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Retention of Vitamin C in Drying Processes of Fruits and Vegetables—A Review

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This article presents a review of drying processes of fruits and vegetables in which vitamin C degradation was considered. Vitamin C is an important and essential nutrient for humans and it can be taken as an index of nutrient quality of processes. Many researchers have reported the effect of different drying methods and the influence of drying conditions on the vitamin C content. In addition, the effect of other parameters related to the sample structure or to pretreatments on the final quality of the dried product is discussed. Vitamin C degradation mechanisms proposed in the literature, models applied to describe its kinetics, and recent advances in drying processes aiming high retention of this nutrient are also provided.

Keywords Ascorbic acid; Degradation kinetics; Drying methods

INTRODUCTION

Changes in food consumption can be noted in this decade. Consumers have been seeking healthier and more natural foodstuffs in order to have a balanced and nutritious diet. In this context, consumers have been encouraged to increase their daily intake of fruits and vegetables since their nutritional value as suppliers of vitamins and minerals is recognized. However, the water content of most of fruits and vegetables is higher than 80%, which limits their shelf-life and makes them more susceptible to storage and transport conditions. Consequently, an expansion in the production and consumption of processed foods has been verified. Among them, dehydrated fruits and vegetables attract attention because they can be easily produced, can be stored and transported at relatively low cost, have reduced packing cost, and their low water content avoids the development of some microorganisms responsible for deterioration of fresh food. Due to the characteristics of conventional drying processes, nutrients sensible to heat, light, and oxygen are degraded during the process.

Vitamin C is an essential substance found mainly in fruits and vegetables. This nutrient not only prevents diseases like scurvy but also plays the role of biological antioxidant. Many animal species are able to synthesize vitamin C, but humans are not. Humans have no capability to manufacture the enzyme L-gulolactone oxidase, which is responsible for the synthesis. Ascorbic acid has four isomers but only the L-ascorbic and araboascorbic (or erythorbic) acids have physiological activity as vitamin C. Ascorbic acid is a white crystalline and odorless substance. Due to its polar characteristics, it is easily soluble in water and its solubility in nonaqueous media, such as ethanol and acetonitrile, is quite limited. The crystalline and pure ascorbic acid is stable when exposed to air, light, and ambient temperature for a long period. However, in aqueous solutions or in foods, its stability is related to the storage conditions and to the composition of the matrix. The vitamin C can be easily degraded, depending on many variables such as pH, temperature, light, and presence of enzymes, oxygen, and metallic catalyzers.[1] Thus, many studies on food processes take vitamin C as a quality indicator of them.

Due to the importance of vitamin C for human nutrition as well as its use as a quality indicator for food processes, this review aims to present the state-of-the-art on the retention of vitamin C in fruits and vegetables submitted do drying processes.

This article is organized in two major sections: degradation kinetics of ascorbic acid and drying methods. Basically, the first section presents some characteristics of the nutrient as well as the parameters that influence its stability. Moreover, some degradation mechanisms proposed in the literature and some models applied to describe ascorbic acid degradation in food products are included in this part.

The second section presents several studies involving drying processes in which the vitamin C content of the product was investigated. This part compiles several works published during 1978–2008. Different drying methods and strategies, from the simplest ones to the most sophisticated, were applied to 60 kinds of fruits and vegetables. Results, discussions, and conclusions about

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potential alternatives to keep vitamin C and possibly other heat-sensible nutrients are also presented.

DEGRADATION KINETICS OF ASCORBIC ACID

As mentioned earlier, ascorbic acid can be easily degraded depending on several variables. It has been reported that the degradation kinetics are significant affected by many environment factors such as pH, temperature, light, and the presence of enzymes, oxygen, and metallic catalyzers. This dependence is illustrated in Fig. 1.

Depending on the environmental conditions, two different types of degradation occur: aerobic and anaerobic degradation. The mechanism of anaerobic degradation is complex and has not been fully established. This type of degradation is relatively insignificant in most food products. On the other hand, the ascorbic acid is oxidized to dehydroascorbic acid under aerobic conditions, followed by hydrolysis and further oxidation.[2] This reaction mechanism can be simplified by:

$$C_6H_8O_6 \leftrightarrow C_6H_6O_6 \rightarrow \text{Products}$$

L-Ascorbic Acid (AA): $C_6H_8O_6$
L-Dehydroascorbic Acid (DHAA): $C_6H_6O_6$

It has been suggested that the degradation of ascorbic acid can be described by first-order kinetics:[3–7]

$$\frac{dC}{dt} = -kC \qquad (1)$$

where C is the concentration of ascorbic acid; t is time; and k is the rate constant.

Singh et al.[8] reported that under low oxygen concentration their experimental data did not follow a first-order mechanism. In addition, Lin and Agalloco[9] commented that when the oxygen concentration is high or when it is not present, the first-order rate equation can be employed to model the kinetics. Nevertheless, if the oxygen concentration is low, a second-order reaction can be assumed. Another point discussed by them was the influence of light on the degradation reaction. When the light intensity was increased, ascorbic acid degradation enhanced. This can be attributed to the fact that lights can be also a source of energy to promote the degradation.

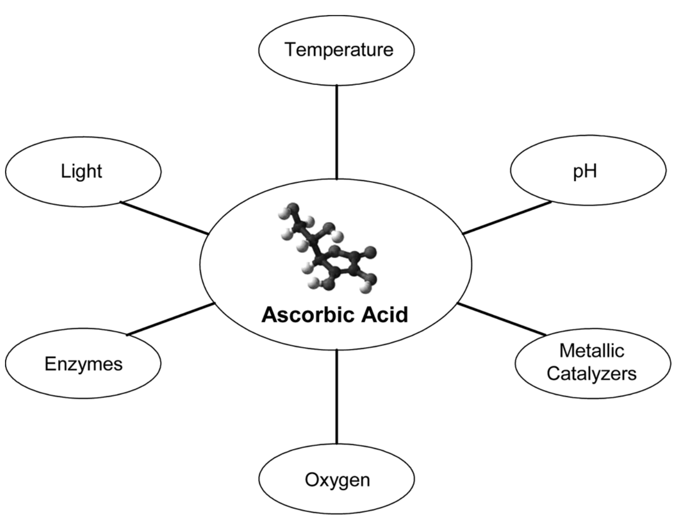

FIG. 1. Parameters affecting the degradation kinetics of vitamin C.

Other important parameters that influence the ascorbic acid degradation are water activity and temperature. Lee and Labuza[4] determined the ascorbic acid degradation as a function of water activity (aw). Varying aw from 0.32 to 0.84, the highest rate of loss was reported at 0.84. Also, the degradation was faster in the desorption system than in the adsorption system. According to the authors, the mechanism by which water controls the degradation reaction is very complex. The mechanism might possibly change depending on water activity. At high water activities, water content may dilute the ascorbic acid concentration, inducing a low degradation rate. Thus, increasing the water activity, the reaction rate is reduced. However, increasing the water content, the aqueous phase becomes less viscous, enhancing diffusion in the media. These effects facilitate the reaction of oxidation and consequently the degradation.

Moreover, during the drying process, ascorbic acid degradation was found to be moisture and temperature dependent.[10] In order to predict ascorbic acid retention during drying, a model system was used and a mathematical model was developed for ascorbic acid degradation as a function of moisture, temperature, and time. This model was applied to simulate the retention during drying and the simulated results were compared to experimental ones. Ascorbic acid degradation followed a first-order reaction. Also, it was observed that in the beginning of the process, the effect of moisture content seems to be predominant, while the temperature effect becomes the predominant one as the process proceeds. A first-order kinetics model was also applied by Mishkin et al.[11,12] to find optimal drying conditions for minimizing ascorbic acid degradation.

Ascorbic acid loss was reported to follow first-order kinetics during drying of potato,[13,14] pineapple,[15] rosehips,[16,17] guava,[18] tomato,[19] and kiwi fruit.[20]

Plotting the natural logarithm of ascorbic acid rate constant (k) versus moisture content, Goula and Adamopoulos[19] observed that the reaction rate increased with the reduction of the moisture content from 95 to 65% (wet basis). When the moisture content reached 65–70% (wet basis), the reaction rate reached a maximum. At moisture contents below 65%, the rate decreased with moisture reduction. This behavior was justified based on the degradation mechanism presented earlier. The reaction rate increase, when the moisture content was lowered from 95 to 65%, was attributed to the concentration of the ascorbic acid in the sample, which became more concentrated. Reaching 65–70% of moisture content, the rate decreased due to the increase of the aqueous phase viscosity or due to the reactants precipitation, affecting the diffusion. These results were obtained using tomato pulp with different moisture contents heated at different temperatures. The degradation kinetics of ascorbic acid in tomato halves during hot air drying was determined and correlated to the proposed mathematical model. According to the authors, it is necessary to introduce a correction coefficient in this model due to the enhanced ascorbic acid degradation in the tomato halves.

The influence of water content on the ascorbic acid degradation was also observed by Khraisheh et al.[14] They reported an initial low rate of ascorbic acid followed by a faster degradation as the moisture content decreased. The increase of ascorbic acid degradation at low moisture content was attributed to the ascorbic acid concentration, which becomes higher as the process proceeds, resulting in an increase of the reaction rate. The low degradation rate at the beginning of the drying was attributed to the integrity of the sample structure. The intact tissue provides a protection effect from the cell oxidative components.

Another factor that also affects the retention and the degradation kinetics of ascorbic acid during drying is temperature. Some studies examined the relation between the temperature and the degradation reaction using the Arrhenius equation.[13,20] Higher values of reaction rate were observed when the drying temperature was enhanced. Carrying out drying experiments with kiwi fruit, the rate of reaction observed by Orikasa et al.[20] at 70°C was more than three times higher than the rate observed at 40°C.

Application of other models used in food processing has also been reported to describe degradation kinetics of ascorbic acid during drying. Thermal Death Time (TDT) model (Eq. (2)), widely used in thermal food processing, and Williams-Landel-Ferry (WLF) model (Eq. (3)), widely used for describing viscous properties of foods applying the glass transition approach, are examples.[21,22]

$$\log\frac{C}{C_0} = -\int_0^t \frac{10^{\frac{T(t)-T_r}{z(w)}}}{D_r(w)}dt \qquad (2)$$

where C is the ascorbic acid content at time t, C_0 is the initial ascorbic acid content, T is the temperature, $D_r(w) = \sum_{i=0}^{n} D_{ri}w^i$, and $z(w) = \sum_{j=0}^{n'} z_j w^j$, both polynomial functions of water content, and w is the water content.

$$\log\frac{C}{C_0} = -\int_0^t \frac{10^{\frac{C_1C_2(T-T_r)}{[C_2+(T_g-T_r)][C_2+(T-T_g)]}}}{D_r}dt \qquad (3)$$

where C is the ascorbic acid content at time t, C_0 is the initial ascorbic acid content, Tg is the glass transition temperature, T the temperature, T_r is a reference temperature and D_r, C_1, and C_2 are WLF model parameters.

In addition, the Weibull model (Eq. (4)) was applied to describe the degradation kinetics of ascorbic acid during drying of camu camu[23] and tomato.[24]

$$\frac{C}{C_0} = \exp\left[-(\alpha t)^{\beta}\right] \qquad (4)$$

where C is the ascorbic acid content at time t, C_0 is the initial ascorbic acid content, α is the constant rate, and β is the shape constant.

During osmotic dehydration, Vial et al.[25] reported that a first-order model for describing the degradation kinetics of ascorbic acid was not adequate. This conclusion was based on the two phenomena that occur during the process: ascorbic acid diffusion from the fruit to the dehydration solution and chemical degradation. They also reported that this chemical degradation is apparently a first-order reaction. A similar effect was reported by Heng et al.[26] during osmotic dehydration of papaya.

It is possible to note that not only the drying conditions affect the degradation kinetics of ascorbic acid during drying of fruits and vegetables. Several variables influence this degradation, which makes this phenomenon quite complex. During the drying process, there are different environment variables. Also, the composition and physical structure of the product change as the process proceeds. These are strong reasons why research aiming to improve the drying technologies is valid, mainly those in which the influence on food quality is studied.

DRYING METHODS

Several drying methods have been applied to fruits and vegetables, from the simplest ones as solar and sun drying to the most expensive, like microwave and freeze drying. In order to get dried products with high nutritional and sensorial attributes, non-conventional drying methods have also been used, like those with modified atmosphere. The second part of this review presents some studies in which these drying methods and vitamin C degradation were involved. This section is organized by the drying methods, as presented schematically in Fig. 2.

In order to facilitate the visualization of the drying methods and the products whose vitamin C degradation in drying processes have been studied, two tables were prepared and are presented in the Appendix. Table A1 shows the products and also indicated if the degradation kinetics study was performed or only the initial and final content were determined. The drying methods that have been used to dry fruits and vegetables are presented in Table A2.

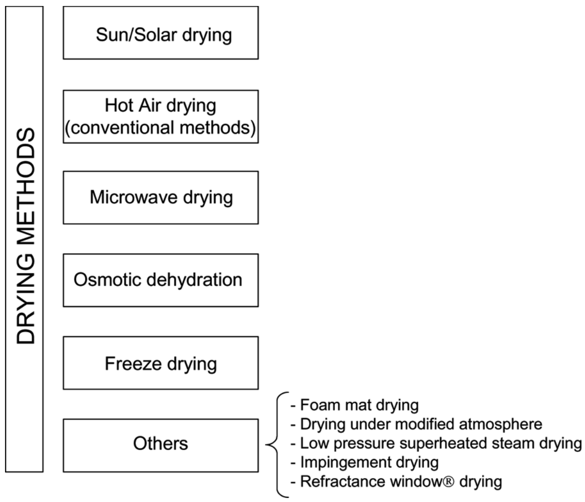

FIG. 2. Drying methods used in studies of vitamin C retention in fruits and vegetables.

Solar and Sun Drying

Solar and sun drying can be considered as the most common drying methods in tropical and subtropical countries, due to the fact that they are relatively cheap processes when compared to others. Many works can be found in the literature about vitamin C degradation in dehydrated fruits and vegetables by such methods. These biological materials are simply exposed to the sun or they are dehydrated in a forced air dryers heated by solar energy.[27–33]

Shitanda and Wanjala,[34] Negi and Roy,[35] and Maeda and Salunkhe[36] determined the vitamin C retention in different vegetables sun-dried through direct and indirect sun exposition. Results obtained by Negi and Roy[35] showed that the retention of the vitamin C is not only dependent on the kind of product but also on the drying procedure. Vitamin C content in sun-dried leaves of amaranth was higher than the content in shade-dried product, while the vitamin content in sun-dried leaves of fenugreek and savoy beet was lower than the content in shade-dried leaves.

Leaves of cassava, spinach, cow pea, and potatoes were studied by Maeda and Salunkhe.[36] For the first three leaves and taking vitamin C as an analysis parameter, shade drying presented better results than sun drying. However, the opposite occurred when the product dried was potato leaves. This last result differs from the results obtained by Mosha et al.[29] Drying the same foodstuff, they reported that shade drying would be better to get a dried product richer in vitamin C. Besides, they carried out experiments using other leaf vegetables and in all cases they did not find a difference between the vitamin content in dried products submitted to these two methods. It is important to mention that these drying methods are totally dependent on season and weather conditions of the place where the food is dried.

Trying to improve quality and nutritional parameters of dried products, several authors[37–44] have applied different pretreatments before solar and sun-drying processes. Kadam et al.[39] immersed samples of cauliflower in hot water followed by immersion in different concentrations of potassium metabisulfite solution. After drying, the highest ascorbic acid content was found in samples blanched in hot water for 3 min, independently of the potassium metabisulfite concentration. The loss of this nutrient was enhanced with the increase of blanching time in hot water, which can be explained by its heat sensibility. Also, the authors studied the stability of the ascorbic acid during storage. In this investigation, both pretreatments (blanching and immersion in potassium metabisulfite solution) seem to affect ascorbic acid content in dried cauliflower samples after 6 months storage. The higher vitamin content was found in samples blanched for 9 min and immersed in a 1.5% potassium metabisulfite solution. It is interesting to note that when the dried product was evaluated after drying process (without storage period), the best blanching time was the shorter one and the potassium metabisulfite concentration did not affect the ascorbic acid retention. However, the higher retention in dried samples stored for 6 months was observed in those in which blanching time and potassium metabisulfite were the highest values investigated. Possibly, enzymatic degradation of ascorbic acid occurs during the storage period, which is reduced with the blanching and potassium metabisulfite treatments.

Studying the effects of different pretreatments on solar-dried amla characteristics, Verma and Gupta[42] reported that potassium metabisulfite did not affect vitamin C retention. However, the pricking and blanching treatments enhanced the ascorbic acid loss. The blanching treatment was carried out by boiling the sample in a sodium chloride solution for 7 min.

El-beltagy et al.[45] investigated the influence of many sample pretreatments on the retention of vitamin C during solar drying of strawberries. They also investigated the influence of the superficial area exposed to the process. Increasing the superficial area increased the vitamin loss during the drying. This might occur due to the high sensibility of the vitamin C to the light.

Another variable investigated by Adom et al.[46] was sample thickness. The authors determined the vitamin C content in solar-dried okra with different slices thicknesses (5, 10, and 15 mm). Vitamin C content was determined at five different drying times (0, 24, 48, 72, 96 h). After 96 h of processing, samples with different thicknesses reached the final moisture content of 90–95 g/kg. The retention of the vitamin in slices of okra after 96 h of drying was about

11%, independent of their thickness. This result suggests that slice thickness does not affect vitamin C retention in dried samples of okra.

On the other hand, the slice thickness had a significant effect on the rate of moisture loss. After 24 h of drying, the moisture content of 10- and 15-mm samples was reduced from 895 g/kg to approximately 500–550 g/kg, while the moisture content of 5-mm samples was reduced to approximately 200 g/kg. Taking moisture content as reference and not the drying time, it is possible to observe an influence of slice thickness on the vitamin C content in dried samples. At 200 g/kg of moisture content, vitamin C content of 5-mm samples was more than three times higher than the content of 15-mm samples. In addition, 24 h was necessary for the 5-mm samples to reach this moisture content and 54 h for the 15-mm samples to reach the same moisture content. Directly, slice thickness cannot affect the vitamin C content of dried samples. However, this variable can affect the drying time and consequently the vitamin retention in dried samples.

Hot Air Drying

Another very common method in the drying of food products is hot air drying. In order to verify the influence of the drying process on the vitamin C content in dried products, some authors studied some conventional processes using hot air drying method. Different kinds of fruits and vegetables and different cultivars have been studied by many researchers. Apples, tomato, mango, apricot, plum, fig, peppers, potato, brinjal, onions, and others are examples of fruits and vegetables whose drying behavior have been studied and their vitamin C retention has been determined.

Vitamin C retention in dried tomatoes or dried tomato pulp was reported by several authors.[19,24,47–51] In these studies the air temperature ranged from 42 to 110°C. In addition, drying time, final moisture content, cultivars, and air velocity varied. In general, the vitamin C retention was low and in some conditions no vitamin was detectable. Carrying out experiments at 80 and 110°C in a cabinet dryer, Goula and Adamopoulos[19] and Zanoni et al.[50] reported that the loss of the vitamin C in tomato halves was about 90% or higher. In both cases the final moisture content of the tomatoes was approximately 10%. Even when the final moisture content was higher, as the samples dried at 80°C by Lavelli et al.,[51] the retention was pretty low. The influence of temperature on the degradation of the referred vitamin can be clearly seen by the results obtained by Zanoni et al.[50] At 80°C, when the moisture content was approximately 46%, the vitamin C loss was about of 62%, while at a close level of moisture content (47.6%) but at 110°C, the loss was about 100%.

A higher retention was reported by Kerkhofs et al.[48] Drying Encore and Aranka tomatoes cultivars at 42°C the retention was higher than 89%. In this case, not only the temperature of drying and the cultivar were different but also the final moisture content (23%) and the condition of tomatoes, which in this case were sliced. Studying the influence of tomato cultivar and its final moisture content after drying experiments, the authors reported a large difference in the retention of the vitamin C between these cultivars and the Flavourine cultivar, in which it was only 25%. Flavourine cultivar tomatoes were also dried at the same temperature by Toor and Savage.[47] In contrast, the vitamin C retention in dried tomatoes reported in the last study was higher than 81%. Although the tomato cultivar and the temperature were the same, the drying time and consequently the final moisture content of the sample were not. The longer the drying time, the lower the retention.

Studying the drying of peppers, Sigge et al.[52] dehydrated green bell peppers at different temperatures and relative humidities. One of their objectives was to verify the influence of the relative humidity on the vitamin C retention. Experiments were carried out at six different relative humidities (15–40%) and these conditions were achieved using a controllable water aerosol. The effect of the relative humidity was not significant when the drying was carried out at 55 and 60°C. However, when the air temperature was higher (65, 70, and 75°C), the increase of the relative humidity resulted in a lower retention of the ascorbic acid. According to the authors, the lower retention at relatively higher humidities is probably due to the longer drying period that is necessary to reach the desired final moisture content.

Still drying peppers, but now red peppers (paprika), several authors[53–59] have investigated the behavior of this vegetable during the drying process. Economically important and considered an excellent source of natural colors and vitamin C, the composition of paprika has been determined and registered. Carvajal et al.[54] verified the varietal influence on the composition of paprika and determined the retention of the vitamin C in this product after drying at 50°C for 2 days in a forced air oven. In most varietals, the retention was about 24–28%, while in one of them this value was about 42%. Considering vitamin C as a nutritional quality indicator, Daood et al.[53] obtained better dried paprika carrying out experiments applying two different drying techniques: forced air drying (variable conditions) and natural drying. Even in the samples that were naturally dried under ambient conditions, independent on their ripening stage, the vitamin C retention was higher than in those obtained by Carvajal et al.[54]

Trying to find an alternative method to what they had considered conventional (drying whole paprika at 80°C for 5 h followed by 60°C for 18 h), Kim et al.[58] proposed a modified method in which the paprika was cut into three parts and then dried at 70°C for 6 h. This modification resulted in a short time and low-temperature drying and can be considered a way to reduce the vitamin C degradation in the case of paprika drying.

Thinking about the possibility of incorporating some herbs into everyday meals, like lemon balm, oregano, and peppermint, Capecka et al.[60] analyzed them before and after drying. The drying procedure was not adequate to retain the majority of vitamin C in the dried product, even when the drying experiments were carried out at a relatively low temperature. In this case, the problem related to the considerable loss was the long drying time. Another foodstuff that is incorporated into meals and used in the food industry as a flavor additive is onion. A good way to add this vegetable in processed products is the dried form. Conducting thin-layer drying experiments, Adam et al.[61] reported not only the influence of the temperature on vitamin C retention but also the influence of the slice thickness. At constant drying conditions, the thicker the onion slice, the lower vitamin C content in dried product. The slice thickness effect could be attributed to the longer drying period that is necessary to dry a thicker slice at final determined moisture content, which results in a higher exposure time to the hot air. The slice thickness effect on the vitamin C was commented on earlier based on the results obtained by Adom et al.[46] Analyzing the vitamin C content in samples dried after 96 h, they concluded that slice thickness did not affect the vitamin C degradation during drying of okra. After 96 h of drying, all samples reached the same final moisture content.

Still running drying experiments without sample pretreatment, the kinetics of ascorbic acid thermal degradation was determined in potatoes[12,13] and in camu-camu[23] during drying. McMinn and Magee[13] concluded that the degradation of the acid appeared to follow a first-order reaction, as reported by Goula and Adamopoulos[19] in tomato drying. The degradation was considered a function of drying temperature and drying time and also as dependent on moisture content. Silva et al.[23] have considered the first-order kinetics inadequate to fit their experimental data and proposed to investigate the applicability of the Weibull model to describe this degradation reaction. They considered this last model adequate to describe thermal degradation of ascorbic acid.

Potato drying was studied by Wang and Chao[62] and Wang and Du.[63] In these cases, the potatoes were previously pretreated with γ-irradiation and then they were hot air dried and their characteristics and final quality were determined. The experiments were conducted in order to study the influence of irradiation dose, air temperature, and slice thickness on the product quality in which vitamin C degradation was included. All the parameters have significantly affected the vitamin C content in dried samples. The irradiation dose also affected the dehydration rate. Increasing the dose, the rate of moisture loss was increased at constant temperature and slice thickness. The same effect occurred with vitamin C. The higher the irradiation dose, the higher the vitamin C loss in dried samples at constant temperature. Thinking that a higher dehydration rate results in a shorter drying period and that long drying periods result in low vitamin C retention, it could be expected that the vitamin C retention in irradiated products would be higher than in non-irradiated products. The authors determined that a possible reason for this lower vitamin C content in irradiated dried potatoes can be attributed to the different cell structure between irradiated and non-irradiated products. During the irradiation process, changes in the vegetable structure occur and some microstructures are damaged or destroyed.

Wang and Chao[64] studied the effect of the irradiation on the characteristics of apple. A similar effect on vitamin C was observed in this case. The irradiation dose increase resulted in a higher dehydration rate and lower vitamin retention. Also, the combination between irradiation dose and slice thickness significantly affected the vitamin content. Differently from the interaction between the drying temperature and slice thickness that did not affect it significantly, at $p <$ or equal to 0.05.

Other kinds of sample pretreatments were applied in order to improve the quality of dried fruits. An immersion in an alkaline solution at 80°C was the treatment before the experimental drying of prunes perfomed by Del Caro et al.[65] and Piga et al.[66] Two varieties of prunes were dried in a laboratory pilot dryer following two different conditions and their ascorbic acid content was recorded. The vitamin C in dried fruits was affected by drying temperature. Higher degradation occurred in samples dried in the higher temperature condition, confirming the heat sensibility of this vitamin. In this case, the shorter drying time was not enough to improve the ascorbic acid retention.

Blanching in boiling water or combined with sulphuring were pretreatments applied to figs before air drying.[67] The authors' main objective with these pretreatments was to reduce nonenzymatic browning and, indirectly, the drying time. The drying time of non-pretreated samples was about 54 h, while the drying time of water blanched samples immersed in $K_2S_2O_2$ was 33 h. The samples that were only blanched in boiling water took 37 h to reach the same final moisture content. The drying time reduction could be the reason for the significantly difference between the ascorbic content in non-pretreated and pretreated fruits. As discussed by the authors, pretreatments can cause micro wounds on the fruit peel, which can make the water easier to remove. The difference between both pretreatments was not significant and their applications resulted in products with high ascorbic acid content.

Some vegetables were also pretreated before drying. Mousa et al.[68] and Bajaj et al.[69] studied, respectively, the effect of potassium metabisulphite blanching in brinjal slices and in fenugreek leaves, a popular green leaf vegetable in India. In addition, Bajaj et al.[69] applied other blanching solutions like sodium chloride, magnesium oxide, sodium metabisulphite, and sodium bicarbonate in order to get better dried products. In both works, the use of sulphite pretreatment increased the ascorbic acid content in dried samples compared to non-pretreated samples. Retention of ascorbic acid in sulphited samples was higher not only compared to non-pretreated samples of fenugreek leaves but also the highest one when compared to all pretreatments. Mousa et al.[68] reported that the retention of the vitamin in brinjal slices increased with the increasing of potassium metabisulphite concentration. This solution concentration ranged from 1 to 1.75% and the last one seems to be the best to avoid ascorbic acid degradation in brinjal during air drying. The use of other blanching solutions in the case of fenugreek leaves drying seems inadequate to retain higher contents of ascorbic acid in dried samples. Most resulted in lower ascorbic acid content than in unblanched samples.

Maharaj and Sankat[70] investigated the quality of dasheen leaves dried under natural and forced convection and the effect of different pretreatments on them. Steam blanching, water blanching, and alkali blanching were applied in this leafy vegetable before air drying experiments at 60°C. Even without pretreatments and at different temperatures, the influence of the kind of dryer on the vitamin C content was clearly observed. Losses of ascorbic acid in samples dried under natural convection were higher than 90% when temperatures ranging from 40 to 70°C were used. These losses ranged from 81.8 to 72.6% when the convection was forced. This difference was attributed to the reduced drying time under forced convection. Analyzing pretreatment effects on vitamin C, all presented negative effects on vitamin C retention. Independent of the blanching procedure, unblanched samples had higher retention. Alkali blanching at 100°C for 10 s was the worst one.

Not only pretreatments with application of heat or chemical solutions can influence the vitamin C retention in a dried product. In some cases, simple procedures that are common and important can affect the vitamin C retention, significantly reducing its initial content. Ramesh et al.[57] reported that the highest loss of this vitamin happened when paprika was cut and washed before drying. As vitamin C is water soluble and the vegetable was cut and then exposed to water, some loss could have occurred during the washing procedure. Márkus et al.[56] reported a loss around 40% due to a centrifugation process of sliced and washed paprika before drying.

So it is important to consider and study each process step. Depending on the process, many steps can be improved and there are different possibilities. Another step that influenced vitamin C content in brinjal slices was the removal of its skin. Mousa et al.[68] showed that the maintenance of brinjal skin during a hot air drying process is the best option to retain more vitamin C during drying. The removal of brinjal skin negatively affected the vitamin content in the dried product due to the contact between the hot air and the peeled vegetable. Consequently, the highest degradation occurred in these samples.

Microwave Drying

Although hot air drying is a conventional method in drying of food products, it often degrades product quality. Case hardening, loss of volatile compounds, and worsening of the color and nutritional content can occur during drying, since the products are exposed to high temperatures for a long period. Therefore, alternative drying methods are necessary for food processing in order to manufacture better products.[71]

Because of its characteristics, microwave drying has gained popularity in the food industry as an alternative method. The use of microwave rays in the drying of fruits and vegetables has several advantages including the shortening of drying time, which can maintain nutritional quality in the dried product, like higher retention of some vitamins, and a homogeneous energy distribution on the material.[72]

Many authors studied the quality changes in foods during microwave drying. Variations of vitamin C content were determined in microwave-dried fruits and vegetables such as spinach leaves,[72] apricot,[73] and potato.[14] Ozkan et al.[72] indicated that the reduction in the ascorbic acid levels of the sample was recorded as dependent on time. As the drying time is related with the microwave power level, the reduction can also be dependent on it. The same result was obtained by Karatas and Kamişli[73] and Khraisheh et al.[14] During the drying of potato, Khraisheh et al.[14] showed that the total ascorbic acid content decreased with increasing processing time at a constant temperature or absorbed microwave power level. At a specific drying time, the loss of vitamin C increased with increasing air temperature. It occurred due to the heat liable nature of the mentioned vitamin. Karatas and Kamişli[73] also studied drying of apricot in infrared drying. The last method seems to be the less indicated considering not only the vitamin C content in the dried fruits but also the content of vitamins A and E.

Considering that the drying rate affects the drying time and consequently the retention of ascorbic acid in the final dried product, it is interesting to mention the results obtained by Ozkan et al.[72] and Sharma and Prasad.[74] The moisture content loss in the product resulted in a fall in the drying rate as the drying progressed, like in a conventional drying process. However, in this case, it happens because the moisture decrease causes a decrease in the absorption of microwave power.[72] Sharma and Prasad[74] studied the optimization of process parameters for microwave drying of garlic cloves. During their studies in a microwave-convective dryer, they reported that increasing the air velocity from 1.0 to 2.0 m/s at same air temperature and power level also increased the drying time. Different from what would be expected during a hot air drying, the drying time increased instead of decreasing considering a same final moisture content of the product. The reason could be that the increase in air velocity could have caused the cooling of the product and then reduced its temperature and moisture diffusion. Despite this, the drying condition in which the dried product presented the highest content of vitamin C was at air velocity of 2.0 m/s, 40 W, and 60°C.

Other studies associated microwave drying process using a vacuum. Lin et al.[75] studied the characterization of vacuum-dried carrot slices. Before drying, they were water blanched to inactivate ascorbic acid oxidase and to prevent enzymatic degradation during drying. Nevertheless, a substantial loss of vitamin C content (approximately 43%) occurred during the blanching process.

Böhm et al.[76] tried to improve the nutritional quality of microwave-vacuum–dried strawberries. Samples pretreated with an aqueous solution of $CaCl_2$ were carried out on a convective predrying, microwave vacuum drying, and convective postdrying. The authors compared the vitamin C content in convective-dried with combined microwave-convective–dried strawberries. They concluded that the attenuation of temperature peaks can increase the stability of vitamin C. Considering costs, an interesting and useful result was obtained by Qing-guo et al.[77] during their study of the combination of microwave with convective drying. Analyzing only vitamin C content in the final product, vacuum-microwave drying and vacuum-microwave-convective drying can be considered equivalent. Practically, there was no significant difference between the retention of vitamin C in both dried products.

Osmotic Dehydration

When a water-rich solid product is soaked in a concentrated aqueous solution (sugar or salt solutions), basically three mass transfer processes occur: water outflow from the product to the solution; solute transfer from the solution to the product; and a leaching out of the product's own components such as sugars, organic acid, vitamins, and others. This dehydration process is called osmotic dehydration.[78]

Osmotic dehydration has been applied to fruits and vegetables as a partial dewatering step or as a direct dehydration process. Vial et al.[25] investigated some of the main variables involved in the osmotic dehydration of kiwi slices and also observed two quality parameters in dried fruits: ascorbic acid and chlorophyll contents. To study the ascorbic acid behavior during the process, a sucrose solution (62°Brix) at three different temperatures was used. According to the authors, a first model for the degradation kinetics on the product during the osmotic dehydration was not satisfactory. The behavior of ascorbic acid loss observed was explained by two phenomena: diffusion of the ascorbic acid from the fruit to the solution and chemical deterioration, which seems to follow a first-order model.

Among the variables studied in that work, process temperature can be considered a very important factor. Carrying out experiments at relatively low temperatures, the ascorbic acid loss in kiwifruit tended toward a pseudo-stationary state as a function of time. On the other hand, in experiments at high temperatures, the loss tended toward 100% as a function of time. Vial et al.[22] suggested that at relatively low temperature the loss occurs mainly due to acid diffusion to the solution, while at relatively high temperatures both phenomena mentioned above (diffusion of acid to the solution and chemical deterioration) seems to be significant to the loss.

Similar behavior was observed by Heng et al.[26] studying osmotic dehydration of papaya. Also, they reported the influence of the solution concentration on the vitamin C degradation. Two different temperatures (50 and 70°C) and two different sucrose concentrations (45 and 72°Brix) were applied in order to investigate their influences. At a constant drying time and considering the same solution concentration, increasing the temperature of the process, the loss was more significant. It is interesting to note the effect of the solution concentration on the loss. The decrease of ascorbic acid content is less when the dehydration solution is more concentrated. Two possible explanations were provided by the authors. First, they attributed this slight drop to the limited ascorbic acid transfer in a viscous sucrose solution. The other reason was based on the sugar concentrated layer formed at the periphery of the sample. This layer may work as a barrier to the ascorbic acid transfer, resulting in a higher retention of it on the final product.

The application of combined drying methods using osmotic dehydration has also been studied. Most of studies have combined osmotic dehydration with hot air drying,[18,79–84] but it was also found the combination with solar[85] and microwave drying.[86]

Osmo-air dehydration is a simple and useful technique applied in food products. Among the different kinds of fruits and vegetables studied, Sharma et al.[81] hot air–dried apples applying osmotic dehydration as a first step. In addition, the authors studied the influence of some pretreatments such as steam blanching and sulfur dioxide treatment on the product quality. Fruits pretreated and non-pretreated were evaluated for chemical composition, including vitamin C. The greater retention of ascorbic acid in dried samples was obtained in those treated with sulfur dioxide followed by osmotic dip and vacuum drying. This result could indicate the positive effect of sulfur dioxide treatment on the retention of ascorbic acid. However, the retention of ascorbic acid in samples treated with sulfur dioxide and dried in a cabinet dryer (without osmotic dehydration) was the lowest one. The authors suggested that the ascorbic acid in this case was oxidized during air dehydration.

Riva et al.[83] studied the osmo-air dehydration process in order to improve the quality of dried apricots. Analyzing vitamin C content in fresh and dried samples, they observed that the retention of this nutrient during air dehydration was higher in samples pretreated in osmotic solutions comparing to non-treated samples with the same final moisture content. In addition, it was reported that the slope of the line obtained by plotting ascorbic acid versus moisture content is affected by the treatment. For samples that were previously treated by osmotic dehydration the slope was lower than for non-pretreated ones. This behavior was linked to the lower phenolase activity and to the protective effect of the sugar. This protective effect is related to the kind of sugar, and sorbitol showed the highest protection effect in apricot samples.

In order to evaluate the osmo-air dehydration process, some studies compared quality attributes of products osmo-air–dried to attributes of products simply hot air-dried. Sanjinez-Argandoña et al.[18] investigated this possible difference drying guava halves. They suggested that the osmotic treatment can reduce the degradation of ascorbic acid during hot air drying since the retention of this nutrient in fruits dried without pretreatment was none, and the loss in pretreated fruits tended to pseudo-stationary state as a function of time.

Although many studies have investigated the osmo-air dehydration applying simply sucrose solutions in osmosis, some research has added other components in the osmotic solution. Among these studies, those carried out by Sagar and Khurdiya[79] and Rashmi et al.[84] can be cited. They formulated their osmotic solution with sugar and potassium metabisulphite. The latter also added citric acid to the solution.

Ade-Omowaye et al.[82] formulated their osmotic solution with sucrose and sodium chloride. In addition, they investigated the influence of high-intensity electric field pulses (HELP) on the vitamin C content in osmo-air–dried paprika. The effect of this treatment on the vitamin C retention was negative applying different field strengths (0.5–2.5 kV/cm). As reported by the authors, the application of HELP significantly reduced the vitamin C content in dried osmosed bell peppers. The authors expected this result since the treatment increases the permeability of the cell membrane, reducing its content in the final product.

Another procedure that has been used is the combination of osmotic pretreatment and microwave-vacuum dehydration. Apples and strawberries retained approximately 60% (of fresh fruits) of their vitamin C content with the procedure applied by Erle and Schubert.[86]

Freeze Drying

Freezing drying is considered as one of the best methods to keep the quality attributes of the materials submitted to drying processes since the combination between absence of liquid water and low temperature stop most degradation reactions.[87] That is why this process is sometimes used as a reference method to compare drying experiments.[88] On the other hand, due to its operation conditions, it has been characterized as the most expensive dehydration process in which the sublimation step is the one that consumes almost 50% of the total process energy.[87]

This characteristic of maintaining some nutritional properties of foods, mainly those influenced by heat, was confirmed by many authors who studied freeze-drying process. Nogueira et al.[89] freeze-dried red guava pulp and its ascorbic acid content was retained by 92%. Guava was also freeze-dried by Marques et al.[90] In order to study freeze-drying characteristics of tropical fruits, they determined some physical and nutritional properties of pineapple, Barbados cherry (acerola), papaya, mango, and guava. Vitamin C content in freshfruits and in dried fruits was measured for comparison. In this case, the retention of ascorbic acid in dried guava (16% of moisture content) was the lowest one compared to the other fruits. Only 29% of ascorbic acid retention was observed in dried guavas, whereas retention in the other fruits was higher than 60%.[1] This result was equivalent to that obtained by Sanjinez-Argandoña et al.[18] drying osmotically pretreated guavas in a tray dryer at 60°C. The ascorbic acid retention in dried guava (11% of moisture content) was around 30–35%.

Other authors freeze-dried fruits and vegetables and compared their vitamin C content to those obtained by hot air drying. The difference obtained by Chang et al.[91] when they carried out drying experiments with two different tomato varieties was large. Considering both varieties, the retention of ascorbic acid in freeze-dried tomato cubes was higher than 90% without any sample pretreatments, while in hot air–dried samples they were lower than 50%. The drying time required in the first process was about 24 h, whereas it was 8 h in hot air drying. As discussed earlier, drying time is one of the variables that influences the ascorbic retention. In most of the cases in hot air drying, with increasing drying time, the retention of this vitamin

[1]The authors were contacted by e-mail and reported that those results were preliminary and more investigation has been done; the results will be published soon.

is reduced. During the freeze-drying process, the temperature of the product is pretty low, which reduces degradation reactions and does not make the drying time crucial.

Another large difference obtained was reported by Martinez et al.[92] Drying sweet peppers at 50°C during 7 days reduced their ascorbic acid content by 88%, while freeze drying did not reduce their vitamin content significantly ($p < 0.05$).

In addition, other products were investigated. Asami et al.[93] determined the ascorbic acid content in freeze- and hot air–dried corn, marionberries, and strawberries grown by conventional, organic, and sustainable cultural practices. The ascorbic acid content of dried samples was compared to the content of frozen samples. Ascorbic acid content in all samples of freeze- and hot air–dried corn and marionberries was not detectable. Also, ascorbic acid was not detected in organically and conventionally grown marionberries samples even when they were frozen (before drying). A small concentration of this nutrient was found in frozen samples of corn. Only dried samples of strawberries retained detectable amounts of ascorbic acid. Comparing freeze-dried and hot air–dried samples, the vitamin content in the first was higher. Taking all these results as reference, it seems that independent on the foodstuff, the freeze-drying process provides a better quality product than conventional air drying.

Vanamala et al.[94] investigated the effect of irradiation dose as a pretreatment on grapefruit compounds and also the effect of the freeze-drying process on the retention of ascorbic acid. The effect of the irradiation dose on the retention of ascorbic acid was negative. The reduction of the vitamin in pretreated samples after drying was about 15% while any reduction was observed in samples without treatment. The authors attributed this result to some oxidative stress injuries that can occur during the irradiation process. A similar effect was observed during hot air drying experiments as mentioned earlier.

Other Drying Methods

As discussed until now, most drying methods affect essential quality attributes of fruits and vegetables. Alternative drying methods and modifications in conventional ones have been studied by different researchers such as foam mat drying, drying under modified atmosphere, superheated steam drying, impingement drying, Refractance Window® drying, and others.

Foam mat drying is an alternative that Rajkumar et al.[95] applied in alphonso mango pulp. As the foaming process changes the characteristic of the product and exposes larger areas of the product surface, it is interesting to know the drying characteristics and the chemical composition of the dried product. Some biochemical components including vitamin C were degraded during the drying of foamed and fresh samples but the retention was higher in foamed pulps. The drying rate was higher in foamed pulps resulting in a shorter drying time and in a lower loss of the heat-sensible vitamin.

Another modification that has been applied in the drying processes of fruits and vegetables in general is the modification of the drying atmosphere. Ramesh et al.[51,55] applied low oxygen conditions during their drying experiments of paprika. In the first one, the use of an inert atmosphere (using nitrogen gas) resulted in a higher drying rate, diffusion, and mass and heat transfer coefficients. Considering all the parameters chosen as a quality attributes (red color intensity, tocopherol, carotenoids, and vitamin C), vitamin C was the only one significantly affected by this modification. According to this study, inert gas processing can reduce vitamin C loss, in accordance with the results reported by Ramesh et al.[55] Vitamin C losses during inert gas processing of blanched paprika were reduced by 13%. This effect could be attributed to the reduced presence of oxygen, which promoted a protective atmosphere and prevented the oxidation.

A similar effect was observed in the investigation of the oxygen influence on the vitamin C degradation during drying of rosehips,[16] guava,[96] and papaya.[96] Rosehip samples were dried in different percentages of air-carbon dioxide mixture and their vitamin C content was determined. The higher retention was obtained when the fruit was dried under pure carbon dioxide. On the other hand, on increasing the concentration of oxygen in the drying atmosphere, the retention of vitamin C was decreased. Carrying out experiments under inert atmosphere, the nutritional quality, considering vitamin C as a parameter, was improved. Compared to the conventional process, the loss could be reduced by 13%.

Studying drying process of papaya and guava, Hawlader et al.[96] reported a positive effect of the inert gas application. The fruits were dried in a heat pump dryer with normal and modified atmosphere (by the addition of carbon dioxide or nitrogen) and the effect of this modification on the vitamin C retention was evaluated. When the inert gases were used in the drying media, independent of the product, the retention of the vitamin was higher than the product dried under normal air. In addition, the foodstuff dried under carbon dioxide retained slightly more vitamin C than that dried under nitrogen. This difference was related to their different drying rates.

A modified atmosphere was also investigated by Santos and Silva,[97] but in this case the atmosphere composition modification was carried out by the addition of ethanol, which was atomized to achieve a gaseous ethanol concentration of 0.5% (v/v). In order to investigate the influence of the atmosphere modification on the drying behavior and the retention of ascorbic in the dried product, pineapple slices were dried in a laboratory-scale tunnel dryer at two temperatures (40 and 60°C), under normal and modified atmosphere, until their moisture content reach approximately 27% (wet basis). The ethanolic atmosphere seems to affect the water removal and consequently the drying time. Analyzing their results at 40°C, the presence of ethanol in the drying atmosphere promoted a more intense water evaporation compared to the conventional process. Also at this drying temperature, the ascorbic acid retention in the fruit dried under modified atmosphere was approximately 8% higher than the retention of the samples dried under normal atmosphere. The authors attributed this higher retention to the shorter drying time to reach the desirable final moisture content.

Santos and Silva[98] investigated this effect but the final moisture content of the samples was lower (7–8%, wet basis). The same behavior was observed when experiments were carried out at 60°C. When the drying atmosphere was modified by the addition of ethanol, the drying time was shorter and the retention of ascorbic acid was higher. These results indicate a new possibility to try to improve the nutritional quality of dried fruits and vegetables.

Low-pressure superheated steam drying (LPSSD) was applied to dry Indian gooseberry, a rich source of vitamin C.[99] This study also investigated the effects of hot air drying and vacuum drying on the vitamin C degradation. All drying experiments were carried out at 75°C. The highest vitamin retention was observed in samples dried by low-pressure superheated steam drying. Due to the particularity of each method, LPSSD required the longest drying time to reach the product final moisture established. Despite the fact that samples submitted to this process spent a longer time in the hot air, this method provided a product richer in vitamin C than the others. The authors noted that the aerobic degradation of ascorbic acid during LPSSD is reduced due to the oxygen-free environment.

Thomkapanich et al.[100] applied intermittent LPSSD to investigate the characteristics of dried banana. Among the quality parameters evaluated in this study, ascorbic acid retention was one of them. The authors observed that this method retained greater amounts of the ascorbic acid in dried banana than vacuum drying, another technique they investigated. Again, the higher retention in the product dried by LPSSD method was related to the low-oxygen drying environment.

Impingement drying, another drying method that can be applied to foodstuffs, was studied by Caixeta et al.[101] Superheated steam impingement drying and air impingement drying were applied to potato chips and their quality attributes were evaluated. Comparing vitamin C retention in dried potatoes, steam impingement drying at 130°C provided potato chips with a higher nutrient amount than those dried by air. This difference was observed only at this temperature; no significant difference was reported when experiments were carried out at 145°C. The authors did not note the reason; perhaps at 145°C the temperature effect was more predominant than the protective effect of the steam.

In order to evaluate Refractance Window® drying, Abonyi et al.[102] compared some characteristics of strawberry puree dried by this method and by freeze drying. No significant difference was observed in ascorbic acid loss between the two methods. The relatively high retention of this sensible nutrient was about 94%. According to Abonyi et al.,[102] the moisture loss was significant during the first minute of Refractance Window drying®, contributing to the reduction of ascorbic acid degradation due to the low partial pressure of oxygen close to the sample surface.

FINAL REMARKS

Various methods can be applied to drying of food products. Due to the unique characteristics of fruits and vegetables, there are different choices for the dehydration process and each one has certain characteristics that affect the drying behavior and the final foodstuff quality and functionality. Efforts have been made to improve traditional drying methods and to design new techniques considering quality attributes such as color, flavor, nutrition, etc.

This article presented several processing possibilities that focused on the vitamin C degradation/retention. It is possible to note that not only the drying conditions affect the degradation kinetics of ascorbic acid during drying of fruits and vegetables. Several variables influence this degradation, which make this phenomenon quite complex. During the drying process, there are different environment variables and the composition and physical structure of the product change as the process proceeds. These are strong reasons why research aiming to improve drying technologies are valid, mainly those in which the influence on food quality are studied.

Losses occur not only during the dehydration process but also during predrying treatments. Washing and peel removal seems to negatively affect the vitamin retention in the dried product while, in general, blanching can be an alternative to avoid some degradation reactions. More recent pretreatments such as irradiation and HELP affect the product structure, which facilitate the water removal but decreases the vitamin C retention.

Among the environmental variables that affect the vitamin C degradation, temperature and time are the most important parameters. Because of the high sensibility of this nutrient to heat, the combination between these two parameters determines its retention. Also, the concentration of oxygen in the drying atmosphere influences the final content in the dried product. Different authors showed the negative effect of oxygen on vitamin C retention.

Consequently, the area exposed to the drying conditions is another factor that affects this nutritional parameter. Increasing the area, the food structure becomes more

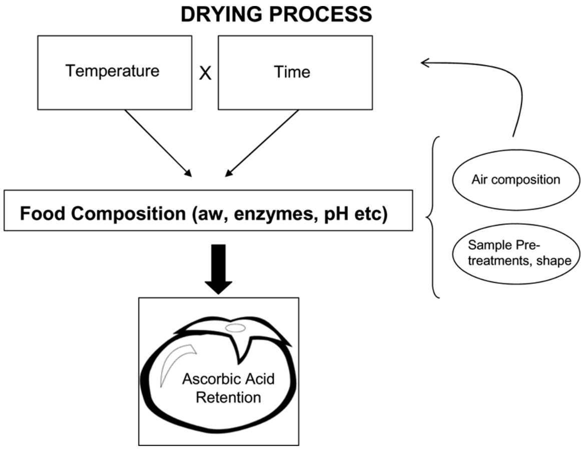

FIG. 3. Parameters studied in drying processes related to vitamin C retention in fruits and vegetables.

exposed and degradation can be enhanced. However, depending on the relation between area exposed and time, the degradation can be reduced since this increase tends to reduce the drying time. An overview of the variables discussed in this article and how they can affect the ascorbic acid retention in the dried product is schematically presented in Fig. 3.

More investigation is needed to provide a better understanding of the oxidative phenomena of the vitamin C during the drying processes since different fruits and vegetables have different chemical and physical characteristics. Improvements to traditional drying methods as well as a combination of different methods and new approaches have been reported to obtain better quality dried products.[103–116]

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APPENDIX

TABLE A1
Fruits and vegetables submitted to drying studies coupled to Vitamin C retention

Product*		Reference	
Number	Name	Drying	Kinetics of Vitamin C degradation
1	Acerola or Barbados Cherry	[90, 103]	
2	African spinach	[36]	
3	Alpine strawberries	[104]	
4	Amaranth leaves	[28, 29, 35, 44]	
5	Amla	[42]	
6	Aonla fruit	[43, 105]	
7	Apple	[62, 81, 86, 106]	[106]
8	Apricot	[73, 83]	[83]
9	Banana	[100]	
10	Bathua leaves	[30]	
11	Brinjal Fruit	[68]	
12	Cabbage	[107]	
13	Camu-camu	[23]	[23]
14	Carrot	[75]	
15	Cassava leaves	[36]	
16	Cassava	[31, 108]	
17	Cauliflower	[39]	
18	Cow pea leaves	[29, 36]	
19	Dasheen leaves	[70]	
20	Edamames	[77]	
21	Fenugreek leaves	[35, 30, 69]	
22	Fig	[67]	
23	Garlic	[74]	
24	Gooseberry	[99, 109]	
25	Grape	[37]	
26	Grapefruit	[94]	
27	Green asparagus	[110]	

(*Continued*)

TABLE A1
Continued

Product*		Reference	
Number	Name	Drying	Kinetics of Vitamin C degradation
28	Green bell peppers	[52]	
29	Guava	[18, 89, 90, 96]	[18]
30	Jute leaves	[34]	
31	Kachari	[41]	
32	Ker fruit	[40]	
33	Kiwi fruit	[20, 25, 80]	[20, 25]
34	Lemon balm	[60]	
35	Mango	[32, 79, 90, 95, 111]	
36	Mint	[30]	
37	Mustard	[30]	
38	Okra	[46]	[46]
39	Onion	[61]	
40	Oregano	[60]	
41	Papaya	[26, 90, 96]	[26]
42	Paprika	[55, 57, 59, 82, 112]	[59]
43	Peanut leaves	[29]	
44	Peas	[113]	
45	Peppermint	[60]	
46	Persimmons	[22]	[22]
47	Pineapple	[15, 84, 90, 97, 98]	[15]
48	Plums	[66]	
49	Potato	[13, 14, 55, 62, 63, 85, 101, 114]	[13, 14]
50	Prunes	[65]	
51	Pumpkin leaves	[29]	
52	Red pepper	[53, 54, 58, 115]	
53	Rosehips	[16, 17, 88]	[17, 88]
54	Savoy beet leaves	[35, 44]	
55	Spinach leaves	[72, 28, 30]	
56	Strawberry	[45, 76, 86, 93, 102]	
57	Sweet peppers	[92]	
58	Sweet Potato	[116]	
59	Sweet potato leaves	[36, 29]	
60	Tomato	[19, 24, 27, 38, 47, 48, 49, 50, 91]	[19, 24, 50]

*The product names are the same used by the authors.

TABLE A2
Drying methods used in studies of Vitamin C retention in fruits and vegetables

Drying method	Product number
Air impingement drying	49
Drum dryer	16
Fluidized bed dryer	6, 44, 49, 52
Foam mat drying	35
Freeze drying	1, 3, 12, 14, 20, 26, 27, 29, 30, 35, 41, 56, 57, 60
Heat pump drying	29, 41
Hot air dryer	4, 6, 7, 8, 10, 11, 12, 13, 14, 19, 20, 21, 22, 24, 27, 28, 29, 31, 33, 34, 35, 36, 37, 39, 40, 42, 45, 46, 47, 48, 49, 50, 52, 53, 54, 55, 56, 57, 60
Infra-red drying	7, 8
Microwave drying	8, 49, 55
Microwave drying combined other method	14, 23, 27, 56
Modified Atmosphere	29, 41, 42, 47, 49, 53
Natural drying	4, 18, 21, 30, 43, 51, 52, 54, 59
Osmotic dehydration	33, 41, 49
Osmotic dehydration combined other method	6, 7, 56
Refractance WindowTM drying	27, 56
Solar drying	2, 4, 5, 6, 15, 17, 18, 21, 31, 32, 35, 38, 49, 54, 56, 59
Spouted bed drying	27, 35
Spray drying	58
Sun drying	2, 4, 6, 10, 15, 18, 21, 25, 30, 31, 36, 37, 43, 51, 54, 55, 59, 60
Superheated steam drying	9, 24
Vaccum drying	7, 12, 24, 29, 30, 41
Vaccum drying combined other method	20