The regular changes of the drying medium preserve the beta-carotene content (by up to 92%). |
| Chong et al. (2014) | Apple | Combined heat pump, Vacuum- microwave | 341 Intermittent Hot Air–Dehumidified Air Cyclic Temperature and Step-Up Temperature Drying (10°C, 60%); Vacuum microwave drying (4 – 6 kPa, 240 W); Heat pump drying (35°C, 20%) | 351 Intermittent heat pump drying only retain higher total polyphenol than convective vacuum microwave drying, which is significantly lower than heat pump vacuum microwave drying. |
| Szadzińska (2014) | Green pepper | Intermittent convective drying | 361 Continuous and intermittent hot air drying at 50, 70°C, intermittency 5 min on / 30 min off, 10 min on / 50 min off | 371 High retention of vitamin C than stationary conditions (up to 88% retention). |
| Zhao et al. (2014) | Tomatoes | 381 Microwave convective drying | 391 Combine hot air 60°C with high (175 W) and low power (140 W) MV drying. PR = 5 s on / 12 s off; PR = 5 s on / 15 s off; PR = 5 s / 18 s off; PR = 5 s on / 20 s off; PR = 5 s on / 23 s off; PR = 5 s on / 26 s off. | 401 IMCD showed the lowest loss of alpha-carotene (11.19%) and beta-carotene (11.28%), while samples dried by microwave drying suffered the most severe nutrient loss as indicated by a carotene reduction of 63.42% (alpha-carotene) and 43.92% (beta-carotene). |
| Aghilinategh et al. (2015) | Apple | Microwave convective | 411 Hot air temperature (40–80°C), velocity (1 – 2 m/s), pulse ratio PR (2 – 6), and microwave power (200 – 600 W) | 421 Minimum physical characteristic, energy usage, and phenolic content can be obtained by increasing the microwave power and decreasing air temperature. |
| An et al. (2016) | Ginger | Microwave convective | 431 700 W microwave, 60°C hot air, initial PR = 5 s on / 5 s off, to 50% moisture content, then PR = 5 s on / 25 s off. | 441 IMCD caused low total polyphenol loss (5.76%) compared to convective drying (19.05%) and microwave drying (29.74%). |

**Table 2.** Chemical quality and product color-related attributes investigated in intermittent drying.

| Chemical Attributes | Reference | Type of Intermittency | Food Material |
|---|---|---|---|
| **Lipid Fatty acids** | Fu *et al.* (2016) | Oven drying | Walnut |
| **beta-carotene** | Kowalski *et al.* (2013) | Non-stationary air drying | Carrot |
| | Pan *et al.* (1999[a,b]) | Tempering-drying | Squash |
| **Betanin** | Kowalski and Szadzinska (2014) | Air drying | Beetroots |
| **Volatile flavor compounds** | An et al. (2016) | Microwave-convective drying | Ginger |
| **Essential oil yield** | Soysal *et al.* (2009) | Microwave-convective drying | Orengo |
| **Enzymes inactivation** | | | |
| **– CAT*, POD*** | Zhang *et al.* (2014) | Immersion | Cucumber |
| **– PPO*, POD*** | Zhu *et al.* (2010) | IR heating | Apple |
| **– LOX*** | Fu *et al.* (2016) | Oven drying | Walnut |
| **Non-enzymatic browning** | Zhu *et al.* (2010) | IR heating | Apple |
| | Ho *et al.* (2002) | Air drying | Potato |

*CAT: Chloramphenicol acetyltransferase; POD: Peroxidase; PPO: Polyphenol oxidase, LOX: lipoxygenase

During drying, transport of this vast amount of water results in many physical quality changes such as changes in material volume, shrinkage, including case hardening and texture, which are discussed below.

Shrinkage is evident in food materials during drying. Plant-based food materials undergo physical and bio/chemical modifications which influence the drying process (Senadeera, 2008). A significant outcome of this modification is shrinkage: a decrease in volume, shape, porosity and changes in hardness (Brasiello et al. 2013). Of the many adverse effects of shrinkage to be found in the available literature, a particularly significant one is the reduction of rehydration capability, which modifies texture rehydration (Jayaraman, Gupta, and Rao 1990; McMinn and Magee 1997a, 1997b).

Food structures, the nature of the solid matrix, food composition, process parameters, and drying processes are the main parameters for deformation of hygroscopic food materials (Kerdpiboon, Devahastin, and Kerr 2007; Prothon, Ahrné, and Sjöholm 2003; Sjöholm and Gekas 1995). In continuous hot-air drying, food samples have shown considerable volume shrinkage at low temperature (20°C), whereas in intermittent conditions such as moderate (50°C) and high (80°C) temperature, materials experienced less deformation (Del Valle, Cuadros, and Aguilera 1998). Wang and Brennan (1995) showed that potato shrinkage was lower at high (70°C) temperature than low (40°C) temperature. Moreover, the shrinkage of apple is not affected only by drying medium temperatures; it also can be affected by varying the relative humidity of drying air

**Table 3.** List of quality estimation models.

| 451 Model | 461 Description | 471 References |
|---|---|---|
| 481 Kinetic<br>491 Arrhenius model | 501 $\frac{dQ}{dt} = -k.Q^n$<br>511 Q is the quality index of a color value, nutritional content at a certain time to the initial content. *n* is the order of the reaction. The reaction rate constant *k* is the function of a process condition. In the drying research, degradation is usually followed zero-, 1st-, or 2nd-order reaction.<br>521 Arrhenius equation $k = k_o.exp\left(-\frac{\Delta E_a}{R.T}\right)$<br>531 where R: universal gas constant: 8.134 (J/kmol), $k_o$ is pre-exponential factor, and $\Delta E_a$ is activation energy (kJ/mol) | 541 (Arslan & Özcan, 2011; Devahastin & Niamnuy, 2010; Di Scala & Crapiste, 2008) |
| 551 Weibull | 561 The model is usually used to describe the collapse of a system subjected to stress conditions over time:<br>571 $\frac{Q_t}{Q_o} = exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$ (5.14)<br>581 $Q_t$ and $Q_t$ are quality value at a particular time and the initial time of the process, respectively.$\alpha$: kinetic reaction constant<br>591 $\beta$: shape factor e.i $\beta = 1$ then the model become 1st order kinetics; $\beta > 1$ reaction rate increases with time, the curve adopts a sigmoidal shape; if $\beta < 1$ the reaction rate reduces with time, and deleterious rate higher than the observed exponential at the initial time. | 601 (Jiang et al. 2014; Uribe et al. 2011; Zheng & Lu, 2011) |
| 611 Williams Landel Ferry | 631 $\log\frac{Q}{Q_o} = -\int_t^0 \frac{10^{\frac{C1C2(T-Tr)}{[C2+(Tg-Tr)][C2+(T-Tg)]}}}{Dr}\,dt$ (5.15) | 651 (Frías & Oliveira, 2001; Nicoleti, et al. 2007) |
| 621 (WLF) | 641 $T_r$: reference temperature; $T_g$: glass temperature; $D_r$: thermal death time at $T_r$; $C_1$, $C_2$ are WLF constant; $Q_t$ and $Q_o$ are quality value at a particular time and the initial time of the process, respectively. | |
| 661 Eyring and Polanyi model | 671 Reaction rate: $k = \frac{k_B}{h}T\times e^{-\frac{\Delta G^*}{RT}} = \frac{k_B}{h}T\times e^{\frac{\Delta H^* - T\Delta S^*}{RT}}$ (5.15)<br>681 where $\Delta H^*$ is the enthalpy of activation (kJ/mol), $\Delta S^*$ is the entropy of activation (J/mol. K), kB is the Boltzmann constant (1.381 91023 J K), h is the Planck constant (6.626<br>691 9 1034 J s) | 701 (Barsa et al. 2012); (Karaaslan, et al. 2014) |
| 711 Multilayer neural networks (ANN) | 721 The multilayer network was modeled based on a multilayer feed-forward algorithm which that maps sets of input data onto a set of appropriate outputs, utilizes a supervised training strategy called back propagation method. | 731 (Devahastin & Niamnuy, 2010; Fathi et al. 2011; Kaminski & Tomczak, 2000; Razavi et al. 2007) |

between 5% and 50% (Ratti, 1994). In microwave-assisted drying, it is considered that the application of microwave irradiation at the early drying stage contributes to overall shrinkage as well as cellular collapse (Khan et al. 2017a, b). However, it helps to remove the strongly bound water content in plant-based food effectively; the inefficient part of conventional convective drying (Maskan, 2001). The cell structure remains intact at low microwave power because of weak force (Khraisheh, McMinn, and Magee 2004; Kumar, Karim, and Joardder 2014). In contrast, higher microwave power causes severe cell membrane breakage, which also led to puffing phenomena (Kumar et al. 2015).

Chafe (1995) investigated the effects of intermittent drying on the collapse of cellular structure and argued that surface or inner cracks can be reduced by intermittent drying. However, Chafe did not clearly show whether it decreased total shrinkage and collapse. To address such gaps, Yang et al. (2010) studied the effect in intermittent drying on material shrinkage, and they argued that intermittent drying reduce the total shrinkage as compared to continuous hot-air drying.

In addition, case hardening or crust formation is a typical phenomenon during drying of food. However, the thickness of this crust significantly depends on the material properties and drying conditions. Case hardening also represents the transition to a glassy state of the material from a rubbery state. Joardder, Karim, and Kumar (2013) studied the contribution of supplying microwave intermittently with convective hot-air drying. They argued that during intermittent microwave-convective drying, moisture and temperature are more uniformly distributed, resulting in less case hardening. Furthermore, during the intermittent drying process, drying process parameters are controlled during the drying time. In the tempering period, there is a homogenization process of moisture and temperature distribution. Similar results have been reported on the effects of resting time on the drying kinetics of rough rice (*Oryza sativa*): drying rates were proportionate to the length of tempering periods (Madamba and Yabes 2005). Steffe and Singh (1980) argued that grain quality could be substantially affected by the occurrence of cracking if the relaxing time is too short. Therefore, selecting proper tempering time for intermittent drying is still an ambiguous issue for designing an optimal drying system.

In addition, the texture of food materials is one of the prime factors for consumer acceptance. It has been found that texture has a strong relationship with the hardness, moisture absorption/desorption rate and brittleness of the product (Chen et al. 2014). It is argued that plant-based dried chips can be crisper and less hard when subjected to an intermittent drying process that employing extreme heating source, e.g., superheated steam, microwave assisted drying (Paengkanya et al. 2015; Thomkapanich, Suvarnakuta, and Devahastin 2007). The few studies specifically addressing the effect of drying process variables on texture attributes during intermittent drying of food material are unlikely to be sufficient for an adequate understanding of the change of textural quality during intermittent drying. Therefore, it is essential to conduct further studies to evaluate the effect of intermittent drying on change of texture of food material.

### Color quality

Color is a vital characteristic of dried food products which influence consumer's choice to purchase a product. The color of dried food products is governed by several structural and biochemical alterations during drying of plant-based food materials, which start from the beginning of the drying process. Many studies have examined the effect of intermittent drying on color changes of dehydrated food product. Chua et al. (2001) inspected the effect of temperature on the color of banana pieces during heat-pump drying. They reported that a step-up and step-down temperature in the range from 20°C to 35°C over the course of drying could reduce the color degradation in banana significantly. Chua et al. (2000) also investigated the changes in color of dehydrated potato, guava, and banana under different temperature control strategies. Compared to other continuous drying methods, they found that intermittent drying with an appropriate temperature pattern significantly reduced the color change. This is may be due to the protective moisture layer repeatedly forming on the surface of the sample during the relaxation period in intermittent drying that ultimately minimizes the reactions for color degradation. The application of intermittent LPSSD was found to minimize the degradation of the color of dried banana chips as compared to vacuum drying. This may be due to the drying medium compose entirely of steam without any oxygen, and therefore oxidative reactions may be reduced. Moreover, during intermittent drying, the relaxing time allows redistribution of the moisture content and cooling down of the sample, ultimately reducing the effect of nonenzymatic browning reaction in the sample. However, a longer drying period does not always improve the color of a food product. It can be explained that the long-time drying process would introduce extra residual oxygen in the drying environment, especially during the tempering period, which eventually affects the color of the dried product. Soysal et al. (2009b) noted that intermittent convective-assisted microwave drying of red pepper produced better sensorial quality such as color and texture as compared to continuous convective assisted microwave drying and conventional drying. These types of color changes depend on three main factors: the degradation of pigments, enzymatic and non-enzymatic browning, and the roughness of dehydrated products, which are discussed below.

### Pigment

There are many types of pigment in food material such as beta-carotene, betanin, lycopene, anthocyanin, and chlorophyll (Cui, Xu, and Sun 2004) which give color to food products. Carotenes are organic pigments that are responsible for a red-orange color in vegetables and fruits, while chlorophyll is responsible for the natural green of plant foods. Both chlorophyll and carotenes are susceptible to light, heat, oxygen, ironic components, enzymes, and pH. Many studies have investigated the mechanism of pigment-related color changes. The isomerization of trans- to cis-carotenoid forms leads to color degradation. These pigments have a significant impact on food quality and biological properties such as provitamin A and antioxidant activity. Recently, Kowalski, Szadzińska, and Łechtańska

(2013) have demonstrated that periodic changes in drying temperature retain much higher beta-carotene than unstructured changes, with approximately 73% to 92% retention. Kowalski and Szadzińska (2014b) examined the effect of nonstationary drying parameters on the betanin, an important pigment which has different bioactivities, including antioxidant and antibacterial activity, in beetroots. The authors demonstrated the benefit of intermittent convective drying in retention and preservation of pro-health natural pigments such as betanin. In contrast, stationary convective drying caused a high loss of betanin (up to 68%) at the drying temperature of 80°C.

### *Enzymatic and nonenzymatic browning*

The enzymatic and nonenzymatic reactions of phenolic ingredients in plant food considerably affect the product color. The enzymatic browning reaction is a chemical reaction which causes the reaction of catechol oxidase, polyphenol oxidase (Tuberoso, et al. 2010) and other enzymes (Walker 1995). Enzymatic browning is beneficial for producing the desired product color and flavor of some specific products such as raisin, prunes, bread and cocoa (Kyi et al. 2005; Walker, 1995). Nonenzymatic browning is the general term for the darkening of a product by turning brown that is not caused by enzymatic activity. The nonenzymatic browning occurs during food processing through the Maillard reaction, caramelization, and oxidative reaction. Enzymatic and nonenzymatic browning in most products is not desirable, since it indicates deterioration in the color, flavor, and nutritional properties. Several features can affect the change of product color are temperature, moisture content, pH, treatment time, and concentration and characteristics of reactants. Higher temperatures result in higher nonenzymatic browning rates, hence lowering the temperature during food processing can help to reduce these browning processes. The application of a time-varying heating medium (intermittency) would reduce the nonenzymatic browning reaction rate during drying. During the relaxing period of intermittent drying, the temperature of the whole sample is reduced by thermal diffusion (especially from hot spot to cold spot) and/or by the other drying medium, resulting a lower overall temperature sample which ultimately reduce the browning rate.

Furthermore, the degradation of ascorbic acid to dehydroascorbic acid and diketogluconic acids contribute to the discoloration of dried plant food. This may be occurred during the last stages of the drying process by interacting with the free amino acids that lead to producing the red to brown discoloration. Therefore, in several researches, the time-varying heat supply (intermittency) was effectively employed at the last stages of drying to minimize discoloration phenomena (An et al. 2016; Zhao, et al. 2014).

### *Surface roughness*

The color observed by human beings is due to the reflection of light wavelengths from the surface of the object and on to the eye's retina (Zielinska and Markowski 2012). The light, once it strikes the surface of an object, will be transmitted, absorbed, or reflected from the sample surface. The color is indicated through the reflected light. Improper application of drying conditions can affect the surface roughness of processed food. This may be due to the modification of microstructure. Hence, the original gloss of food will be reduced which decreases the brightness of the product, ultimately making the product darker and less attractive. Intermittent heat-pump drying of salak fruit provided superior color with the cells being less wrinkled, more uniform surface roughness compared to product subjected to constant heat-pump drying, approaching the color of a fresh sample (Ong and Law 2011). Another positive benefit of intermittent drying was also found by Wang et al. (2013) in drying stem lettuce slices by pulsed-air microwave-assisted vacuum drying. They found that the product has the lighter appearance, less color change with less shrunk cell surface compared to conventional microwave vacuum drying method. Therefore, it can be argued that intermittent drying might provide a smooth surface with appealing colorful products.

## Intermittent drying with product stability

Drying is a popular processing method used to preserve food by inhibiting the growth of microorganisms and delaying the initiation of some deteriorative biochemical reactions in biomaterials such as food and agricultural products. During drying, the supply of heat energy decreases the water activity ($a_w$) preventing microbial growth and chemical reactions. However, apart from $a_w$, the shelf stability of dried food relies on several factors including pH, activity of electrons, temperature, and additives (Tapia, Alzamora, and Chirife 2008). Prolonging tempering time during drying can accelerate microbial activity in the biomaterial when the sample temperature cools down to the optimum temperature for microbiological development in sufficient time. Therefore, knowledge of ideal tempering time for different biomaterials is essential in terms of the microbiological safety of dried foods (Carmo et al. 2012; Dong et al. 2009). Changes in water activity during intermittent drying of carrot (Kowalski, Szadzińska, and Łechtańska 2013), green pepper (Szadzińska, 2014), red pepper (Soysal et al. 2009b), cranberries (Beaudry, Raghavan, and Rennie 2003), beetroots (Kowalski and Szadzińska 2014b), cherries (Kowalski and Szadzińska 2014a) and the combined effect of convective intermittent drying and ultrasonic pretreatment of carrot (Kowalski, Szadzińska, and Pawłowski 2015) have been described. Kowalski, Szadzińska, and Łechtańska (2013) and Szadzińska (2014) studied the effects of different pulsations and scales of the time-varying air temperature on dried carrots (*Daucus carota* L.) and green pepper (*Capsicum* L.) respectively. They found that convective-intermittent drying increased the product's stability. They also observed that the lowest water activity was $a_w = 0.288 \pm 0.045$ for green pepper and $a_w = 0.49 \pm 0.06$ for carrot at intermittent conditions with 5 min heating (70°C) and 30 min cooling cycles. Shorter tempering periods resulted in dried samples with slightly lower water activity than those with longer ones.

In addition, intermittent drying with proper pretreatment also enhances the product shelf-life. Kowalski and Szadzińska (2014a) examined the effect of combined osmotic treatment with ultrasound and intermittent hot-air drying on quality parameters, like color and water activity of cherries (*P. cerasus* L.). They revealed that the combination of ultrasound-assisted osmotic pretreatment and intermittent convective drying decreased the water activity value to 0.440 ± 0.06 which might indicate the product stability. Moreover, Kowalski, Szadzińska, and Pawłowski (2015) obtained similar results in their investigation of the combined effect of intermittent convective drying and ultrasonic pretreatment on the stability of carrot. They indicated that ultrasonic-assisted osmotic dehydration under intermittent conditions can reduce water activity up to 0.328 ± 0.02 which may inhibit the microbial growth.

From the works cited above, it can be concluded that intermittent drying can provide high stability product. However, a complete understanding of the effect of intermittent drying on microorganism growth, sporulation, survival and contaminant production is still lacking.

## Prediction of food quality during intermittent drying

Plant-based food materials are diverse and complex in nature and their heterogeneous structures make it challenging to interpret the physio, biochemical changes that occur during drying. An in-depth understanding of fundamental physical, chemical and nutritional changes is needed to minimize the severe effect of heat on quality attributes of dried food. In this section, a comprehensive review on existing modelling on color, nutrients and other biochemical properties of dried food will be presented.

Intermittent drying is a promising drying control method that has potential to increase the energy efficiency while maintaining product quality. In literature, many attempts have been made to model the change of product quality in food processing, which can be applied in intermittent drying. Most of the models were developed based on empirical relationships to predict changes in color, microbiological, nutrients and other physicochemical properties of dried food. These models demonstrate the relationships between food quality characteristics and processing conditions in the drying process. Response Surface Methodology (RSM) is a mathematical model that is often applied for modeling and optimizing of food processing. It allows food processing researchers to investigate the process of interest efficiently (Madamba, 2002). However, as purely empirical models contain no fundamental chemical/physical mechanisms, they are only applicable in the range of experimental conditions (Kumar, Karim, and Joardder 2014).

There are increasing numbers of studies that employ artificial intelligence, including, fuzzy logic, genetic algorithms and artificial neural networks (ANN), to model food processing. Kaminski and Tomczak (2000) examined the capability of first-order reaction models, multilayer perceptron (MLP) models, and combined models to predict changes in vitamin C level in some types of vegetables during intermittent vibrofluidized bed drying. The first order kinetics models provided a better fit in testing for silica gel and potatoes. For cabbage, a combined model performed better than the others, while an MPL model was more suitable for potatoes. The suitability of various models for different food materials mainly depends on the diverse nature of the food matrix. Razavi et al. (2007) employed ANN to predict the color change of combined osmotic treatment and hot-air drying of pumpkins. The authors claimed that the model delivers better fit than empirical and semi-empirical models to simulate quality changes of some types of fruits and vegetables during drying (Alli, Ramaswamy, and Chen 2001). However, the predictions of ANN models are highly dependent on the number of neurons, and ANNs are subject to overfitting or memorization instead of generalization. Table 3 provides an overview of frequently employed predictive models used by researchers, along with experimental conditions in modeling as well as the different quality attributes gained for various food materials when employing intermittent drying.

Kinetic models are a more fundamental modeling approach obtained from energy and mass transfer relationships. This type of model is widely adopted to simulate the reduction of nutrient content and color of fruits and vegetables in thermal food processing. These kinetic models have been successfully applied many studies of drying to predict the changes of the quality index with time. The reaction rate in the kinetic model is widely applied to Arrhenius equation, which gives temperature dependence.

The change of biological quality index of dried products is often described as an $n$th order reaction kinetic approach (Valdramidis et al. 2012):

$$\frac{dQ}{dt} = -k.Q^n \tag{1}$$

where Q is the quality index (representing the value of color value, nutritional content and even food texture index at a certain time relative to the initial content) and $n$ is the order of the reaction. The reaction rate constant $k$ is a function of dehydration condition, i.e., moisture content $X_m$ and sample temperature $T_m$ which depends on the local position in the drying material (Kaminski and Tomczak 2000).

$$k = f(X_m(t), T_m(t)) \tag{2}$$

As drying temperature is varying during the intermittent dehydration process, the concept of equivalent temperature can be considered, which represent the similar biochemical quality degradation observed under unknown nonstationary heating conditions. This approach was used in studying the kinetic of vitamin C decomposition in intermittent drying guava (Chua et al. 2000).

Equation (1) can be solved by integration with reference to Equation (2) if variables in Equation (2) are known.

By integration with time, the quality index values can be obtained:

$$Q^{1-n} = Q_o^{1-n} + (n-1).k.t \; for \; n \neq 1$$

where $Q_o$ is the quality index at the initial condition.

In food drying research, quality change rate under heat treatment usually follow zero order, first order or second order reactions and the reduction rates are given in Equations (4), (5) and (6) respectively:

$$\frac{dQ}{dt} = -k \quad (4)$$

$$\frac{dQ}{dt} = -k.Q \quad (5)$$

$$\frac{dQ}{dt} = -k.Q^2 \quad (6)$$

After integration, Equations (4), (5) and (6) become:

$$Q = Q_o - k.t \quad (7)$$

$$Q = Q_o.\exp(-kt) \quad (8)$$

$$\frac{1}{Q} = \frac{1}{Q_o} + kt \quad (9)$$

As food quality changes owing to biochemical reactions and physical alterations strongly depend on food matrix characteristics, no generic modeling by theoretical approach can be applied. The relation between the reaction rate constant, *k,* and the process conditions are usually nonlinear. In the literature, the reaction rate constant, *k,* is often calculated from the Arrhenius law, which depends on equivalent temperature (Chua et al. 2000) as in the following equation (Goula and Adamopoulos 2006):

$$k = k_o\exp\left(-\frac{\Delta E_a}{R.T}\right) \quad (10)$$

Equation (10) can also be rewritten to:

$$\ln k = \ln k_o - \frac{\Delta E_a}{R.T} \quad (11)$$

where $R$ is a universal gas constant: 8.134 (J/kmol), $\Delta E_a$ is activation energy, and $k_o$ is a pre-exponential factor. $\Delta E_a$ and $k_o$ can be considered as functions of moisture content as in Mishkin, Saguy, and Karel (1984a) report:

$$k_o = A_o + A_1.M + A_2.M^2 \quad (12)$$

$$\Delta E_a = B_o + B_1.M + B_2.M^2 \quad (13)$$

where $M$ is the moisture content in dry basis (g water/g solid mass) and $A_o$, $A_1$, $A_2$, $B_o$, $B_1$, and $B_2$ are constants estimated by a suitable fitting method. A suitable reaction rate can be calculated by a two-step linear or one-step nonlinear regression analysis from experimental data to obtain quality index Q.

The degradation of nutrient, color changes predicted by kinetic models are mostly found to follow zero, first, second order reactions. Chua, Chou, et al. (2000) successfully applied the kinetic model to predict the degradation of ascorbic acid of guava pieces dried in nonstationary conditions by using the equivalent temperature concept. The Weibull model, an expanded version of Arrhenius models that were originally used to predict the collapse of the structure and microbiological inactivation, has been increasingly used by researchers to model color and chemical deterioration (Boekel, 2008). This model provided adequate prediction in several studies to describe the kinetics of nutrient changes, color changes or microbial inactivation processes (Jiang, Zheng, and Lu 2014; Liu et al. 2011; Van Boekel, 2002; Zheng and Lu 2011).

The prediction of texture, color, enzymatic reaction, microbial inactivation, and nutrient change of dehydrating fruits and vegetables can also be implemented by applying other models. The Williams–Landel–Ferry (WLF) equation is derived from polymer science and newly imported the Eyring–Polanyi model from physical chemistry (Barsa, Normand, and Peleg 2012). The WLF model uses the glass transition temperature (Tg) and thermal death time (DT) to describe the kinetics of some nutrient deterioration of food under thermal treatments. As the Arrhenius equation is not suitable to describe the degradation of food in the rubbery condition, the kinetics of food modification may be affected by molecular food mobility, free volume, molecular relaxation time and glass transition temperature, $T_g$. The kinetic temperature dependence of physical and biochemical properties in this state can be described by WLF model.

In addition, the correlation between the reaction rate k and the reciprocal of the drying temperature (*1/T*) in the Arrhenius equation has to be linear, which is an issue in some real cases. The Eyring–Polanyi model has been recently suggested as a substitute for the Arrhenius equation where the plot of *ln[k(T)]* versus *1/T* is curved (Başlar et al. 2014). It has been applied in modeling total phenol retention and total anthocyanins in dried pomegranate pods (Karaaslan, et al. 2014); thermal decomposition of anthocyanins in blood orange, blackberry, and roselle (Cisse et al. 2009); and chlorophyll and vitamin C in nectar (Diop Ndiaye et al. 2011).

However, the aformentioned simple analytical or semi-empirical models provide little insight about the fundamental understanding of physical phenomena during drying, and therefore are inadequate to generalize the findings. Mechanistic models of quality, which present theoretical correlations between quality attributes and the drying parameters, are very complex to formulate. A combination of the analytical and kinetic model with a physics-based drying model is believed to have the benefits of combining the advantages of each approach in predicting food quality change. These models can be used in intermittent drying by incorporating intermittent heating pattern in these drying models and to determine the spatial temperature and moisture distribution throughout the drying process. During the drying process, the distributions and gradients of temperature and moisture content in the drying sample characterize the degradation rate of the quality of dried foods, which can be used as continuous inputs to the incorporated analytical and kinetic quality model to calculate the dried food quality indexes during drying.

Recently, some efforts have been made to predict food quality change by combining physics-based models with available physio/biochemical kinetic models. Lespinard et al. (2009) studied the shrinkage and enzyme inactivation during blanching of mushrooms using COMSOL Multiphysics package to model the change of PPO under thermal treatment. Curcio et al. (2015) developed a multiphase transport media model to predict microorganism inactivation and colour change during drying. By incorporation of kinetic of color and microbial change, the effects of drying conditions on quality indexes were determined. In predicting nutrient quality change in intermittent drying, an attempt has been made by Defraeye (2016) by combining heat and mass transfer simulations of the intermittent drying process with a biological kinetic model for quality prediction during drying. The work can be considered as a good example in simulating quality change in intermittent drying. However, the quality-predicting model was not calibrated or validated, and the author's primary purpose was merely to assess and compare the quality difference between continuous and intermittent drying.

However, biochemical reactions in foods do not regularly happen without interaction with other ingredients and/or in conjunction with other reactions. These bio/chemical reactions occur reversibly and/or irreversibly with the contribution several reactants, intermediates, and products. Most of the kinetic models used to predict quality change are single-response kinetic models, which are still considered pseudo-model, ignoring the contribution of intermediary products by which the reaction took place in very short time. Employing multiple responses of a reaction to model biochemical changes in food during processing is considerably more powerful than a single response modeling. This method requires the detailed scheme of a comprehensive reaction network. The advantages of multi-response modeling compared to single response modellings are: (i) thorough check of kinetic models and interaction, (ii) insightful kinetic parameter estimation, (iii) increased understanding of the actual reaction scheme during processing the food material. Currently, most multi-response modeling work has been done for food in liquid or paste conditions (Achir et al. 2015; Achir et al. 2011; Mogol and Gokmen 2013; Verbeyst et al. 2013). Moreover, coupling models between simultaneous heat and mass transfer with complicated chemical reactions are needed for a high-quality product and process design. However, there is very limited material in the available literature that deals with coupling models. These coupling models have to consider the kinetics of the overall quality changes in multiphase rather than focusing on the retention of specific attributes of dehydrated food products.

## Challenges and future prospects

For intermittent drying, energy is utilized effectively with avoiding overheating and over-drying the surface of the dried food during the dehydration process. However, understanding of the effective relaxation time during intermittent drying is important for obtaining a better quality product. The existing research is, at present, insufficient for an optimum intermittent drying system: a better understanding of the calculation of the tempering period, active drying duration and amplitude is needed, although there are many studies highlighting the benefit of intermittent strategy. Therefore, identification of optimum tempering periods for intermittent drying is a key challenge for further research on intermittent drying systems.

The bio/chemical reactions that determine the quality degradation of food material depend on the material characteristic, the process states, and the pattern of drying process. The effect of drying conditions on quality results from the combination of different factors; some are internal while others are external. The application of time-varying heat supply for high drying rate method helps to minimize the negative characteristics to improve the physical, chemical, and nutrient quality. The stability and safety aspect of the product are also maintained. However, most of the existing works have mainly been based on experimental and empirical data. The literature lacks a comprehensive model based on a fundamental understanding of quality aspects during intermittent drying. The fundamental relationships between mathematics, chemical reactions, biology, and drying kinetics need to be established to improve the performance of drying systems and obtain a better-quality product. For establishing these relationships, a more complex model should be developed and applied. Moreover, validation of this model is also a challenge for future research. Furthermore, other factors, such as pH and oxygen, have substantial roles in oxidation reaction but limited data are available on the effect of those factors on nutrient reduction rates.

## Conclusion

A conventional drying system is the easiest way of drying although it has some adverse effects associated with longer time consumption, crusting at the surface due to an elevated temperature, lower energy efficiency and poor-quality attributes. To overcome these problems intermittent drying has been introduced and successfully applied. The intermittent process can be made by varying drying conditions such as the heat source, airflow, pressure, humidity and active drying time, depending on the type of sample. In intermittent drying research, sufficient understanding of the quality attributes and their prediction is crucial to optimize the drying conditions and achieve a better quality product. A comprehensive review of the effect of intermittency on different quality parameters during intermittent drying has been presented in this paper. A comparative study of various intermittent approaches and their effects on aspects of quality has been presented. It has been found that proper application of intermittent drying can improve the plant based foot quality as compared to conventional dehydration methods. In this paper, an overview of effect pretreatments on food quality during intermittent drying has also been presented. It has been found that pretreatments applied before intermittent drying may improve quality. However, the treatment type, design, and its application should be chosen according to the food characteristics and its contribution in related processing techniques. The necessity for a fundamental and accurate model that is flexible enough to be adapted for different products to predict better food quality has been discussed. The findings from this review will enhance the understanding of quality attributes and their prediction during intermittent drying in future studies.

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