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Review

Thermal Degradation of Bioactive Compounds during Drying Process of Horticultural and Agronomic Products: A Comprehensive Overview

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Abstract: Over the last few decades, many researchers have investigated in detail the characteristics of bioactive compounds such as polyphenols, vitamins, flavonoids, and glycosides, and volatile compounds in fruits, vegetables and medicinal and aromatic plants that possess beneficial properties, as well as consumer acceptance and preference. The main aim of this article is to provide an updated overview of recent research endeavors related to the effects of the drying process on the major bioactive/effective compounds in agricultural products. Particular emphasis was placed on details related to the changes occurring in vitamin C, polyphenols, flavonoids, glycosides and volatile compounds, as well as the antioxidant activity. An analysis of the degradation mechanisms of these compounds showed that vitamin C, phenols, flavonoids and glycosides react with oxygen during the convective drying process under high drying temperatures, and the reaction rate results in degradation in such bioactive compounds due to high reducibility. On the other hand, high temperature results in a short drying time, thus minimizing the degradation of bioactive compounds. The reviewed research works addressing this trend revealed that the ideal drying temperatures for retaining vitamin C, polyphenols, flavonoids, glycosides, volatile compounds and their antioxidant activity were 50–60 °C, 55–60 °C, 60–70 °C, 45–50 °C, 40–50 °C and 50–70 °C, respectively. In conclusion, to maintain plant bioactive components, convective drying at relatively low drying temperatures is strongly recommended.

Keywords: bioactive compounds; drying temperature; thermal degradation; agricultural products

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1. Introduction

As a vital postharvest process, drying, which is used to dehydrate plants by decreasing their moisture content, aims not only to retain the organoleptic characteristics and prevent the oxidation of plants' chemical contents but also to prevent enzymatic breakdown and microbial growth in the dried plants, consequently preserving these products and extending their shelf life [1–3]. Drying is one of the most commonly applied processing routines for sustaining quality in food products due to its effectiveness at facilitating handling, transportation, and storage [4]. Traditional convective hot air drying is the most frequently used method in the food sector, since it is inexpensive to perform and simple to regulate [5]. Hot air drying, however, has a negative impact on important aspects of food security, such as nutrient quality and environmental sustainability, as it frequently alters the nutritional value, flavor, and texture of the products being dried and can potentially oxidize and degrade heat-sensitive compounds [6]. Foods that have been heated for a long time lose their organoleptic qualities and bioactive compounds [7]. In convection drying, the material is heated by the hot airflow. The temperature difference between the material's surface and the airflow has an impact on how hot the material becomes.

A variety of internal and external factors, including raw material types, process variables, and others, interact during the drying process. In order to preserve foodstuffs at room temperature for longer periods of time, the drying process seeks to decrease water activity (a_w) [8]. In addition to changes in moisture content, shape and volume [9], the drying process is also accompanied by changes in the products' ingredients, including basic nutrients such as sugar, protein, crude fiber, minerals [10] and functional bioactive compounds [11]. Today's consumers need conveniently healthy products that have similar qualities to those of fresh ones. Additionally, the efficiency of the drying equipment itself has recently been evaluated on the basis of its capacity to retain nutrients with minimal production cost. Producing such high-quality dried foods is a challenge for the food industry and scientific community [12]. It is rather difficult to interpret the process with complex modeling because the drying approach includes transient energy, momentum, or mass transfer via a medium with phase change, and only very seldom with chemical reactions [13]. The drying of food materials is therefore related to a variety of changes, including microstructural modification, volume deformation, and the loss of nutrients and their degradation.

Despite these disadvantages, drying is gaining popularity as a preservation method over other methods such as freezing and refrigeration for many reasons. Drying reduces the moisture in foods, making them lightweight and convenient to store, and it can easily be used in place of other food preservation techniques. In fact, one can even use drying along with other food preservation techniques such as freezing or canning, making the process of food preservation even better. Drying food is simple, safe and easy to learn. Being easy to store and carry and requiring no refrigeration makes dried foods ideal for domestic use as well as for use in the rough outdoors. Moreover, dried foods are good sources of quick energy and wholesome nutrition. Therefore, dried foods are an easy food option for busy executives, hungry backpackers and active women and children, all of whom can benefit from the ease of use and nutritional content of dried foods. Dried foods have various advantages, including improved storage stability, reduced packing requirements, and reduced transit bulk.

As one of the sources supplying various nutrients required for human nutrition, fresh fruits and vegetables have high nutritional value, as they are rich in nutrients such as proteins, fats, sugars, vitamins, phenols, flavonoids and terpenes. Since the shelf life of agricultural commodities is usually short, people often use drying technology to preserve these products, which is convenient for storage and transportation. Due to the influence of temperature, oxygen concentration, moisture content and other factors, various nutrient degradation occurs during the drying process, resulting in a decline in the quality of fruit products. In addition, spices (such as garlic, ginger, black pepper, cardamom, clove, nutmeg and turmeric) are generally subjected to sun exposure or drying after harvesting, and the content of effective ingredients such as aroma volatiles in spices are liable to degrade during this period. Medicinal materials generally need to be dried and processed into decoction pieces, which is also accompanied by the loss of medicinal ingredients.

Bioactive compounds including vitamins, polyphenols, carotenoids, flavonoids, organic acids and phytosterols are found in fruits and vegetables in appreciable amounts. These compounds provide health advantages beyond their essential nutritional value [14]. Bioactive compounds are substances that have the ability to treat metabolic diseases, pro-inflammatory states, and oxidative stress while influencing calorie intake [15]. Therefore, due to the increase in consumer awareness about the importance of bioactive components and their potential health merits, the contents of bioactive compounds in food products have recently been used as an important criterion for assessing overall product quality [16].

Hence, food producers are potentially paying great attention to bioactive compounds and their retention during food processing to meet increasing market demands [17].

As all fresh products are highly perishable and vulnerable to physical and microbiological deterioration, numerous studies have been focused on studying how the drying process affects different quality parameters of foodstuffs. For instance, Kumar et al. analyzed the food quality parameters during the intermittent drying, and many physicochemical properties such as physical modifications, color, ascorbic acid, sugar, β-carotene, and caffeine concentration were measured [18]. Another study by Rathnayaka et al. analyzed recent developments in the numerical modeling of foodstuffs and concentrated on the changes in the morphological features of food tissues during drying [19]. On the other hand, Arvaniti et al. reviewed the changes in some bioactive compounds such as polyphenols, flavonoids and antioxidant activity during the drying process of figs [20]. Additionally, Rocha et al. studied the factors affecting the retention of vitamin C during the drying processes of fruits and vegetables and medicinal plants [1]. Kamiloglu et al. studied the effects of different drying techniques on major antioxidants of fruits and vegetables [21]. McSweeney et al. presented an overview of drying technologies and their impact on the content of polyphenols in vegetables and fruits. Polyphenol degradation mechanisms proposed in literature and pretreatments that potentially lead to higher retention of polyphenols during drying were discussed [22].

The focus on the bioactive compounds varies depending on the type of plant and its use. In this literature review, the changes in some bioactive compounds (vitamin C, polyphenols, flavonoids, glycosides, and volatile compounds) in four major types of plants (fruits, vegetables, spices, and Chinese herbal medicines) during the drying process are discussed, and the mechanisms of degradation of these compounds are explored.

2. Influence of Drying Temperature on Bioactive Compounds

Because water constitutes the continuous liquid phase in food products and is the predominant constituent in most fresh products, it significantly affects the palatability, digestibility, physical structure, handling ability, and thermophysical characteristics of foodstuffs. As most deteriorative processes are influenced by the temperature, concentration and mobility of water inside the food materials, perishable commodities are more stable at low moisture content and at low storage temperature. Thus, it is quite important to apply different drying techniques for dewatering such products with the purpose of making these products more stable and extending their storage shelf life as well as reducing postharvest losses. In general, the initial water content varies with the cultivar, the maturity stage, and the growing conditions. A wide range of methods are available in the literature that have been used successfully for drying food products.

Petikirige et al. reported that each drying method affects product quality characteristics differently and to varied degrees, but in most cases, high-temperature drying methods affect the qualities more than low-temperature drying methods [23]. Kim et al. and Chang et al. found that modified drying, which involves low-temperature drying for shorter periods of time, is more successful than conventional drying when color, total phenolic compounds, antioxidant activity, and vitamin C levels are determined [24,25].

Convective drying is a drying method that uses hot air to remove the steam generated by the wet material during the drying process. Practically speaking, convective drying could be defined as the balanced manipulation and control of air exchanges, heat, and vapor pressure differential to create optimum conditions for evaporation, reduction, and control of moisture. It is a relatively common method for most materials except heat-sensitive materials. Convective drying has the advantages of simple operation, high production efficiency, low cost and high material handling capacity. The effect of convective drying on different bioactive compounds (e.g., vitamin C, polyphenols, flavonoids, antioxidants and volatile compounds) in fruits and vegetables has been investigated intensively by numerous authors. Depending on the drying techniques applied, the convective drying method has different degrees of influence on the bioactive compounds, organic matter, and nutrients.

2.1. Influence of Drying Temperature on Vitamin C

Vitamin C, or ascorbic acid, is a water-soluble vitamin primarily found in many fruits and vegetables. It is an essential nutrient that has a substantial importance in many metabolic pathways in the human body, because it is necessary for the best possible activity of several key biosynthetic enzymes and as a cofactor in many enzymatic reactions [26]. Being an antioxidant is one of vitamin C's most advantageous qualities. However, it possesses a wide variety of antioxidant characteristics and can neutralize most physiologically active radicals [27]. The nutrient quality of food products originating from fruits or vegetables is customarily measured using vitamin C as an indicator. This is because it is much more susceptible to different types of degradation during food processing and subsequent storage. The aqueous solution of vitamin C is unstable under normal conditions, because it is susceptible to changes in temperature [28]. Thus, it is worth mentioning that studying the stability of vitamin C under different drying temperatures; in particular, the change in its content during the drying process can be used as a guide for the efficient processing, storing and usage of vitamin C. The fact that vitamin C is still present in dried foods shows that the processing conditions were not harsh, and as a result, it is likely that the other micronutrients in the food matrix have also been preserved [29]. Processing is a great way to increase shelf life, but it also causes large losses in several substances, including vitamin C, which is the least stable vitamin and is readily destroyed during processing [30].

Table 1 shows the effect of drying temperature on the content of vitamin C in different products during convective drying. It can be seen from Table 1 that the drying temperature obviously influences the content of vitamin C in dried products. In general, the vitamin C retention of dried samples is lower than that of fresh samples, and within a certain range, lower retention rates of vitamin C content occur at higher drying temperatures. However, the effect of the same drying temperature on vitamin C content differs depending on the products being dried. When drying bananas [31], the content of vitamin C in samples dried at 65 °C was higher than that at 45 °C; meanwhile, the content of vitamin C in bee pollen samples dried at 65 °C was lower than that at 35 and 50 °C [32], as shown in Table 1. This contradictory effect can be also shown for roselle calyx and sweet pepper at temperatures of 40 and 50 °C. On the other hand, sweet pepper and tomato showed the same response of vitamin C at drying temperatures in the range from 40 to 60 °C [33,34]. It can be concluded from the studies listed in Table 1 that the optimal temperatures for vitamin C retention in the investigated products ranged from 40 to 60 °C. This conclusion is in agreement with the findings reported by Idah et al. that the best range for drying a vegetable is between 35 °C and 63 °C, while the medium range temperature is roughly 48 °C for most fruits and vegetables [35].

Table 1. Effect of temperature on the content of vitamin C in different products processed with convective drying.

Product	Temperature	References
Banana	Fresh > 65 °C > 45 °C	[31]
Bee pollen	Fresh > 35 °C > 50 °C > 65 °C	[32]
Blueberry	Fresh > 90 °C > 50 °C > 60 °C > 70 °C > 80 °C	[36]
Chrysanthemum	55 °C > 65 °C > 75 °C	[37]
Mango	50 °C > 65 °C	[38]
Nettle leaves	Fresh > 75 °C > 50 °C	[39]
Onion	Fresh > 50 °C > 60 °C > 70 °C > 80 °C > 90 °C	[40]
Papaya	40 °C > 50 °C > 60 °C > 70 °C	[41]
Pomegranate leather	50 °C > 60 °C > 70 °C	[42]
Red bell-pepper	Fresh > 50 °C > 60 °C > 70 °C	[43]
Red pepper	Fresh > 50 °C > 60 °C > 70 °C > 80 °C > 90 °C	[44]

Table 1. *Cont.*

Product	Temperature	References
Rosehip	50 °C > 60 °C > 70 °C	[45]
Roselle calyx	Fresh > 50 °C > 40 °C > 60 °C	[33]
Sweet pepper	Fresh > 40 °C > 50 °C > 60 °C	[34]
Tomato	Fresh > 40 °C > 50 °C > 60 °C	[34]
Tomato	60 °C > 90 °C	[46]
Tomato	Fresh > 30 °C > 90 °C	[35]

">" means "better", for example, "Fresh > 65 °C > 45 °C" means that the content of vitamin C in fresh samples is higher than that in samples dried at 65 °C, and the content of vitamin C in samples dried at 65 °C is higher than that at 45 °C.

Several studies have been conducted investigating the effect of different drying conditions on vitamin C content in agricultural products. For instance, Adam et al. reported not only the influence of the temperature on vitamin C retention, but also the influence of slice thickness. Under constant drying conditions, the thicker the onion slice, the lower the vitamin C content in the dried product. The effect of slice thickness can be attributed to the longer drying period necessary for drying thicker slices to the final determined moisture content, which results in a higher exposure time to the hot air [47]. Kerkhofs et al. investigated the influence of tomato cultivar and its final moisture content after drying experiments, and reported large differences in the retention of vitamin C between Encore and Aranka tomato cultivars and the Flavourine cultivar, in which it was only 25% [48]. Igwemmar et al. investigated the effect of heating time on the vitamin C content of some vegetables (pepper, green peas, spinach, pumpkin, carrot). They found that the heating time had a significant effect on the vitamin C content of all the selected vegetables; as the heating time increased, the percentage loss of vitamin C increased, too. The percentage loss of vitamin C in the vegetables was in the ranges (9.94–16.57%), (29.94–37.43%) and (49.91–64.71%) after 5, 15 and 30 min of drying, respectively. Vitamin C was easily destroyed by excessive heat and water, as well as by exposure to air [49]. In another study, Ojike et al. studied the effect of sun drying on vitamin C content in pawpaw [50]. The outcomes of such studies indicate that plants should generally be dried at low temperatures while meeting the standards for drying rate in order to preserve the vitamin C content in dried products.

Furthermore, Dağhan et al. came to the conclusion that the degradation rate of vitamin C was lower during vacuum drying than that during hot air drying. According to these findings, vacuum drying was more practical than hot air drying for obtaining nutritionally stable products [51]. Ascorbic acid degradation during drying was found to be moisture and temperature dependent [52]. To estimate ascorbic acid retention during drying, a mathematical model for ascorbic acid degradation as a function of moisture, temperature, and time should be developed. It was discovered that the degradation of ascorbic acid followed a first-order reaction kinetic. Additionally, it was observed that at the start of the degradation process, the influence of moisture content is the predominant factor, while the temperature effect was significant as the process proceeded. Demiray and Tulek, also utilized a first-order kinetics model to identify the ideal drying conditions for reducing ascorbic acid degradation [53].

2.2. Influence of Drying Temperature on Phenols, Flavonoids and Glycosides

Fruits, vegetables, and other agricultural products are rich in phenolic compounds (e.g., simple phenolics, coumarins, lignans, flavonoids, isoflavonoids, anthocyanins, proanthocyanidins and stilbenes), which are a class of biologically active plant secondary metabolites, and their unique chemical structure and properties cause them to have multiple functional properties. Polyphenols have excellent properties, such as anti-oxidation, anti-inflammatory, anti-tumor, anti-cardiovascular diseases and other beneficial effects [54]. Their consumption may play a role in the prevention of several chronic diseases, prevention of diseases induced by oxidative stress, and prevention of some specific cardiovascular and neurodegenerative diseases (such as Alzheimer's or Parkinson's, type II diabetes, cancers, urinary tract infections) [55].

Polyphenols are a diverse category of chemical molecules that are thought to be secondary metabolites of plants. Chemically, phenolic compounds are molecules that include functional derivatives and have an aromatic ring and a benzene ring with one or more hydroxide groups (esters, methyl esters, glycosides, etc.) [56]. In plants, they often exist as conjugates with one or more glucose residues linked to the hydroxyl groups, while in some circumstances, direct junctions may form between glucose molecules and aromatic carbons. Because they are soluble in both water and organic solvents, glycosides are the most prevalent form in which they are discovered in nature. Additionally, they may be found attached to lipids, carboxylic acids, organic acids, amines, and other phenolic compounds. Depending on the number of phenolic rings, polyphenols are categorized into various groups that they possess, and the structural elements attached to them [57].

Flavonoids, a group of natural compounds with varying phenolic structures, are abundant in fruits, vegetables, grains, roots, stems, flowers, tea, and wine. The health benefits of these natural compounds are well known, and efforts are being made to separate the flavonoids from the other constituents. In a wide range of nutraceutical, pharmacological, therapeutic, and cosmetic applications, flavonoids are now regarded as an essential component. This is explained by their ability to influence important cellular enzyme functions in addition to their anti-oxidative, anti-inflammatory, anti-mutagenic, and anti-carcinogenic capabilities [58]. There are many subclasses of flavonoids, including chalcones, flavones, flavonols, and isoflavones. There are distinct major sources for these subgroups. For instance, two important food sources of flavonols and flavones are onions and tea. In general, flavonoids are relatively stable, but some of their derivatives show high reducibility, such as baicalein in *Scutellaria baicalensis*, which oxidizes easily to become green [59]. The most important phytochemicals in diets are flavonoids, particularly glycosides, which are of significant interest due to their varied bioactivity. Most natural flavonoids are found in plants in their O-glycoside or C-glycoside forms [60]. Generally, flavonoids refer to compounds in which two benzene rings with phenolic hydroxyl groups are connected to each other through the central three carbon atoms. Flavonoids are abundant in fruits, vegetables, tea, seeds, and plant roots. The main flavonoids in agricultural products include flavonol, flavanone, flavanol and isoflavone [54].

Glycosides are compounds containing sugar connected to another functional group by a glycosidic bond. In living organisms, glycosides have a variety of important functions. Some plants store chemical substances in the form of inactive glycosides that can be activated by enzyme hydrolysis [61], which causes the sugar part to be broken off, making the chemical available for use. Glycosides from plants are frequently utilized in medicine. Numerous researchers have further stipulated that a sugar must be joined to a substance other than sugar in order for a molecule to be classified as a glycoside, thus disqualifying polysaccharides. The non-sugar group is therefore referred to as the aglycone or genin component of the glycoside, while the sugar group is known as the glycone. According to the difference of glycosidic bond atoms, glycosides are divided into oxygen glycosides, nitrogen glycosides, glucosinolates and carbon glycosides.

Whether greater phenol, flavonoid and glycoside contents are retained during the drying process is an important indicator for evaluating the advantages and disadvantages of a drying method. Different drying methods and conditions have significant effects on the contents of phenols, flavonoids, and glycosides in dried products. According to the investigations conducted by Jeong et al., orange peel's antioxidant activities and total phenolic content can change more dramatically as a result of temperature increases at specific drying temperatures and heat duration intervals [62].

Table 2 shows the effect of drying temperature on the content of phenols, flavonoids, and glycosides in different agricultural products during convective drying. The drying temperature has a significant effect on the content of phenols, flavonoids, and glycosides. In general, the content of these three compounds in dried samples is lower than that in fresh samples of the same product (Table 2). In addition, these three compounds are usually affected by temperature in different degrees, which is the reason for their different optimal drying temperatures for the same product and for the different products. For instance, the mango showed different optimal drying temperatures for the three different compounds, where the optimal temperature for phenols and flavonoids ranged from 50 to 55 °C and from 45 to 50 °C, respectively. Meanwhile, a suitable drying temperature for glycosides in mango is 45 °C [38,63], as seen in Table 2. On the other hand, *Ganodermalucidum* showed the same suitable temperature of 70 °C for the three compounds [64].

Table 2 also shows that the content of polyphenols and flavonoids may increase during drying. These results are in accordance with those of Nyangena et al. who observed an increase in the content of polyphenolics for dried mango samples when compared to fresh [38]. There are similar findings associating the increased content of phenolics in dried fruits to the formation of Maillard reaction products, which may trigger the development of new phenolic complexes from their precursors at elevated temperatures [65–67].

Table 2. Effect of temperature of convective drying on the content of phenols, flavonoids, and glycosides in different products.

Compounds	Product	Temperature	References
Phenols	Bee pollen	Fresh > 65 °C > 35 °C > 50 °C	[32]
	Bitter orange	45 °C > 60 °C	[68]
	Blueberry	50 °C > 40 °C > 30 °C	[69]
	Blueberry	Fresh > 90 °C > 80 °C > 60 °C > 70 °C = 50 °C	[36]
	Cherry	Fresh > 50 °C > 60 °C > 70 °C	[70]
	Chrysanthemum	45 °C > 75 °C	[71]
	Chrysanthemum	55 °C > 65 °C > 75 °C	[37]
	Cordyceps militaris	70 °C > 60 °C > 50 °C > 40 °C	[72]
	Ganoderma lucidum	70 °C > 50 °C	[64]
	Lemon	75 °C > 50 °C	[73]
	Lemon myrtle- leaf	90 °C > 70 °C > 50 °C	[74]
	Mango	55 °C > 65 °C	[63]
	Mango	50 °C > 65 °C > Fresh	[38]
	Maquiberries	Fresh > 60 °C > 70 °C > 50 °C > 40 °C > 80 °C	[10]
	Papaya	60 °C > 70 °C > 80 °C	[75]
	Papaya	Fresh > 50 °C > 60 °C > 70 °C	[76]
	Pomegranate leather	70 °C > 60 °C > 50 °C	[42]
	Red pepper	Fresh > 60 °C = 90 °C > 70 °C > 80 °C > 50 °C	[44]
	Strawberry	50 °C > 60 °C	[77]
	Sweet pepper	Fresh > 60 °C > 50 > 40 °C	[34]
	Tomato	Fresh > 60 °C > 50 > 40 °C	[34]
	Tomato	Fresh > 70 °C > 60 °C > 50 °C	[78]
Flavonoids	Chrysanthemum	75 °C > 45 °C	[71]
	Chrysanthemum	55 °C > 65 °C > 75 °C	[37]
	Ganoderma lucidum	70 °C > 50 °C	[64]
	Lemon	75 °C > 50 °C	[73]
	Lemon myrtle-leaf	90 °C > 70 °C > 50 °C	[74]
	Mango	45 °C > 60 °C	[63]
	Mango	50 °C > 65 °C	[38]
	Maquiberries	Fresh > 70 °C > 50 °C > 60 °C > 40 °C > 80 °C	[10]
	Myrciaria jaboticaba	55 °C > 65 °C > 75 °C	[79]
	Pomegranate leather	50 °C > 70 °C > 60 °C	[42]
	Sweet pepper	Fresh > 60 °C > 50 > 40 °C	[34]
	Tomato	Fresh > 60 °C > 50 > 40 °C	[34]
	Tomato	Fresh > 60 °C > 70 °C > 50 °C	[78]
Glyco sides	*Ganoderma lucidum*	70 °C > 50 °C	[64]
	Ginseng	50 °C > 60 °C > 70 °C	[80]
	Mango	45 °C > 60 °C	[63]

">" means "better", for example, "Fresh > 65 °C > 45 °C" means that the phenolic compound in fresh samples is higher than that in samples dried at 65 °C, and the content of vitamin C in samples dried at 65 °C is higher than that at 45 °C.

In general, under the premise of meeting the requirements of drying rate, in order to ensure high content of phenols in dried products, the samples are usually dried at a temperature of 55–60 °C. The most ideal drying temperatures for flavonoids and glycosides are 60–70 °C and 45–50 °C, respectively. The main reason for the difference in the ideal drying temperature of the three compounds is the difference in the molecular structures of these compounds. These three compounds are all reductive, but glycosides have a greater reducibility than that of phenols and flavonoids, and are more affected by temperature and oxygen concentration. Due to the lower reducibility of phenols and flavonoids compared to glycosides, they are less affected by temperature and oxygen concentration. Besides, some of the oxidation products of phenols at high temperature are flavonoids, so there is a phenomenon whereby "the retention rate of flavonoids at high temperatures is higher than that at low temperatures". Due to the different optimal drying temperatures for different ingredients, temperatures can be selected according to the types of ingredients that need to be retained when plants are dried.

2.3. Influence of Drying Temperature on Volatile Compounds

Agricultural products such as fruits, vegetables and medicinal plants contain a wide range of volatile compounds, which provide their characteristic aromas and flavors, and which play a key role in providing the distinctive qualities of these products. Although many of the volatile and nonvolatile compounds responsible for aromatic features have been identified, many of their biochemistry pathways are still not well explained [81]. The volatile aromatic substances that constitute the fruit aroma mainly include low-molecular-weight, low-boiling compounds such as alcohols, aldehydes, ketones, esters, lactones, terpenoids (terpenes) and apocarotenoids [82,83]. The type and content of aroma volatile compounds are important indicators of the overall flavor and consumer acceptance [84]. The key volatile compounds related to the typical sensory properties of these products and their respective aromatic features are summarized in Table 3 and more information can be found in Gou et al. and Xu et al. [85,86].

Table 3. Odor descriptions of volatile compounds responsible for sensory attributes of agricultural products (adopted from Gou et al. and Xu et al. [85,86]).

Volatile Compounds	Odor Descriptions
Alcohols	
(E)-2-hexenol	green, fruity
1-butanol	overall flavor, sweet aroma
1-hexanol	fresh, green, earthy
1-octen-3-ol	mushroom
3-mercaptohexan-1-ol	sulfur and passion fruit
3-octanol	earthy, mushroom, herbal
Benzyl alcohol	bitter almond-like, fruity
Benzene ethanol	flowery, floral, vegetal, woody
Linalool	citrus-like, flowery
Furaneol	sweet, caramel, candy
Methanethiol	sulfur, gasoline, and garlic
Octanol	jasmine, lemon
Menthol	mint-like
Aldehydes	
(E)-2-heptenal and (E)-2-octenal	green, leaf, and fat
3-methylbutanal	malty
Benzaldehyde	sweet, fruity, roasted, almond, fragrant
Phenylacetaldehyde	sweet and fruity
Hexanal and heptanal	green, grassy
Furfural	bread, almond, and sweet
Nonanal and octanal	fat, citrus, green and fruity
(E)-2-octenal	green and leaf
Pentanal	almond, malt, pungent
Octanal	green, fruity, orange, citrus
Vanillin	vanilla-like, sweet
Decanal and nonanal	sweet, aldehydic, waxy and rose

Table 3. *Cont.*

Volatile Compounds	Odor Descriptions
Acids	
Propanoic acid and acetic acid	sour-like, sweaty
Hexanoic acid and butyric acid	sweaty, sour, cheesy and stink
Decanoic acid	soapy, musty
Nonanoic acid	moldy, pungent
Esters	
γ-octalactone	sweet, coconut, and peach
γ-hexalactone	sweet, spicy, coconut, and hay
Methyl benzoate, ethyl 2-methylbutanoate	herbal, fruity and flower
Ethyl propanoate	fruity, strawberry
Pentyl acetate	fruity, banana
Butyrolactone	sweet, flowery
Butyl butanoate	rotten apple
Hexyl butanoate	green
Methyl butanoate	fruity, sweet (lulo-like)
Ethyl butanoate, ethyl heptanoate	fruity
Methyl hexanoate	fruity, sweet (pineapple-like)
Ethyl hexanoate	fruity and wine
Ethyl octanoate	fat
3-mercapohexyl acetate	sulfur, grapefruit, and fruity
Butyl acetate, ethyl acetate	sweets, fruity and ethereal

Like other bioactive compounds, the content of volatile compounds in fresh products is usually higher than in dried products. The effect of drying temperature on the content of volatile compounds in different agricultural products during convective drying is listed in Table 4. Generally speaking, higher retention of volatiles in dried products is reported at lower drying temperatures. This is mainly due to the low boiling point of alcohols, aldehydes, ketones, esters and terpenes, which have high heating sensitivity. However, not all products follow this rule (Table 4). For example, yew (Taxus) has a higher retention of volatiles when dried at 60 °C than at 30 °C [87]. The reason for this phenomenon may be that when the yew is dried at 60 °C, the drying rate of the sample is high, resulting in a short drying time. Accordingly, the loss of volatile content is higher at 30 °C due to the long drying time and the long period of exposure to oxygen. Another example of this attitude was observed in the drying of Guaco leaves (*Mikania micrantha*), where the content of compounds of the dried sample was higher than that of the fresh sample [88]. This may be due to the conversion of other substances into the corresponding alcohols, aldehydes, ketones, esters and terpenes during the drying process, causing an increase in volatile content. It can be concluded from Table 4 that drying agricultural products at temperatures ranging from 40 to 50 °C is the proper choice for retaining volatile compound content during drying.

Table 4. Effect of temperature on the content of volatile compounds in different products processed with convective drying.

Products	Temperature	References
Apple	Fresh > 30 °C > 50 °C > 70 °C	[89]
Aromatic plants	40 °C > 50 °C = 60 °C > 70 °C = 80 °C = 90 °C	[90]
Brazilian linalool	40 °C > 50 °C > 60 °C > 70 °C	[91]
Chamomilla recutita	Fresh > 40 °C > 30 °C > 90 °C > 60 °C = 70 °C > 50 °C = 80 °C	[92]
Cordyceps militaris	40 °C > 50 °C > 60 °C > 70 °C	[72]
Cymbopogon citratus	50 °C > 30 °C > 70 °C > 90 °C	[93]
Guaco leaves	50 °C > 70 °C > 40 °C > 60 °C > 80 °C > fresh	[88]
Mint	50 °C > 60 °C > 70 °C	[94]
Mint	50 °C > 40 °C > 60 °C > 70 °C > 80 °C	[95]
Pepper	50 °C > 35 °C > 45 °C > 55 °C > 60 °C > 40 °C	[96]

Table 4. *Cont.*

Products	Temperature	References
Rosmarinus	60 °C > 50 °C > 70 °C	[97]
Rosmarinus officinalis	40 °C > 50 °C = 60 °C >> 70 °C = 80 °C > 90 °C	[90]
Tarragon	fresh > 90 °C > 45 °C > 60 °C	[98]
Taxus	60 °C = 50 °C = 40 °C > 30 °C	[87]
Thymus vulgaris	Fresh > 30 °C > 60 °C	[99]

">" means "better", for example, "Fresh > 65 °C > 45 °C" means that the content of volatile compounds in fresh samples is higher than that in samples dried at 65 °C, and the content of vitamin C in samples dried at 65 °C is higher than that at 45 °C.

2.4. Influence of Drying Temperature on Antioxidant Activity

Antioxidants play an important role in food preservation by preventing oxidation processes, and they contribute several health benefits through their inclusion in numerous dietary supplements, nutraceuticals, and functional food ingredients [100]. Antioxidant activity represents an important indicator for measuring the quality of fruits and vegetables, and antioxidants are usually referred to as free-radical fighters, as they generously donate electrons to free radicals without turning into electron-scavenging substances themselves. There are hundreds of different substances that can act as antioxidants. The most common ones are vitamin C, vitamin E, beta-carotene, and other related carotenoids, along with the mineral's selenium and manganese. It has become well known that low intakes of antioxidant-rich fruits and vegetables will cause a risk for developing chronic conditions compared with people who ate plenty of those foods. It is for this reason that antioxidants are usually employed as weapons against chronic diseases. The indicators used to evaluate the antioxidant capacity of fruits and vegetables mainly include measurement of Oxygen Radical Absorbance Capacity (ORAC) [101], measurement of 2,2-diphenyl-1-picrylhydrazyl (DPPH), measurement of Ferric ion reducing antioxidant power (FRAP), and measurement of Trolox equivalent antioxidant capacity (TEAC) [102]. Antioxidant capacity is the general term for the antioxidative ability possessed by all antioxidant free radicals. This article presents the effect of drying temperature on the antioxidant capacity by calculating the total antioxidant capacity value of some products after being dried.

Several researchers have conducted experimental studies on the effects of drying on antioxidant activity, coming to the conclusion that raising the drying temperature reduces the nutritional characteristics [103–108]. Related studies have looked into how different drying techniques (primarily vacuum drying, freeze drying, and hot air drying) affect the antioxidant content of fruits [109,110]. High antioxidant potentials of dried fruits were reported by Kamiloglu and Capanoglu, despite the fact that numerous researchers have stated that drying is generally viewed as being unfavorable due to the potential for inducing oxidative decomposition, either enzymatically or by thermal degradation of polyphenols [111]. Furthermore, drying has even been observed to result in increased phenolic and flavonoid content, as well as antioxidant activity [112,113].

It has been discovered that chemical changes that impact the phenolic and flavonoid content of dried products can occur during the drying process at various temperatures ranging between 40 and 80 °C [114]. The elevated antioxidant activity in fruits and vegetables after drying may be due to the fact that partially oxidized polyphenols have higher antioxidant activity than nonoxidized polyphenols [115]. Additionally, the Maillard reaction products, which can form as a result of heat treatment or prolonged storage and which typically exhibit strong antioxidant properties, may be connected to increased antioxidant capacity after drying [111].

Recent research by Chen et al. revealed that although the content of total phenolic compounds and antioxidant activity of the samples generally decreased with increasing drying temperatures, the content of specific phenols varied with drying temperature, and chlorogenic acid underwent a clear transformation at higher temperatures (80–90 °C). The authors also reported that the ideal drying temperature for Xuan-Mugua fruit slices was 70 °C, considering the phenolic profile and concentration as well as the antioxidant activity [108].

Table 5 shows the effect of convective drying temperature on antioxidant activity in different agricultural products. In general, the antioxidant capacity of most products after drying is lower than that before drying, but the degree of loss of antioxidant capacity of samples is different at different drying temperatures. It can be concluded from Table 5 that drying temperatures in the range from 50 to 70 °C are the best, with minimal loss of antioxidant capacity. When the drying temperature is lower than 50 °C, the loss of the antioxidant capacity of the sample should theoretically be small. However, due to the drying efficiency being lower than that at high temperatures, the loss of antioxidant capacity will still actually be large. At the same time, it is generally difficult for the low drying rates at low temperature to meet the requirements of industrial production.

Table 5. Effect of temperature on antioxidant activity in different products processed with convective drying.

Products	Temperature	References
Bee pollen	Fresh > 50 °C > 35 °C > 65 °C	[32]
Bell pepper	Fresh > 60 °C > 50 °C > 40 °C	[34]
Bitter orange	60 °C > 45 °C	[68]
Blueberry	50 °C > 40 °C > 30 °C	[69]
Cherry	Fresh > 70 °C > 60 °C > 50 °C	[70]
Chrysanthemum	75 °C > 45 °C	[71]
Ganoderma	70 °C > 50 °C	[64]
Lemon myrtle leaf	90 °C > 70 °C > 50 °C	[74]
Mango	50 °C > 65 °C	[38]
Maquiberries	Fresh > 80 °C = 60 °C > 70 °C > 50 °C > 40 °C	[10]
Onion	70 °C > 60 °C > fresh	[116]
Papaya	60 °C > 70 °C > 80 °C	[75]
Papaya	Fresh > 60 °C > 50 °C > 70 °C	[76]
Pomegranate	60 °C > 50 °C = 70 °C	[42]
Red bell-pepper	70 °C > 50 °C > fresh	[43]
Red pepper	70 °C > 50 °C > 60 °C > 90 °C > 80 °C > fresh	[44]
Strawberry	50 °C > 60 °C	[77]
Tomato	Fresh > 60 °C > 50 °C > 40 °C	[34]
Tomato	Fresh > 70 °C > 60 °C > 50 °C	[78]

">" means "higher or better", for example, "Fresh > 65 °C > 45 °C" means that the content of antioxidants in fresh samples is higher than that in samples dried at 65 °C, and the content of antioxidants in samples dried at 65 °C is higher than that at 45 °C.

3. Degradation Mechanisms of Bioactive Compounds

The bioactive compounds in fruits, vegetables, herbs, and spices are very vulnerable and can be easily degraded by different factors, including enzymes, thermal treatment, pH, oxidation, light, and/or hydrolysis (Figure 1). Some of the main examples of degradation reactions include: oxidation and hydrolysis of vitamin C, oxidation of phenols, flavonoids, glycosides and hydrolysis of esters [117]. Therefore, actions taken for preventing such degradation are critically important not only for producers, but also for consumers, for whom the presence of these compounds is desirable for health-related requirements. In particular, the degradation of bioactive compounds during thermal treatment (e.g., blanching, pasteurization, sterilization and/or drying) represents a severe problem that must be tackled in the food industry. Many research works have been carried out investigating the thermal degradation of bioactive compounds in fruits [29,41], vegetables [17,53], and medicinal plants [4,59]. The degradation mechanisms of these compounds are discussed below.

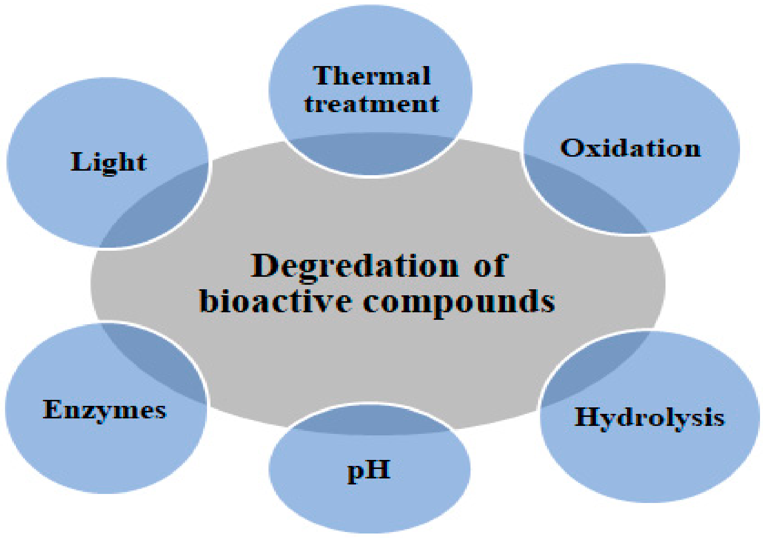

Figure 1. Parameters affecting the degradation kinetics of bioactive compounds.

3.1. Degradation Mechanism of Vitamin C

The spatial structure of vitamin C (i.e., L-ascorbic acid) is shown in Figure 2, characterized by being easily soluble in water, less soluble in ethanol, and insoluble in organic solvents such as chloroform, benzene, ether, petroleum ether, grease, etc. There are three isomers of vitamin C (i.e., D-ascorbic acid, L-isoascorbic acid, and D-isoascorbic acid) that can be mutually converted into ascorbic acid (vitamin C) under certain conditions. The main difference in chemical structure between L-ascorbic acid and its isomers is shown in Figure 3. During the drying process under the influence of temperature, oxygen, water vapor and other factors, vitamin C undergoes oxidation and hydrolysis reactions. Under certain conditions, L-ascorbic acid can be oxidized to produce L-dehydroascorbic acid. The L-dehydroascorbic acid can also be reduced in the plant and converted back to L-ascorbic acid as shown in Figure 4. This change is reversible, such that L-dehydroascorbic acid still has biological activity. However, when L-dehydroascorbic acid is further oxidized and hydrolyzed to form 2,3-Diketo-L-gulonic acid, its activity disappears, causing vitamin C to lose its effectiveness, and this process is irreversible [28]. The oxidation reaction of vitamin C is as follows (this change is reversible):

$$2C_6H_8O_6\ (\text{L-ascorbic acid}) + O_2 \rightleftharpoons 2C_6H_6O_6\ (\text{L-dehydroascorbic acid}) + 2H_2O$$

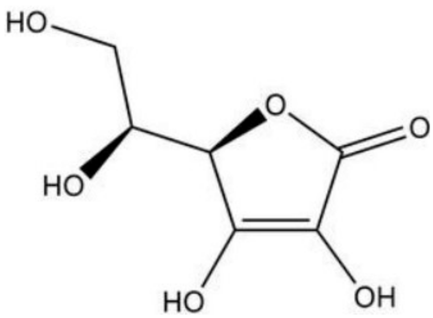

Figure 2. The spatial structure of vitamin C.

The reduction of L-dehydroascorbic acid to L-ascorbic acid under certain conditions is as follows:

$$C_6H_6O_6 + 2H \xrightarrow{\text{certain conditions}} C_6H_8O_6$$

The hydrolysis reaction of L-dehydroascorbic acid is as follows:

$$2C_6H_6O_6+3O_2+H_2O \rightarrow C_6H_8O_7\ (2,3\text{-Diketo-L-guloni acid})+3C_2H_2O_4(\text{oxalic acid})$$

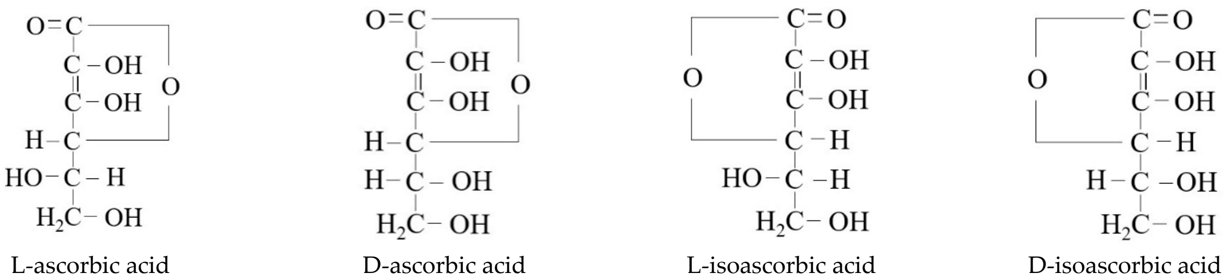

Figure 3. The chemical structure of vitamin C and its isomers.

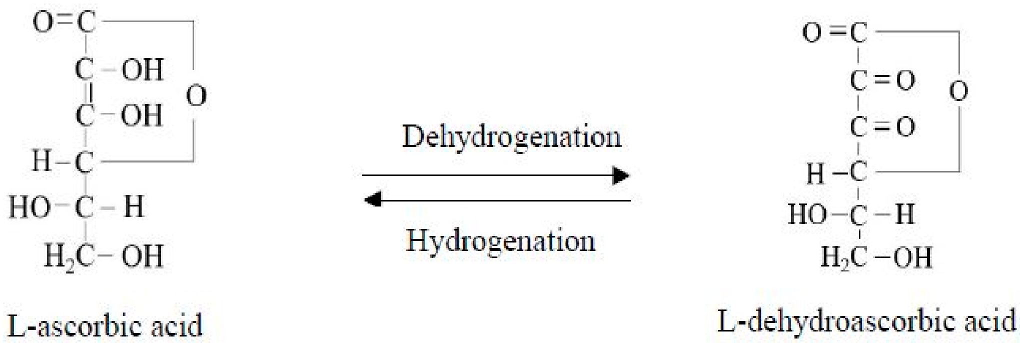

Figure 4. Interconversion of L-ascorbic acid and L-dehydroascorbic acid.

3.2. Degradation Mechanisms of Phenols, Flavonoids and Glycosides

Except for flavonoids and glycosides, all other polyphenols are classed as phenols, mainly including phenolic acids (such as gallic acid, ellagic acid and ferulic acid) and tannin (such as caffetannins, labiataetannins and phlorotannins) [118]. Meanwhile, phenolic acids are the most common phenols. Figure 5 presents the chemical structure of common phenols, flavonoids, and glycosides.

According to Figure 5, phenols, flavonoids, and glycosides have a common feature in that their molecular structure contains a benzene ring and a variable number of hydroxyl groups (–OH), which have strong reducibility. The hydroxyl groups are often oxidized to aldehyde groups, ketone groups or carboxyl groups when heated. Since the phenols, flavonoids and glycosides can be degraded with oxidation reactions, the vacuum environment is better for retaining effective ingredients content. It has been reported that vacuum drying and vacuum freeze-drying are better than other methods.

The hydroxyl group (–OH) is dehydrogenated to form aldehyde group (–CHO), and the resultant aldehyde group is further oxidized to carboxyl group.

$$2RCH_2\text{–}OH + O_2 \rightarrow RCHO + 2H_2O(\text{Dehydrogenation})$$

$$2RCHO + O_2 \rightarrow 2RCOOH(\text{Oxygenation})$$

Dehydrogenation reaction of hydroxyl group (–OH) to form ketone group (C=O), as,

$$4R\text{–}OH + O_2 \rightarrow 2RCOR + 2H_2O(\text{Dehydrogenation})$$

Oxygenation of hydroxyl group (–OH) to carboxyl group (–COOH):

$$2R\text{–}OH + O_2 \rightarrow 2RCOOH(\text{Oxygenation})$$

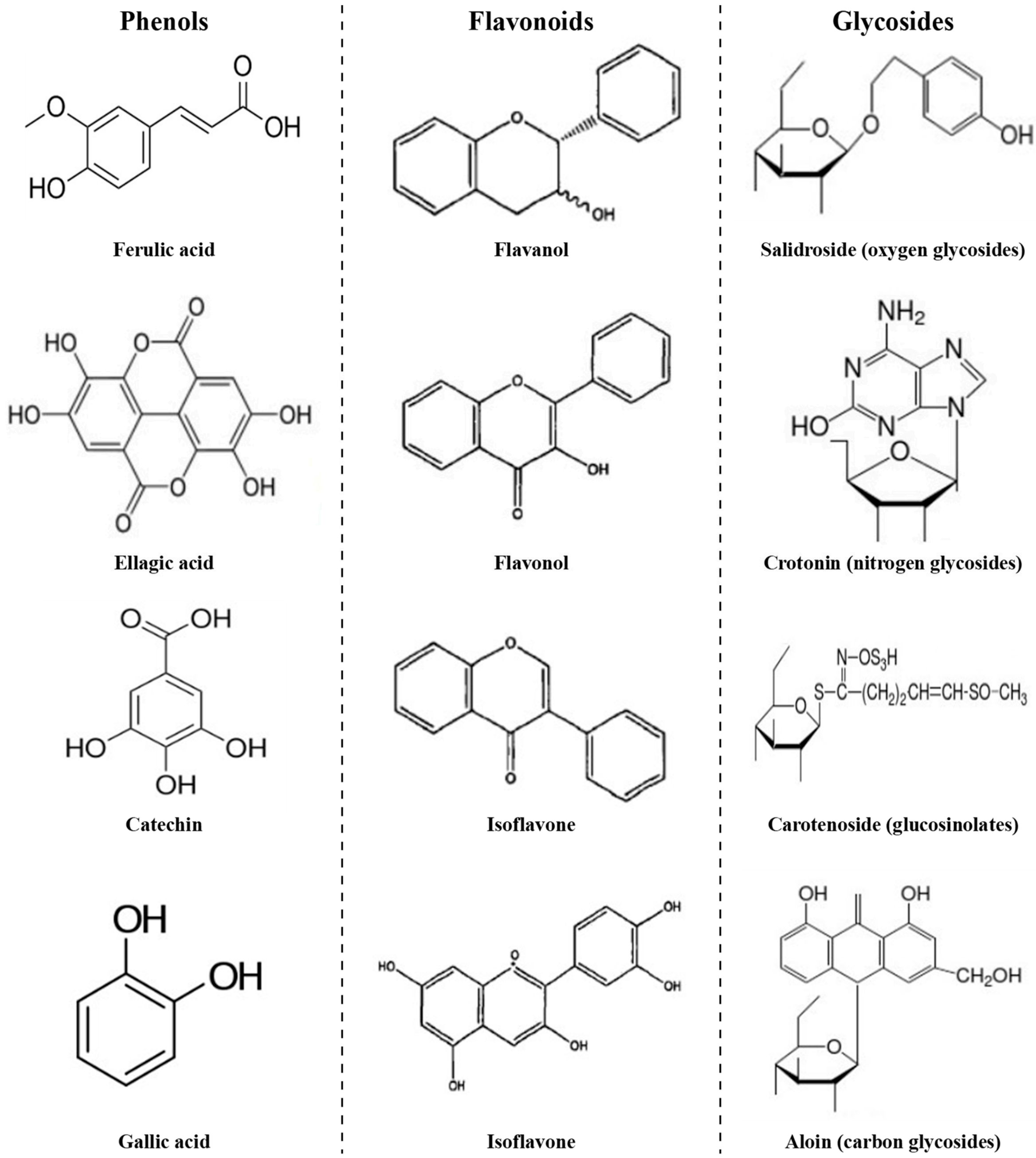

Figure 5. Chemical structure of phenols (**left**), flavonoids (**middle**) and glycosides (**right**).

During the drying process of fruits and other materials, the degradation of the bioactive compounds is based on the above basic reactions and the degradation speed is mainly affected by temperature, oxygen and moisture content. The following are the typical degradation reactions of phenols and flavonoids (catechins and baicalein):

(1) Catechins (phenols) is oxidized to theaflavins [119]:

$$2C_{15}H_{14}O_6(H_2O)(\text{catechins})+2O_2 \rightarrow C_{29}H_{24}O_{12}(\text{theaflavins})+CO_2+3H_2O(\text{Dehydrogenation})$$

The molecular structure of catechins and theaflavins is shown in Figure 6.

(2) Oxidation of baicalein (flavonoids) [59]:

$$2C_{15}H_{10}O_5(\text{baicalein})+O_2 \rightarrow 2C_{15}H_8O_5(\text{Ketones})+2H_2O(\text{Dehydrogenation})$$

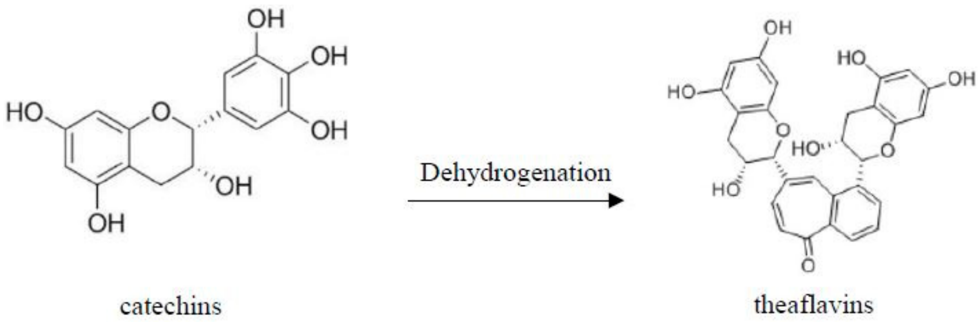

Figure 6. Formation of theaflavins from catechins through dehydrogenation.

The chemical structure of baicalein and its oxidation product are shown in Figure 7. When baicalein is oxidized into corresponding ketone compounds, the original yellow color changes to green, and the efficacy of the bioactive ingredients is degraded.

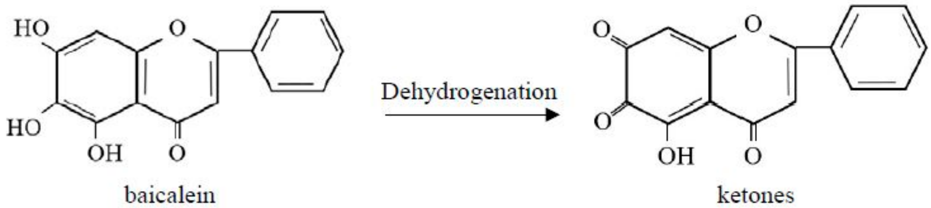

Figure 7. Chemical structure of baicalein and its oxidation products.

3.3. Degradation Mechanism of Volatile Compounds

Volatile substances provide the flavor and aroma of many economically important herbs, spices, and medicinal plants. The main volatile substances in fruits and spices are aroma volatiles, and constitute one of the important indices for the quality evaluation of products. Different fruits have different scent characteristics due to their different contents and types of volatile aromatic substances. However, not every volatile aromatic substance has the characteristic aroma components of fruits. The volatile aromatic substances constituting the fruit fragrance mainly include low-molecular-weight alcohols and esters, as well as small amounts of a low-molecular-weight, low-boiling-temperature substances such as aldehydes, ketones and terpenes. Alcohols are volatile and easily lost when heated during the drying process. Esters are generally hydrolyzed to alcohols and acids, and the hydrolyzing reaction is affected by temperature and moisture. After the volatilization of alcohols, the acidic substances remain, eventually causing the aroma components to become worthless [120].

The hydrolysis reaction of esters can be expressed by the following general formula:

$$R_1COOR_2 + H_2O \rightarrow R_1COOH + R_2OH$$

Taking the hydrolysis of ethyl acetate and ethyl formate as an example:

$$CH_3COOCH_2CH_3(\text{ethyl acetate}) + H_2O \rightarrow CH_3COOH + CH_3CH_2OH$$

$$HCOOCH_2CH_3(\text{ethyl formate}) + H_2O \rightarrow HCOOH + CH_3CH_2OH$$

In addition, medicinal plants contain volatile oil, which is generally a colorless or light-yellow transparent liquid, with a special aroma and spicy burning taste. It oxidizes and deteriorates easily once in contact with air, and its volatilization is usually related to temperature, oxidation and water content during the drying process. The higher the temperature in the drying process, the faster the volatilization rate of the volatile oil, while the lower the temperature and the shorter the drying time, the more volatile oil can be retained.

In brief, the thermal degradation mechanisms of bioactive compounds discussed above are greatly affected by drying temperature. Gąsecka et al. reported that the greatest decreases in the bioactive compounds of *Leccinum scabrum* was generally occurred at 70 °C. The inhibition of free radicals decreased in the following order: fresh samples > air-dried samples > samples dried at 40 °C > samples dried at 70 °C [121]. In grape pomace dried at temperatures below 60 °C, Teles et al. hypothesized that bioactive components may be subject to oxidation by polyphenol oxidase, because temperatures of 50 °C and 40 °C were likely insufficient to inactivate this enzyme. The preservation of phenolic compounds was improved by the influence of temperature as well as a decrease in water activity, which may have also led to the decrease in enzyme activity and the occurrence of chemical reactions [122].

4. Conclusions

This review provided an overview of recent findings on the effects of convective drying on major bioactive ingredients in agricultural products. In particular, changes in vitamin C, phenols, flavonoids, glycosides, volatiles and antioxidant activity were discussed in detail. Different bioactive ingredients are affected by temperature to different degrees, mainly as a result of their different molecular structures. Vitamin C reacts with oxygen due to high reducibility during the convective drying process. Higher drying temperatures result in a faster reaction rate of vitamin C. At the same time, the isomers of vitamin C, including D-ascorbic acid, can be mutually converted to ascorbic acid (vitamin C) at high drying temperatures. Phenols, flavonoids and glycosides show the same thermal degradation behavior as vitamin C. On the other hand, phenols are reductive and easily oxidized during the drying process and the higher drying temperatures result in a faster reaction rate in phenols. Therefore, lower drying temperatures are preferred in order to achieve a higher retention rate of phenols. The degradation of volatiles is mainly due to heat volatilization and dissipation. Thus, lower drying temperatures result in higher retention rates of volatiles.

An overview of the degradation mechanisms of bioactive compounds during drying was also presented and discussed in this article. Bioactive compounds can be easily degraded by different factors, including enzymes, thermal treatment, pH, oxidation, light and/or hydrolysis. Degradation reactions of bioactive compounds mainly include oxidation and hydrolysis of vitamin C, oxidation of phenols, flavonoids, glycosides and hydrolysis of esters. Therefore, action taken to prevent such degradation is critically important, not only for producers but also for the consumers, for whom the presence of these compounds is desirable for health-related requirements. In particular, the degradation of bioactive compounds during drying represents a severe problem that must be tackled in the food industry.

More investigation is needed to provide a better understanding of the degradation mechanisms of bioactive compounds during the drying process, since different fruits and vegetables have different chemical and physical characteristics. Degradation of bioactive compounds during convective drying is mainly due to the exposure of food and agricultural products to high temperatures for long periods of time. Improvements in convective drying methods as well as a combination of different methods and new approaches should be used to obtain better quality dried products. Several drying methods, such as microwave freeze drying, infrared and vacuum drying, have shown advantages over convective drying in terms of product quality, but there are still some challenges, such as high cost and energy consumption. Research and development are needed to achieve optimal drying methods with high product quality and low cost that save energy and are eco-friendly. In recent years, microwave drying has gained popularity as an alternative drying method for a wide variety of food and agricultural products. The food industry is now a major user of microwave energy, especially in the drying of pasta and post-baking of biscuits. Microwave treatment can greatly reduce the drying time of biological products without a deterioration in quality, and it can be considered one the most optimal drying methods.

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