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Kinetics, physicochemical properties, and antioxidant activities of *Angelica keiskei* processed under four drying conditions

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ABSTRACT

The herb Japanese angelica (*Angelica keiskei*) has been consumed for centuries as a healthy vegetable. The drying kinetics, microstructure, color, and polyphenol components, as well as antioxidant capacity of stems and leaves of *A. keiskei* were investigated and compared, after undergoing natural drying (ND), convective drying (CD), freeze-drying (FD), and vacuum oven drying (VOD). The freeze-dried products showed the lowest color differences compared with their fresh counterpart, and also provided the highest retention of the main polyphenol components (i.e., quercetin, luteolin, and chlorogenic acid) and antioxidant activity (DPPH and FRAP), followed by ND. The CD and VOD processes at 60 °C in which heat was applied caused the additional loss of color, total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity. In addition, the leaves exhibited stronger antioxidant activity and contained higher phenolic content than stems; for example, the quercetin content in fresh stems and leaves was 89.82 *vs* 638.20 mg/kg dry weight, respectively. Our results implied that FD could be a superior drying technique for *A. keiskei,* however, high cost of FD procedures may limit its application. Natural drying thus could be an alternative method when finance becomes the main concern.

1. Introduction

Angelica keiskei Koidz. (Umbelliferae), commonly known under the Japanese name of Ashitaba or Japanese angelica, is a cold-hardy perennial plant that was originally grown on the Izu Islands and Miura Peninsula of Japan (Nakamura et al., 2012). The aerial parts have been consumed for centuries as a healthy vegetable. Additionally, it is a medicinally important herb used as a diuretic, laxative, and stimulant as well as a tonic for restoring vitality (Kim et al., 2014). There are also several beneficial effects of *A. keiskei* that have been reported in animal models and clinical trials, including anti-hypertension (Shimizu et al., 1999), anti-tumourigenesis (Kang, Park, Kim, & Kim, 2004), anti-thrombosis (Son, Park, Yu, Lee, & Park, 2014), vasodilation (Matsuura, Kimura, Nakata, Baba, & Okuda, 2001), and hepatoprotection (Noh, Ahn, Yun, Cho, & Paek, 2015). *Angelica keiskei* is an important source of health-promoting constituents, such as coumarins, flavanones, chalcones, and phenolic acids (Aldini et al., 2011; Kim et al., 2014). In particular, phenolic acids and flavanones are very important constituents in *A. keiskei* and have been proven to possess strong free radical scavenging and antioxidant capacities (Kim et al., 2014; Li et al., 2009).

Angelica keiskei is widely cultivated in Asia due to a significant consumer demand for functional foods. Having an initial moisture content of 85–95 g/100 g, fresh *A. keiskei* is easily perishable because it is highly susceptible to mechanical damage and microbial spoilage under environmental conditions. The drying process reduces the moisture content to a safe level and is the most commonly used method to inhibit microbial growth and delay deteriorative biochemical reactions. Therefore, drying preserves *A. keiskei* and prolongs its shelf-life. The dry powder is the fundamental ingredient used in *A. keiskei* products such as snacks, flour, and cosmetics (Bao, 2014; Heo, Kang, Jung, & Shin, 2013; Wu, Yang, & Wang, 2012). Another advantage is easier transport due to reduced weight and volume, which can potentially expand markets for *A. keiskei*-based products. However, the drying process is complex and significantly influences the bioactive potential of the final ingredient. Previous studies have shown that the drying process could potentiate or reduce the amounts of compounds with potential biological activity (Yábar, Pedreschi, Chirinos, & Campos, 2011). Conventionally, natural drying (ND) and thermal treatments are relatively more common methods used to preserve and extend the shelf-

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Table 1
Parameters of different drying models applied to dried *A. keiskei*.

Model	Model equation	Drying method	Detected part	Parameters				Statistics	
				A	*k*	*B*	*C*	RMSE	R^2
Modified Page	$MR = A·exp(-k·t^B)$	CD	stems	0.9557	0.1324	1.2581		0.0160	0.9882
			leaves	0.9975	0.6873	0.6789		0.0036	0.9956
		VOD	stems	0.9241	0.0115	2.2496		0.0156	0.9886
			leaves	1.0047	0.1605	1.3907		0.0036	0.9969
		ND	stems	0.9756	0.0126	1.4487		0.0061	0.9962
			leaves	0.9854	0.1143	1.0247		0.0099	0.9910
Henderson Pabis	$MR = A·exp(-k·t)$	CD	stems	1.0202	0.2222			0.0273	0.9812
			leaves	0.9404	0.4656			0.0261	0.9702
		VOD	stems	1.1136	0.1659			0.1399	0.9064
			leaves	1.0774	0.2990			0.0276	0.9787
		ND	stems	1.0597	0.0548			0.0330	0.9807
			leaves	0.9900	0.1212			0.0099	0.9918
Logarithmic	$MR = A·exp(-k·t)+B$	CD	stems	1.0715	0.1819	−0.0770		0.0016	0.9879
			leaves	0.9218	0.5561	0.0414		0.0166	0.9793
		VOD	stems	4.4988	0.0213	−3.4780		0.0215	0.9843
			leaves	1.1364	0.2463	−0.0813		0.0171	0.9855
		ND	stems	1.1081	0.0471	−0.0633		0.0243	0.9845
			leaves	0.9827	0.1249	0.0102		0.0093	0.9915
Wang&Singh	$MR = A + B·t + C·t^2$	CD	stems	0.9487		−0.1404	0.0052	0.0154	0.9886
			leaves	0.7632		−0.1693	0.0091	0.1191	0.8518
		VOD	stems	1.0231		−0.0968	0.0010	0.0212	0.9845
			leaves	1.0145		−0.2045	0.0103	0.0118	0.9900
		ND	stems	0.9985		−0.0353	3.0216E-4	0.0179	0.9886
			leaves	0.7974		−0.0409	4.7667E-4	0.1371	0.8754

Note:ND: natural drying; CD: convective drying; VOD: vacuum oven drying; FD: Freeze-drying.

life of various vegetables due to their low-cost and simplicity. However, ND has some disadvantages, mainly that it is time-consuming with inconsistent quality standards (Soysal & Oztekin, 2001). In this sense, convective drying (CD) is always an alternative for drying vegetables in the food industry. It should be noted that CD usually causes degradation of thermo sensitive bioactive components, flavors, and colors (An et al., 2016). According to Jiang et al. (2017), convective drying of okra may have negative effects on bioactive compounds, such as flavone and phenolic compounds, compared with their fresh counterparts, thus reducing their antioxidant activity. Freeze-drying (FD) can effectively retain the original properties, including bioactivity of phytochemical compounds, flavor, and shape; however, this method is a time-intensive and costly method (Karam, Petit, Zimmer, Djantou, & Scher, 2016).

The effects of drying methods on polyphenolics and antioxidant activities of *A. keiskei* have not yet been systematically investigated. Therefore, the study of drying technologies in order to determine the most optimal conditions to maximize presentation of color, as well as both active constituents and antioxidant activity, is crucial to produce dried *A. keiskei* powder for use as a food coloring, as an ingredient for snacks, or a functional ingredient to be included in other products. Additionally, previous research found that the content of polyphenolics in *A. keiskei* significantly varied across the different parts of plant (Kim et al., 2014; Luo, Ya-Li, Zhu, & Shen, 2017). Accordingly, the aim of this work was to explore the changes in the drying process and their effect on the drying kinetics, structural properties, color characteristics, polyphenolic composition, and antioxidant capacity of *A. keiskei* between stems and leaves.

2. Materials and methods

2.1. Raw materials

Fresh *A. keiskei* was sourced from a farm at Rizhao, Shandong, PR China, in July 2017. The moisture content of the fresh stems and leaves was 11.51 ± 0.43 and 5.78 ± 0.15 kg kg-1 db (dry basis), respectively. Before drying, each plant was separated into leaves and stems before cutting into small pieces (20 ± 0.5 mm, length; 20 ± 0.5 mm, width).

2.2. Drying procedure

The initial mass of approximately 400 g of fresh leaves or stems was evenly distributed and subjected to four different drying methods:

(i) ND – fresh leaves and stems were dried by placing them in a shaded location between 18 and 25 °C.
(ii) CD –*A. keiskei* samples were subjected to 60 °C in an electric thermostatic drying oven (DHG-9070A; Shanghai Jinghong Experiment Instrument Co., Shanghai, China).
(iii) Vacuum oven drying (VOD) –the leaves and stems of *A. keiskei* were placed in a vacuum oven (DZF-6050; Shanghai Jinghong Experiment Instrument Co., Shanghai, China) at 60 °C. The vacuum was set to 25 Pa and maintained by controlling the vacuum pump and air inlet.
(iv) FD –samples were frozen at −80 °C for 12 h, and then were quickly placed into a freeze dryer (SCIENTZ-18N; Ningbo Science Biotechnology Co., Ltd., Ningbo, China) at a vacuum pressure of 47 Pa. During FD, the temperature in the cold trap was −50 °C, while the temperature of the drying chamber reached −25 °C.

All of the samples were dried until the moisture content was below 0.1 kg kg-1 db to meet microbial safety requirements. The moisture content was determined by placing samples in a hot air oven at 105 °C until a constant weight was attained (China GB5009.3–2016).

2.3. Modeling of drying kinetics

The drying curves were drawn based on mass losses of *A. keiskei* samples. The moisture ratio (MR) was calculated using Equation (1):

$$MR = (M_t - M_e)/(M_0 - M_e), \quad (1)$$

Where M_t is the moisture content of the sample (kg water kg dry basis-1) at time t, M_0 is the initial moisture content, and M_e is the equilibrium moisture content of the sample. In Equation (1), the value of the