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Effect of Thermal Processing on Key Phytochemical Compounds in Green Leafy Vegetables: A Review

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ABSTRACT

Green leafy vegetables are widely cultivated and consumed in South East Asia. These vegetables are rich in phytochemicals, which have been associated to particular health benefits. Preparation/processing, particularly those involving heat, prior to consumption can change the level of phytochemicals in the vegetables following various mechanisms, including thermal breakdown, oxidation, leaching, and matrix degradation. Appropriate processing should minimize degradation of phytochemicals so that the optimum intake toward health promotion be achieved. Better understanding of how processing influence the retention of phytochemical compounds is therefore crucial to provide guidelines on the processing of green leafy vegetables while maximizing their nutritional values.

KEYWORDS

Green leafy vegetables; phytochemicals; thermal processing; degradation; nutritional values

Introduction

For centuries, green leafy vegetables have been staples in the diets of South East Asian people.^[1] These vegetables contribute significantly to fulfill human nutrition needs. The vegetables contain a substantial amount of protein, carbohydrate, lipids, fibers, minerals, vitamins, and particularly, phytochemical compounds.^[2,3]

Green leafy vegetables are consumed either raw or cooked/processed. Various types of processing are commonly applied to inactivate microorganism and enzymes leading to improved product safety and quality. Processings are also aimed to enhance palatability and to inactivate antinutritional compounds.^[4,5] Thermal processing methods commonly applied to green leafy vegetables are blanching, steaming, boiling, drying, microwave cooking, pressure cooking, and frying. Processing may cause significant changes in nutritional and especially phytochemical content in green leafy vegetables.^[6,7] Different methods of thermal processing can lead to various degree of changes of the phytochemical contents.

Therefore, the selection of an appropriate method to process green leafy vegetables should be critically considered. In this paper, we review the effect of processing methods on the retention of phytochemical compounds in green leafy vegetables. The retention level is calculated from previous publications reporting concentration of the phytochemicals both in the raw and the processed green leafy vegetables. The underlying mechanism leading to changes of phytochemical compounds in green leafy vegetables during processing are discussed by providing thorough information of each processing method, such as

time and temperature, pressure, and amount of water or oil, which lead to the changes via mechanisms of, e.g. cell lysis, matrix degradation, enzyme inactivation, thermal degradation, and oxidation. Previous studies have been reviewed the interaction of processing and bioavailability and bioaccessibility of phytochemicals in vegetables.^[8-11] The mechanism of absorption, distribution, metabolism, and excretion of phytochemicals have also been reviewed.^[7,8,12-15]

Phytochemicals in green leafy vegetables and their potential health benefits

Vegetable consumption has been identified to promote health, e.g. against chronic diseases such as cardiovascular disease, diabetes, obesity, alzheimer, and cancer.^[4,16] These health benefits have been associated to, for example antioxidant and anticarcinogenic activities of phytochemical compounds in vegetables. Key phytochemicals in green leafy vegetables are phenolic compounds,^[17] carotenoids,^[18] chlorophyll,^[19] ascorbic acid,^[20] flavonoids,^[21] and glucosinolates,^[22] which will be briefly discussed in the following subsection.

Polyphenols

The phenolic compound is chemically defined as a compound containing an aromatic ring, which is linked with one or more hydroxyl group.^[23] The number and position of hydroxyl groups affect its ability to scavenge free radicals and chelate metal cations, which can decrease the risk of chronic disease.^[24,25] Total polyphenol concentration in green leafy vegetables varies between 23 and 231 mg GAE/100 g fresh weight (FW) (Table 1). Most of the polyphenols in green leafy vegetables degrade during processing at 100°C or higher.^[6,26,39]

Table 1. Phytochemical compounds in green leafy vegetables.

Phytochemical compounds	Vegetables	Concentration (mg/100 g FW)	References
Total polyphenol	Spinach	23	[26]
	Water spinach	42	[27]
	Celery	35	[28]
	Coriander leaves	42	[26]
	Cassava leaves	50	[29]
	Papaya leaves	231	[30]
	Chinese mustard	63	[31]
Carotenoid	Spinach	2	[32]
	Water spinach	2	[32]
	Coriander leaves	5	[33]
	Drumstick leaves	7	[32]
	Sweet potato leaves	8	[32]
	Lettuce	3	[34]
	Chinese mustard	2	[31]
Chlorophyll	Spinach	1	[20]
	Water spinach	2	[35]
	Celery	4	[36]
	Coriander leaves	4	[36]
	Drumstick leaves	216	[37]
Ascorbic acid	Spinach	69	[20]
	Water spinach	16	[35]
	Celery	3	[38]
	Drumstick leaves	271	[37]
	Cassava leaves	48	[29]
	Papaya leaves	40	[30]
	Chinese mustard	31	[31]

The bioavailability of polyphenols depends on the matrix composition and chemical structure that could be induced by food processing.^[9,12] Food processing causes degradation and modification of cell wall composition that can increase the bioavailability of polyphenols.^[9] The bioactive metabolites could be absorbed into the circulatory system and exert antioxidant activity that gives beneficial effect on human health.^[40] Cory *et al.*^[41] have also reviewed the impact of polyphenols on human health. The antioxidant and anti-inflammatory properties of polyphenols were reported to reduce the risk of cancer, cardiovascular diseases, type 2 diabetes, obesity, and neurodegenerative diseases.

Carotenoids

Carotenoids are oil-soluble yellow-orange pigments that consist of isoprene units linked covalently in either a head-to-tail or tail-and-tail to form a symmetrical molecule.^[20,42] Carotenoids in vegetables are mostly located in chloroplasts and covered by chlorophylls. Therefore, the yellow-orange color of carotenoids becomes more evident when chlorophyll decomposes.^[42] Carotenoids commonly found in plants are in forms of lutein, zeaxanthin, lycopene, β -carotene, α -carotene, and β -cryptoxanthin.^[18] Lutein and β -carotene are the most dominant carotenoids in green vegetables.^[43]

In green leafy vegetables, the carotenoid content ranges between 2 and 8 g/100 g FW (Table 1). Carotenoids are mostly bound to proteins that may decrease their bioavailability. The absorption of carotenoids is also influenced by dietary fat. Dietary fat and bile salt could be bound with the carotenoid to form micelles that allow carotenoid absorption to the intestine. Fortunately, appropriate processing could increase carotenoid bioavailability by breaking down the cell wall and protein-carotenoid complexes. Processing combined with oils also can increase the bioavailability of carotenoids.^[40,43]

The diffusion of carotenoids from the blood circulatory system to various tissues by lipoprotein could provide beneficial effects on human health.^[43] Carotenoids could protect the cellular membranes and lipoproteins against photooxidative damage in plant and human due to their ability to scavenge reactive oxygen species, singlet molecular oxygen, and peroxy radicals. Carotenoids also contribute to macular pigment formation that could absorb harmful blue light. Thus, increased consumption of a diet rich in carotenoids could reduce the risk of diseases such as erythema, cancer, cardiovascular-linked diseases, light blindness, keratomalacia, xerophthalmia, cataract, and macular degeneration.^[44,45]

Chlorophyll

Chlorophyll structurally consists of a porphyrin ring containing a magnesium ion located at the center.^[42] Various levels of chlorophyll in green leafy vegetables were reported, ranging from 1 to 216 mg/100 g FW (Table 1). Heat treatment can lead to the formation of pheophytin because magnesium in chlorophyll can be easily displaced by two hydrogen atoms. The harsher thermal load may eventually remove the carbomethoxy group in chlorophyll to form pirochlorophyll. Further heating can release either magnesium atom in pirochlorophyll or carbomethoxy group in pheophytin to form piropheophytin.^[46]

Interestingly, the conversion of chlorophyll to pheophytin, pyropheophytin, and pheophorbide during processing can increase the bioavailability of chlorophyll. Chao *et al.*^[47] showed that pheophytin and pheophorbide are the main chlorophyll derivatives found in the

human blood, indicating chlorophyll derivatives might be easily absorbed. Chlorophyll derivatives are reported to possess antioxidant, antimutagenic, and anticancer activity.^[48]

Moreover, an in vivo and in vitro study reported chlorophyll could suppress pancreatic cancer cell viability by inhibiting heme oxygenase mRNA expression and enzymatic activity.^[49] Antioxidant activity in chlorophylls and their derivatives can prevent oxidative DNA damage and lipid peroxidation by chelating reactive ions and scavenging free radicals.^[19]

Ascorbic acid

Ascorbic acid, or commonly known as vitamin C that presents mostly in L-ascorbic acid form, is the enolic form of 3-keto-L-glucofuranolactone.^[50] Table 1 shows the broad spread of ascorbic acid content in various green leafy vegetables. Among others, drumstick leaves notably contain the highest level of ascorbic acid, while celery has the lowest.^[20,29-31,35,37,38]

L-ascorbic acid can terminate radical chain reaction, scavenge reactive species, donate an electron to a substrate, and regenerate other antioxidant compounds that may protect DNA and protein from oxidative stress.^[13] Accordingly, ascorbic acid was reported to improve the utilization of iron and prevent cardiovascular diseases, cancer, cataracts, type 2 diabetes, and inflammation due to their antioxidant and antihistamine effects.^[38,51] Unfortunately, ascorbic acid is easily degraded via oxidation reaction, especially when catalyzed by metal ions (i.e. Cu^{2+} and Fe^{3+}). Heat, light, and oxygen may accelerate oxidation.^[42] The enediol groups at carbon atom numbers 2 and 3 are prone to oxidation and can be easily altered to diketone groups. This transforms ascorbic acid to dehydroascorbic acid.^[50] Dehydroascorbic acid is unstable at physiological pH and it is easily converted to 2,3 diketogulonic acid. The alteration of ascorbic acid to dehydroascorbic acid is reversible but the products of the latter oxidation stages are irreversible.^[38] Most ascorbic acid is therefore lost during processing, cooking, and storage.

Glucosinolates

Glucosinolates are a group of secondary plant metabolites in family *Cruciferae* or *Brassicaceae*, such as broccoli, Chinese mustard, pak choi, kale, and cabbage.^[52] A glucosinolate consists of β -D-thioglucoside N-hydroxysulphate, which is a sulphur-linked β -D-glucopyranose moiety and a side chain (R).^[53] Natella, Maldini, Leoni, & Scaccini^[52] reported that glucosinolates have a weak antioxidant capacity. Two glucosinolates, i.e. sinalbin and gluconasturtiin were found to quench ABTS radical and to chelate copper that leads to low-density lipoprotein inhibition, respectively. Nevertheless, isothiocyanates, ones of the derivative products of glucosinolates were reported to play a role as cancer chemo-preventive.^[54,55] Reviews on the effect of thermal processing on glucosinolates in vegetables can be found elsewhere.^[22,56,57]

Processing methods and their impacts on phytochemical compounds in green leafy vegetables

Blanching

During blanching, vegetables are briefly exposed to hot water or steam. It is usually carried out preceding other processes (e.g. freezing, canning, or drying) to inactivate enzymes, modify the textures, and preserve color. Hot water blanching is performed at temperatures

between 70°C and 100°C for 2 to 5 min, followed by rapid cooling. Steam blanching is carried out at 100°C at a considerably shorter time than water blanching because the heat transfer of condensing steam is more efficient than hot water.^[58]

The impact of blanching on phytochemical compounds varies depending on the type of vegetables and the blanching parameters as summarized in [Table 2](#). Hot water blanching reduced phenolic compounds, carotenoids, and flavonoids in water spinach, celery, pak choy, Chinese mustard, black night shade, and jute mallow. Decrease of phenolic compounds, flavonoids, and carotenoid are often associated with thermal degradation, leaching from vegetable tissue into the blanching water^[26,39,60], oxidation reaction, and isomerization.^[61] In contrast, various levels of increase of total phenolic content after blanching have been reported in coriander leaves (36% to 156% after water blanching and 11% to 131% after steam blanching) and nearly eight-fold in basil.^[27,59] Blanching can liberate phenolic compounds such as hydroxycinnamic acid (which is bound to cell polymer and chlorogenic acid), thus improves its extractability upon analytical measurement. Inversely, the prolonged or higher temperature of blanching decreased the retention of total polyphenolic content in coriander leaves.^[59]

Increase of flavonoids bioavailability in spinach and cassava leaves have also been reported.^[62] The underlying mechanisms involve disruption of hydrogen bonding of complex molecules, which then liberates flavonoids from leaf matrices. Blanching for a short time (30 s) increased chlorophyll content in basil and coriander leaves of 23% and 169%, respectively. This short time blanching facilitates the breakdown of organelles that contain phytochemical compounds, while the degradation can be maintained minimal.^[27]

In general, blanching decreases of phytochemical compounds due to oxidation reaction, thermal degradation, enzymatic degradation, and disruption of vegetable tissue which release water-soluble phytochemical compounds into the processing medium. However, this disruption may also lead to higher extractability of the compounds.

Boiling

Boiling is the most common method to cook green leafy vegetables. Cooking affects membrane disruption, loss of turgor, and reduction of cell adhesion strength, which will lead to loss of firmness or softening.^[63] Boiling time of green leafy vegetables may vary, depending on the type of vegetables and consumer preferences in relations to, e.g. texture, color, and taste.^[22,64] From the phytochemical retention perspective, boiling is more suitable for processing vegetables that contain fat-soluble compounds, such as carotenoid, due to less diffusion and leaching into cooking water.^[65,66]

Generally, boiling reduces phytochemicals in vegetables ([Table 3](#)), which is considered higher than that of blanching, and the magnitude is highly varied. Boiling leads leaching of water-soluble phytochemical compounds into the cooking medium.^[39] Thermal degradation of heat-sensitive compounds such as ascorbic acid^[81,85], oxidation, and degradation of, e.g. chlorophyll into their derivatives such as pheophytin further reduces the phytochemical compounds of vegetable subjected to boiling. Acidic cooking condition and longer cooking times facilitate the formation of pheophytin.^[17,79] Leaching and degradation of the phytochemical compounds are higher during boiling than blanching due to the extended time and temperature applied during boiling.^[39,61]

Table 2. The effect of blanching on the phytochemical compounds in green leafy vegetables.

Phytochemical compounds	Vegetables	Method	Temperature	Time (min)	Ratio or Mass	Phytochemical retention (%) ^a	References
Phenolic acid	Celery (<i>Apium graveolens</i>)	Hot water blanching	96–98°C	3	1:10 (vegetable: water)	80	[39]
	Water spinach (<i>Ipomoea aquatica</i>)	Hot water blanching	Boiling water	0.5	1:5 (vegetable: water)	77	[27]
Total polyphenol	Spinach (<i>Spinacea oleracea</i>)		100°C	2	100 g	92	[26]
	Basil (<i>Ocimum basilicum</i>)		Boiling water	0.5	1:5 (vegetable: water)	893	[27]
	Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)		96–98°C	3	1:10 (vegetable: water)	65	[39]
	Coriander leaves (<i>Coriander sativum</i>)		90°C	1, 5, 7, 10	500 g	136–250	[59]
	Coriander leaves (<i>Coriander sativum</i>)		100°C	1, 5, 7, 10	500 g	97–256	[59]
	Coriander leaves (<i>Coriander sativum</i>)		Boiling water	0.5	1:5 (vegetable: water)	91	[27]
	Coriander leaves (<i>Coriander sativum</i>)		100°C	2	100 g	84	[26]
	Pak choi (<i>Brassica rapa</i> var <i>chinensis</i>)		98°C	5	1:5 (vegetable: water)	43	[60]
	Chinese mustard (<i>Brassica juncea</i>)		98°C	15	1:5 (vegetable: water)	37	[60]
			98°C	5	1:5 (vegetable: water)	18	[60]
			98°C	10	1:5 (vegetable: water)	76	[60]
			98°C	15	1:5 (vegetable: water)	46	[60]
			98°C	5	1:5 (vegetable: water)	80	[60]
			98°C	10	1:5 (vegetable: water)	50	[60]
			98°C	15	1:5 (vegetable: water)	45	[60]
Carotenoid	Chinese cabbage (<i>Brassica rapa Pekinensis</i>)		98°C	5	1:5 (vegetable: water)	47	[60]
			98°C	10	1:5 (vegetable: water)	74	[60]
			98°C	15	1:5 (vegetable: water)	122	[60]
	Green cabbage (<i>Brassica oleracea</i> var <i>capitata</i>)		98°C	15	1:5 (vegetable: water)	46	[60]
			98°C	5	1:5 (vegetable: water)	80	[60]
			98°C	10	1:5 (vegetable: water)	50	[60]
			98°C	15	1:5 (vegetable: water)	45	[60]
			98°C	5	1:5 (vegetable: water)	47	[60]
			98°C	10	1:5 (vegetable: water)	74	[60]
			98°C	15	1:5 (vegetable: water)	122	[60]
		100°C	1, 5, 7, 10	500 g	111 – 231	[59]	
Coriander leaves (<i>Coriander sativum</i>)	Steam blanching	100°C	1, 5, 7, 10	500 g	111 – 231	[59]	
Water spinach (<i>Ipomoea aquatica</i>)	Hot water blanching	Boiling water	0.5	1:5 (vegetable: water)	131	[27]	
Spinach (<i>Amaranthus tricolor</i>)		95 ± 3°C	1	1:200 (vegetable: water)	69	[20]	
Basil (<i>Ocimum basilicum</i>)		Boiling water	0.5	1:5 (vegetable: water)	140	[27]	
Coriander leaves (<i>Coriander sativum</i>)		Boiling water	0.5	1:5 (vegetable: water)	169	[27]	
Black nighshade (<i>Solanum scabrum</i> Mill.)		92 °C	2	30 g	72	[61]	
Jute mallow (<i>Corchorus olitorius</i> L.)		92 °C	2	30 g	2	[61]	

Flavonoid	Spinach (<i>Amaranthus viridis</i>)	Hot water blanching	Boiling water	5	2:5 (vegetable: water)	1185	[62]
	Spinach (<i>Spinacea oleracea</i>)		100°C	2	100 g	90	[26]
	Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)		96-98°C	3	1:10 (vegetable: water)	74	[39]
	Cassava leaves (<i>Manihot esculenta</i>)		Boiling water	5	2:5 (vegetable: water)	437	[62]
	Coriander leaves (<i>Coriander sativum</i>)		100°C	2	100 g	68	[26]
	Water spinach (<i>Ipomoea aquatica</i>)	Hot water blanching	Boiling water	0.5	1:5 (vegetable: water)	69	[27]
	Spinach (<i>Amaranthus tricolor</i>)		Boiling water	3, 6, 9, 12, 15	250 g	48-26	[46]
	Spinach (<i>Amaranthustricolor</i>)		95 ± 3°C	1	1:200 (vegetable: water)	57	[20]
	Basil (<i>Ocimum basilicum</i>)		Boiling water	0.5	1:5 (vegetable: water)	123	[27]
	Coriander leaves (<i>Coriander sativum</i>)		Boiling water	0.5	1:5 (vegetable: water)	269	[27]
Ascorbic acid	Spinach (<i>Amaranthus tricolor</i>)	Hot water blanching	95 ± 3°C	1	1:200 (vegetable: water)	33	[20]

^aThe retention level is calculated from the concentration of the phytochemicals both in the raw and the processed green leafy vegetables.



Table 3. The effect of boiling and steaming on the phytochemical compounds in green leafy vegetables.

Phytochemical compounds	Method	Vegetables	Temperature	Time (min)	Amount of water (mL)	Mass (g)	Phytochemical retention ^a	References
Boiling								
Phenolic acid	Boiling	Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water (celery added into water at 70°C)	10	400	100	61%	[39]
Water soluble phenol		Water spinach (<i>Ipomoea aquatica</i>)	Boiling water	5	100	150	181%	[67]
Total polyphenol		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	-	200	121%	[6]
		Water spinach (<i>Ipomoea aquatica</i>)	Boiling water	Cooked until tender	150	100	160 ^b	[68]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	5	300	300	83%	[69]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	Cooked until tender	150	100	145 ^b	[68]
		Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water (celery added into water at 70°C)	10	400	100	59%	[39]
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	20–25	-	2000	290 mg/100 g ^c	[70]
		Drumstick leaves (<i>Moringa oleifera</i>)	Boiling water	5	250	50	165	[71]
		Drumstick leaves (<i>Moringa oleifera</i>)	Boiling water	10	250	50	171	[71]
		Drumstick leaves (<i>Moringa oleifera</i>)	Boiling water	20	250	50	169	[71]
		Sweet potato leaves (<i>Ipomea batatas</i>)	100°C	2	500	100	69%	[72]
		Chinese mustard (<i>Brassica juncea</i>)	100°C	5	140	100	120%	[31]
		Chinese mustard (<i>Brassica juncea</i>)	100°C	13	300	200	137%	[73]
		Tatsoi (<i>Brassica napinosa</i>)	100°C	5	800	300	76%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		3	50	5	25%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		5	50	5	100%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		10	50	5	100%	[74]
Flavonoid		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	-	200	159%	[6]
		Water spinach (<i>Ipomoea aquatica</i>)	Boiling water	Cooked until tender	150	100	155%	[68]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	Cooked until tender	150	100	115 ^b	[68]
		Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water (celery added into water at 70°C)	10	400	100	54%	[39]
		Chinese mustard (<i>Brassica juncea</i>)	100°C	5	140	100	103%	[72]
		Galega Kale (<i>Brassica oleracea</i> var. <i>acephala</i> cv. <i>galega</i>)	100°C	20	200	20	36%	[75]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		30	50	5	33%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		3	50	5	89%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		5	50	5	114%	[74]
		Bush Sorrel (<i>Hibiscus surrattensis</i>)		10	50	5	186%	[74]
Carotenoid		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	-	200	100%	[6]
		Spinach (<i>Basella alba</i>)	Boiling water	2-8	-	20	66%	[76]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	5	50	10	37% ^b	[77]
		Basil (<i>Ocimum basilicum</i>)	100°C	1	200	10	103%	[78]
		Basil (<i>Ocimum basilicum</i>)	Boiling water	2-8	-	20	89%	[76]



Phytochemical compounds	Method	Vegetables	Temperature	Time (min)	Ratio or Mass	Phytochemical retention	References	
Chlorophyll	Steaming	Celery (<i>Apium graveolens</i>)	Boiling water	2-8	-	20	81%	[76]
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	3	-	2	45%	[79]
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	20 – 25	-	2000	38 mg/100 g ^c	[70]
		Coriander leaves (<i>Coriander sativum</i>)	100°C	1	200	10	102%	[78]
		Sweet potato leaves (<i>Ipomea batatas</i>)	100°C	1	200	10	109%	[78]
		Choy sum (<i>Brassica rapa var parachinensis</i>)	100°C	1	200	10	102%	[78]
		Chinese mustard (<i>Brassica juncea</i>)	100°C	13	300	200	78%	[31]
		Black nighthshade (<i>Solanum scabrum</i> Mill.)	100°C	30	2000	30	33%	[61]
		Jute mallow (<i>Corchorus olitorius</i> L.)	100°C	30	2000	30	0%	[61]
		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	-	200	90%	[6]
		Tatsoi (<i>Brassica narinosa</i>)	100°C	5	800	300	99%	[73]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	5	50	10	36% ^a	[77]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	4.5	65	220	75%	[80]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	8	4	1	25%	[81]
		Spinach (<i>Spinacea oleracea</i>)	Boiling water	30	-	4	68%	[82]
		Cassava leaves (<i>Manihot esculenta</i>)	Boiling water	-	-	20	70%	[83]
		Chinese mustard (<i>Brassica juncea</i>)	100°C	13	300	200	31%	[31]
Ascorbic acid	Steaming	Galega Kale (<i>Brassica oleracea var. achepala cv. galega</i>)	100°C	20	200	20	20%	[75]
		Tatsoi (<i>Brassica narinosa</i>)	100°C	30	-	18%	[73]	
		Tatsoi (<i>Brassica narinosa</i>)	100°C	5	800	300	68%	[73]
		Spinach (<i>Amaranthus carentus</i>)	-	10	40 g	-	134%	[84]
		Water spinach (<i>Ipomoea aquatica</i>)	100°C	3-5	2000 g	2000 g	65 mg/100 g ^c	[70]
Phenolic Acid	Steaming	Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	200 g	200 g	75%	[6]
		Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water	10	1:2 (vegetable: water)	-	98%	[39]
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	3-5	2000 g	2000 g	260 mg/100 g ^c	[70]
		Sweet potato leaves (<i>Ipomea batatas</i>)	-	2	100 g	100 g	109%	[17]
		Chinese mustard (<i>Brassica juncea</i>)	Boiling water	7.5	100 g	100 g	96%	[72]
		Chinese mustard (<i>Brassica juncea</i>)	-	8	200 g	200 g	122%	[31]
		Tatsoi (<i>Brassica narinosa</i>)	Boiling water	5	3:1 (vegetable: water)	-	117%	[73]
		Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water	10	1:2 (vegetable: water)	-	93%	[39]
		Spinach (<i>Amaranthus carentus</i>)	-	10	40 g	40 g	125%	[84]
		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	200 g	200 g	62%	[6]
Flavonoid	Steaming	Celery (<i>Apium graveolens</i> , <i>Cryptotaenia japonica</i> Hassk)	Boiling water	10	1:2 (vegetable: water)	-	92%	[39]
		Chinese mustard (<i>Brassica juncea</i>)	Boiling water	7.5	100 g	100 g	66%	[72]
		Galega Kale (<i>Brassica oleracea var. achepala cv. galega</i>)	-	20	1:20 (vegetable: water)	-	90%	[75]
		Galega Kale (<i>Brassica oleracea var. achepala cv. galega</i>)	Boiling water	30	1:20 (vegetable: water)	-	89%	[75]
		Galega Kale (<i>Brassica oleracea var. achepala cv. galega</i>)	Boiling water	30	1:20 (vegetable: water)	-	89%	[75]

(Continued)

Table 3. (Continued).

Phytochemical compounds	Method	Vegetables	Temperature	Time (min)	Amount of water (mL)	Mass (g)	Phytochemical retention ^a	References
Carotenoid		Water spinach (<i>Ipomoea aquatica</i>)	100°C	3–5	2000 g		20 mg/100 gc	[70]
		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	200 g		60%	[6]
		Drumstick leaves (<i>Moringa oleifera</i>)	110°C	15	2 g		93%	[79]
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	3–5	2000 g		39 mg/100 g ^c	[70]
		Chinese mustard (<i>Brassica juncea</i>)	–	8	200 g		77%	[31]
		Water spinach (<i>Ipomoea aquatica</i>)	100°C	2	200 g		90%	[6]
Chlorophyll		Spinach (<i>Spinacea oleracea</i>)	Boiling water	7.5, 15, 30, 45, 60	250 g		25 6%	[46]
		Tatsoi (<i>Brassica narinosa</i>)	Boiling water	5	3:1 (vegetable: water)		98%	[73]
Ascorbic acid		Spinach (<i>Spinacea oleracea</i>)	Boiling water	8	1 g		66%	[81]
		Spinach (<i>Amaranthus carentus</i>)	–	10	40 g		71%	[84]
		Tatsoi (<i>Brassica narinosa</i>) ⁶⁶⁶	Boiling water	5	3:1 (vegetable: water)		81%	[73]
		Galega Kale (<i>Brassica oleracea</i> var. <i>achepala</i> cv. <i>galega</i>)	–	20	1:20 (vegetable: water)		78%	[75]
				30			66%	

^aThe retention level is calculated from the concentration of the phytochemicals both in the raw and the processed green leafy vegetables.

^bNumbers are estimated from the data reported in the graphs.

^cNo data on the amount of phytochemical compounds before processing

In contrast, Ng *et al.*^[67] reported that the concentration of water-soluble polyphenol compounds in boiled water spinach was 81% higher as compared to the ones in raw spinach.^[67] Boiling notably increased total polyphenol and flavonoid contents in water spinach, drumstick leaves, and Chinese mustard.^[6,71,72] Accordingly, a slight increase of β -carotene after boiling was found in basil, coriander leaves, sweet potato leaves, and pak choi.^[78]

Similar to blanching, the increase of phytochemical compounds is likely an artifact due to the softening of the vegetable matrix due to heat, which subsequently increases extractability.^[71,74] An *in vitro* study reported that boiling could enhance the extractability of polyphenols in *Bidens pilosa* leaf matrix. Although bioaccessibility of polyphenols reduced after duodenal digestion, polyphenols still have sufficient antioxidant activity to protect cells from oxidative damage.^[66] Gehse *et al.*^[86] also reported short boiling time (less than 10 min) could increase the bioavailability of carotenoid in vegetables. This is due to disruption of the carotenoid-protein complexes, inactivation of carotenoid oxidizing enzymes,^[78] the formation of secondary plant metabolites, destruction of complex phenolics,^[6,66,69] and release of active aglycones from flavonoid conjugates.^[67]

Steaming

Steaming is probably the most appropriate cooking method to retain water-soluble phytochemical compounds in vegetables.^[75,81] This is due to the fact that during steaming vegetables are actually not in direct contact with water.^[87] Loss of nutritional contents after steaming is, however, still observed in green leafy vegetables (Table 3). Thi & Hwang^[6] reported that steaming at temperature 100°C for 2 min reduced the concentration (in dry weight basis) of polyphenol, flavonoid, carotenoid, and chlorophyll in water spinach. Minor loss of carotenoid in drumstick leaves,^[79] total polyphenol and flavonoid in celery,^[39] and ascorbic acid in tatsoi^[73] were also observed. Thermal degradation is suspected of playing a major role in the loss of phytochemical compounds during steaming.^[6,79,84]

Teng & Chen^[46] reported a slight increase in chlorophyll degradation in spinach with heating time and temperature. The formation of pheophytin (a marker of chlorophyll degradation) is higher during wet heating methods (steaming, blanching) than dry heating methods (baking, microwaving cooking). This is probably because the liberation of organic acids from the leaf matrices due to moist heat are greater than due to dry heat. Moreover, higher heating time and temperature may facilitate the removal of the carbo-methoxy group from chlorophyll.^[46]

In contrast, an increase of total polyphenol concentration in sweet potato leaves (by about 9%) and in spinach (34%) and increase of flavonoid compounds in spinach (25%) after steaming have been also reported.^[17] It is likely that the strength of the cell walls influences the amount of extracted phytochemicals after steaming.^[88] It was reported that the breakdown of cell wall due to heating might promote the release of phenolic compounds from vegetable tissue^[84] and the breakdown of complex structures, thus liberating the phenolic compounds.^[17]

Yao and Ren^[39] reported that steaming retains more polyphenol, phenolic acid, and flavonoid in celery than blanching or boiling. In steaming, direct contact between vegetables tissue and water is avoided, which significantly minimize losses of water-soluble phytochemical compounds through leaching. Steaming may also increase the bioaccessibility of

micronutrients such as lutein, β -carotene, and α -tocopherol through cell ruptures.^[79] Breakdown of cellulose structure and denaturation of carotenoid-protein complexes may be responsible for the increase of carotenoid content of vegetables after steaming.^[6]

Drying

Drying is often applied to increase shelf life by preventing the microbial growth and enzymatic reaction through the reduction of water content and water activity.^[89] Proper selection of appropriate drying methods is crucial to retain aroma, appearance, and nutritional characteristics^[90,91] while optimizing the energy (cost) efficiency.^[92–94] Various drying methods are commonly applied to green leafy vegetables, such as shade drying, sun drying, oven drying, cabinet drying, and freeze-drying.^[95]

During shade drying, significant reduction of ascorbic acid in drumstick leaves, papaya leaves, and spinach was reported. To a lesser degree, shade drying also reduced the availability of carotenoid and flavonoid content.^[20,30,96] During shade drying, despite carried out at relatively low temperatures (30–35°C), long drying time (1–3 weeks) significantly decreased phytochemical contents in vegetables.^[20,97] Shorter drying time during oven drying and the absence of thermal load during freeze-drying ensured a lower degree of thermally induced degradation of heat-sensitive chlorophylls.^[30] In contrast, the increase of available chlorophyll of 147% and carotenoid of 36% has been reported for shade drying of spinach.^[20] Raja *et al.*^[30] also reported the increase of total phenolic content in papaya leaves between 6% and 15% after shade drying. This could be due to the formation of new products from maillard reaction during heating.^[98]

Sun drying has been reported to decrease phytochemical compounds (phenolic, flavonoid, carotenoid, ascorbic acid, and chlorophyll) in green leafy vegetables ranging from 35% to 100% (Table 4). Sriwichai *et al.*^[79] reported a 63% decrease of carotenoid content in drumstick leaves upon sun drying, which is more severe than that of steaming, freezing, and sterilization. Direct light exposure is hypothesized to induce the oxidation reaction of heat-sensitive phytochemical compounds in green leafy vegetables.^[37] Moreover, grinding prior to drying can increase the contact area of vegetable and air/light, which subsequently increases the rate of autooxidation.^[79,109]

Speek *et al.*^[76] reported the decrease of carotenoid in spinach (51%) and basil (55%) after sun drying, which likely relates to decomposition and trans-cis isomerization of carotenoid. During sun drying, chlorophyll may be transformed into pheophytin via the displacement of magnesium by a hydrogen atom. Chlorophyll A is more susceptible to thermal degradation than chlorophyll B. Thus, after sun drying the decrease of chlorophyll A is usually more pronounced than chlorophyll B.^[35]

After sun drying total polyphenol, carotenoid, and chlorophyll in spinach increased by 223%,^[100] 5%^[20] and 109%,^[20] respectively. Similarly, a dramatic increase of total polyphenol in cassava leaves and chlorophyll in water spinach after drying has been reported.^[20,29,100] This may be explained by the increase of dry solid in the vegetable matrices,^[110] increase extractable carotenoid via release from matrix cell,^[18,35] and/or breakdown of the cell wall during drying, which disturbs the bond of phenolic compounds.^[97]

After oven drying, most of the phytochemical compounds (phenolic, flavonoid, carotenoid, chlorophyll, and ascorbic acid) in green leafy vegetables decreased between 4% and 100% (Table 4). Saini *et al.*^[37] reported that cabinet drying of drumstick leaves decreased



Table 4. The effect of drying on the phytochemical compounds of green leafy vegetables.

Phytochemical compounds	Method	Vegetables	Temperature or Power	Time	Mass (g)	Phytochemical retention ^a	References	
Total Polyphenol	Shade drying	Drumstick leaves (<i>Moringa oleifera</i>)	Shade place	1 week	-	9535 mg/100 g ^c	[99]	
		Coriander leaves (<i>Coriander sativum</i>)	Shade place (35°C)	2 days	500	78% ^b	[36]	
	Sun drying	Papaya leaves (<i>Carica papaya</i>)	28°C	3 days	500	106%	[30]	
		Papaya leaves (<i>Carica papaya</i>)	28°C	3 days	500	115%	[30]	
		Spinach (<i>Amaranthus carentus</i>)	Sunlight	1 week	-	323%	[100]	
	Oven drying	Drumstick leaves (<i>Moringa oleifera</i>)	Sun light	2–3 days	2000	65%	[37]	
		Cassava leaves (<i>Manihot esculenta</i>)	35–38°C	3 days	250	520% ^b	[29]	
	Cabinet drying	Spinach (<i>Spinacea oleracea</i>)	50 ± 2°C	3 days	250	70 mg/g ^c	[101]	
		Celery (<i>Apium graveolens</i>)	48°C	60 minutes	-	114% ^b	[102]	
		Drumstick leaves (<i>Moringa oleifera</i>)	50°C	12.5 hours	2	83%	[103]	
		Drumstick leaves (<i>Moringa oleifera</i>)	100°C	2.5 hours	2000	96% ^b	[37]	
		Drumstick leaves (<i>Moringa oleifera</i>)	50°C	12 hours	2000	58%	[36]	
		Coriander leaves (<i>Coriander sativum</i>)	70°C	4 hours	500	65% ^b	[36]	
		Coriander leaves (<i>Coriander sativum</i>)	50 ± 2°C	-	-	-	22 mg/g ^c	[101]
		Papaya leaves (<i>Carica papaya</i>)	40°C	7 hours	-	-	162%	[30]
Papaya leaves (<i>Carica papaya</i>)		40°C	7 hours	-	-	164%	[30]	
Spinach (<i>Spinacea oleracea</i>)		60°C	10–12 hours	100	97%	[26]		
Flavonoid	Cabinet drying	Drumstick leaves (<i>Moringa oleifera</i>)	50°C	6 hours	2000	61%	[37]	
		Coriander leaves (<i>Coriander sativum</i>)	60°C	10–12 hours	100	57%	[26]	
	Microwave drying	Drumstick leaves (<i>Moringa oleifera</i>)	850 W	30 seconds	2000	59%	[37]	
		Coriander leaves (<i>Coriander sativum</i>)	100°C	3 minutes	500	57% ^b	[36]	
	Freeze drying	Drumstick leaves (<i>Moringa oleifera</i>)	-35°C, 0.312 mbar	24 hours	2000	58%	[37]	
		Papaya leaves (<i>Carica papaya</i>)	-100°C, 0.001 mbar	24 hours	2000	147% ^b	[30]	
	Oven drying	Drumstick leaves (<i>Moringa oleifera</i>)	Shade place	1 week	-	6543 mg/100 g ^c	[99]	
		Celery (<i>Apium graveolens</i>)	48°C	60 minutes	-	40%	[102]	

(Continued)



Table 4. (Continued).

Phytochemical compounds	Method	Vegetables	Temperature or Power	Time	Mass (g)	Phytochemical retention ^a	References
Carotenoid	Cabinet drying	Kenikir leaves (<i>Cosmos caudatus</i>)	60°C	-	-	78%	[104]
		Spinach (<i>Spinacea oleracea</i>)	60°C	10-12 hours	100	89%	[26]
		Coriander leaves (<i>Coriander sativum</i>)	60°C	10-12 hours	100	59%	[26]
Carotenoid	Shade drying	Spinach (<i>Amaranthus tricolor</i>)	-	Until the vegetables contain 7-9% moisture	-	136%	[20]
		Drumstick leaves (<i>Moringa oleifera</i>)	Room temperature	6 days	100	183%	[91]
		Coriander leaves (<i>Coriander sativum</i>)	Shade place (35°C)	2 days	500	52% ^b	[36]
		Black nighshade (<i>Solanum scabrum</i> Mill.)	25.8-31.4 °C		30 g	11%	[61]
		Jute mallow (<i>Corchorus olitorius</i> L.)	25.8-31.4 °C		30 g	2%	[61]
		Spinach (<i>Amaranthus tricolor</i>)	Sun light	2 days	-	49%	[76]
		Spinach (<i>Amaranthus tricolor</i>)	Sun light	Until the vegetables contain 7-9% moisture	-	105%	[20]
		Basil (<i>Ocimum basilicum</i>)	Sun light	2 days	-	45%	[76]
		Drumstick leaves (<i>Moringa oleifera</i>)	Sun light	2-3 days	2000	53%	[37]
		Drumstick leaves (<i>Moringa oleifera</i>)	30°C	8 hours	2	37%	[79]
Carotenoid	Oven drying	Drumstick leaves (<i>Moringa oleifera</i>)	Sun light	4 days	100	187%	[91]
		Cassava leaves (<i>Manihot esculenta</i>)	35-38°C	3 days	250	3% ^b	[29]
		Drumstick leaves (<i>Moringa oleifera</i>)	60-80°C	24 hours	-	36 - 17 mg/100 g ^c	[105]
		Drumstick leaves (<i>Moringa oleifera</i>)	50°C	12 hours	2000	58%	[37]
		Drumstick leaves (<i>Moringa oleifera</i>)	60°C	3 hours	2	81%	[79]
		Drumstick leaves (<i>Moringa oleifera</i>)	60°C	4-5 hours	100	182%	[91]
		Coriander leaves (<i>Coriander sativum</i>)	70°C	4 hours	500	34% ^b	[36]
		Coriander leaves (<i>Coriander sativum</i>)	45 ± 2°C	24 hours	5-10	65%	[106]
		Black nighshade (<i>Solanum scabrum</i> Mill.)	50 °C		30 g	7%	[61]



	Jute mallow (<i>Corchorus olitorius</i> L.)	60 °C				7%	[61]
		50 °C			30 g	0%	
		60 °C				0%	[20]
Cabinet drying	Spinach (<i>Amaranthus tricolor</i>)	65 ± 5°C	Until the vegetables contain 7-9% moisture			304%	
	Drumstick leaves (<i>Moringa oleifera</i>)	50°C	6 hours	2000		60%	[37]
Microwave drying	Drumstick leaves (<i>Moringa oleifera</i>)	850 W	30 seconds	2000		48%	[37]
	Coriander leaves (<i>Coriander sativum</i>)	100°C	3 minutes	500		17% ^b	[36]
	Coriander leaves (<i>Coriander sativum</i>)	180, 300, 450, 600, 850 W	30-90 seconds	5-10		135-140%	[106]
Freeze drying	Drumstick leaves (<i>Moringa oleifera</i>)	-35°C, 0.312 mbar	24 hours	2000		61%	[37]
	Drumstick leaves (<i>Moringa oleifera</i>)	-40°C	24 hours	2		64%	[79]
Shade drying	Spinach (<i>Amaranthus tricolor</i>)	-	Until vegetables contain 7-9% moisture			247%	[20]
	Coriander leaves (<i>Coriander sativum</i>)	35°C	2 days	500		41% ^b	[36]
Sun drying	Water spinach (<i>Ipomoea aquatica</i>)	Sun light (27-32°C)	48 hours	1000		221% ^b	[35]
	Spinach (<i>Amaranthus tricolor</i>)	Sunlight	Until the vegetables contain 7-9% moisture			209%	[20]
	Drumstick leaves (<i>Moringa oleifera</i>)	Sun light	2-3 days	2000		65%	[37]
Oven drying	Water spinach (<i>Ipomoea aquatica</i>)	65 ± 5°C	12 hours	1000		226%	[35]
	Drumstick leaves (<i>Moringa oleifera</i>)	50°C	12 hours	2000		65%	[37]
	Coriander leaves (<i>Coriander sativum</i>)	70°C	4 hours	500		36% ^b	[36]
	Coriander leaves (<i>Coriander sativum</i>)	45 ± 2°C	24 hours	5-10		35% ^c	[106]
Cabinet drying	Basil (<i>Ocimum basilicum</i>)	50°C	4.5 hours	18		13%*	[107]
	Spinach (<i>Amaranthus tricolor</i>)	65 ± 5°C	Until the vegetables contain 7-9% moisture			144%	[20]
	Drumstick leaves (<i>Moringa oleifera</i>)	50°C	6 hours	2000		70%	[37]
	Coriander leaves (<i>Coriander sativum</i>)	45, 50, 55, 60 and 65 ± 1°C	3 minutes	2000		1-3 mg/Lc	[108]

(Continued)



Table 4. (Continued).

Phytochemical compounds	Method	Vegetables	Temperature or Power	Time	Mass (g)	Phytochemical retention ^a	References
	Microwave drying	Basil (<i>Ocimum basilicum</i>)	1100 W	5 minutes	18	29% ^b	[107]
		Drumstick leaves (<i>Moringa oleifera</i>)	850 W	30 seconds	2000	56%	[37]
	Freeze drying	Coriander leaves (<i>Coriander sativum</i>)	100°C	3 minutes	500	9%	[36]
		Water spinach (<i>Ipomoea aquatica</i>)	-	72 hours	1000	272%	[35]
		Basil (<i>Ocimum basilicum</i>)	-35°C - 20°C	72 hours	18	16% ^{bb}	[107]
		Drumstick leaves (<i>Moringa oleifera</i>)	-35°C, 0.312 mbar	24 hours	2000	74%	[37]
Ascorbic acid	Shade drying	Spinach (<i>Amaranthus tricolor</i>)	-	Until the vegetables contain 7-9% moisture	-	78%	[20]
	Sun drying	Papaya leaves (<i>Carica papaya</i>)	28°C	3 days	-	25-63% ^b	[30]
		Water spinach (<i>Ipomoea aquatica</i>) Spinach (<i>Amaranthus tricolor</i>)	Sunlight (27-32°C) Sunlight	48 hours	1000	49%	[35]
	Oven drying	Spinach (<i>Amaranthus crenatus</i>)	Sunlight	moisture	-	46%	[20]
		Drumstick leaves (<i>Moringa oleifera</i>)	Sunlight	1 weeks	-	63%	[100]
		Cassava leaves (<i>Manihot esculenta</i>)	35-38°C	2-3 days	2000	38%	[37]
		Water spinach (<i>Ipomoea aquatica</i>) Celery (<i>Apium graveolens</i>) Drumstick leaves (<i>Moringa oleifera</i>)	65 ± 5°C 48°C 60-80°C	3 days 12 hours 60 minutes 24 hours	250 1000 - -	0% ^b 82% 94% 450 - 436 µm/100 g ^c	[29] [35] [102] [105]
	Cabinet drying	Papaya leaves (<i>Carica papaya</i>)	50°C	12 hours	2000	40%	[37]
		Spinach (<i>Amaranthus tricolor</i>)	40°C 65 ± 5°C	7 hours	- -	72-78% ^b 104%	[30] [20]
	Microwave drying	Drumstick leaves (<i>Moringa oleifera</i>)	50°C	moisture 6 hours	2000	44%	[37]
		Drumstick leaves (<i>Moringa oleifera</i>)	850 W	30 seconds	2000	64%	[37]
	Freeze drying	Water spinach (<i>Ipomoea aquatica</i>)	-	72 hours	1000	346%	[35]
		Drumstick leaves (<i>Moringa oleifera</i>)	-35°C, 0.312 mbar	24 hours	2000	98%	[37]
		Papaya leaves (<i>Carica papaya</i>)	-100°C, 0.001 mbar	24 hours	-	82% ^b	[30]

^aThe retention level is calculated from the concentration of the phytochemicals both in the raw and the processed green leafy vegetables.

^bNumbers are estimated from the data reported in the graphs.

^cNo data on the amount of phytochemical compounds before processing.

total polyphenol, carotenoid, chlorophyll, and ascorbic acid. Cabinet tray drying was also reported to decrease total polyphenol and flavonoid in spinach and in coriander leaves.^[26]

The retention of chlorophyll A and B is higher during cabinet drying than oven drying, thus cabinet drying produces the dark green color of the powder, which consumers prefer to choose. It is mostly due to forced convection of heated air in the cabinet dryer which can reduce the drying time.^[37]

Carotenoids retention in vegetables was higher after oven drying than after sun drying because the closed condition in oven drying mitigates the risk of photooxidation.^[18] Compared to shade drying, the decrease of total polyphenol, carotenoid, and chlorophyll in coriander leaves^[36] and β -carotene of black nightshade and jute mallow leaves^[61] after oven drying was higher, which relate to the imposed thermal load. High drying temperature needs to be avoided to mitigate trans-cis isomerization of β -carotene and lutein. The provitamin activity of the cis- form of carotenoid is lower than the trans- form.^[37,61,79]

Drying at 60°C decreased flavonoid content in *kenikir* (*Cosmos caudatus*) leaves because the increase of flavonoid degrading enzyme activity such as polyphenoloxidase enzyme.^[104] However, the enzyme activity could be reduced by drying at temperatures higher than 70°C. The content of phytochemical compounds in vegetables can also have further losses during storage.^[102] Grinding could increase the surface area of the dried product that leads to further losses through autooxidation. Therefore, dried or powdered vegetables must be protected from air and light.^[37]

Wangcharoen & Gomolmanee^[103] reported that drying of drumstick leaves at 50°C decreases total phenolic contents in vegetables. However, when drying was performed at a higher temperature (100°C), phenolic contents initially decrease then increase again in the later stage. The fluctuation of total phenolic contents could be due to the formation of new antioxidant compounds of non-enzymatic browning and due to thermal degradation of insoluble and bound phenolic compounds that occurs at high temperature. Raja *et al.*^[30] also observed the formation of maillard products formed due to heat treatment, which increased total phenolic contents in papaya leaves between 6% and 64%. Similarly, Negi & Roy^[20] reported that drying could increase carotenoid and vitamin C in spinach. This relates to the increase of solid fraction, thus concentrating the phytochemical compounds.^[26]

Table 4 shows that most of the phytochemical compounds in vegetables decreased during microwave drying ranging between 36% and 91%, which was more pronounced than that of oven-, freeze-, or cabinet drying.^[36,37,107] This might be due to the imposed higher temperature during microwave drying than the other drying methods. Dev *et al.*^[111] also reported that the color change of drumstick leaves was more severe after microwave drying than that of oven drying. Retention of chlorophyll was however higher after microwave drying than after air drying. The degradation of chlorophyll pigment to pheophytin is shown by color transformation from bright green to olive brown. The formation of pheophytin was affected by the liberation of plant acid compounds and the release of chlorophyll from protein complex.^[107] Divya *et al.*^[106] found that microwave drying increased carotenoid in coriander leaves ranging from about 35% to 40%. This is due to heating that could liberate carotenoid bound to membranes and other pigments, such as chlorophyll. This study found no trans-cis isomerization of β -carotene during microwave drying.

Lyophilization or freeze drying is a dehydration process that involves freezing then sublimation of ice. Freeze drying is slower and more energy intensive than another conventional drying.^[92,112] Freeze drying was reported to decrease total polyphenol,

carotenoid, chlorophyll, and ascorbic acid in drumstick leaves.^[37] Other studies also reported the decrease of ascorbic acid in papaya leaves and chlorophyll in basil.^[79,107] Formation of ice crystal can damage cell walls and release oxidative- and hydrolytic-enzymes, which degrade phytochemicals such as phenolic compounds.^[30]

Compared to other drying methods, freeze drying remains the best method to retain trans-lutein, trans-luteoxanthin, trans- β -carotene, total carotenoid, α -tocopherol, ascorbic acid, chlorophyll A, and chlorophyll B.^[37] Increase of total phenolic contents in papaya leaves, and chlorophyll and ascorbic acid in water spinach have also been reported.^[30,35] It is believed that the use of low temperature during freeze-drying prevents thermal degradation of these heat sensitive compounds.^[110] Furthermore, the formation of ice crystals can rupture cell walls, thus allowing the release of cellular components, which consequently improves extractability.^[97]

Microwave cooking

Water is often added during microwave cooking of vegetables. This may lead to leaching of water-soluble phytochemical compounds.^[67,69] Microwave cooking has been reported to decrease chlorophyll contents in spinach^[46] and tatsoi.^[73] Induced by heat, the removal of magnesium or carbomethoxy group from chlorophylls may occur to form pheophytins and may subsequently transform to pirochlorophylls. Microwave cooking reduced phenolic compounds in water spinach,^[67] drumstick leaves,^[113] sweet potato leaves,^[17] Chinese mustard^[72], tatsoi,^[39] and bush sorrel.^[74] Microwave cooking also reduced a significant amount of flavonoid,^[72] carotenoid,^[31] and ascorbic acid^[31] in Chinese mustard, and chlorophyll and ascorbic acid in tatsoi.^[39] Thermal breakdown, leaching (when water is added during cooking), and oxidation are the responsible mechanisms of phytochemical degradation during microwave cooking.^[31,67,69,113]

In contrast, increase of total polyphenols in Chinese mustard^[31] and drumstick leaves,^[71] ascorbic acid in spinach,^[80] and flavonoid in drumstick leaves have been reported.^[80] Breakdown of cell walls and complex phenolic compounds during heating may increase the availability of these phytochemical compounds.^[71,74,80,114]

Pressure cooking

Employing high pressure enables cooking at temperatures higher than the normal boiling point of water. Heat sensitive phytochemicals are better retained because cooking time can be considerably reduced. However, water-soluble phytochemical compounds may be leached due to the presence of added water during pressure-cooking.^[67] Veda *et al.*^[33] reported that pressure-cooking at 15 psi for 10 min decreased carotenoid in spinach, in drumstick leaves, and in coriander leaves. Pressure-cooking also decreased carotenoid and ascorbic acid content in Chinese mustard by about 13% and 69%, respectively^[31], which likely relates to leaching, oxidation, and formation of cis isomers from all trans- β -carotene.^[33]

Pressure cooking, however, has been reported to increase total phenolic concentration in Chinese mustard^[31] and in drumstick leaves.^[115] This is likely due to the softening of vegetable matrices that improve extractability, the liberation of phenolic compounds from pectin or cellulose networks, the formation of secondary plant metabolites, inactivation of

oxidative enzymes (e.g. polyphenol oxidase), and release of active aglycones from flavonoid conjugates during heating.^[67,114,115]

Frying

Frying is performed by increasing the surface temperature of food and then vaporizing a proportion of water.^[112] Based on the media for heat transfer, frying can be categorized into frying in oil (stir frying and deep frying) and frying with the addition of water such as stewing and sauteing.^[32] Frying is usually applied at high temperatures to maximize the heat transfer.

Frying generally decreased carotenoid content in basil leaves, drumstick leaves, coriander leaves, sweet potato leaves, and pak choi (Table 5). The decrease of β -carotene in vegetables was reported to be higher in deep fat frying than in shallow contact frying.^[33] This may relate to degradation or isomerization of carotenoids, the release of carotenoids to oil, and cell disruption during frying.^[65,79] Moreover, the release of carotenoid into oil is affected by the amount of oil, frying time, location, and chemical and physical structure of carotenoid.^[32]

Frying, especially stir-frying, could increase the availability of β -carotene in water spinach and spinach.^[33] The presence of oil during frying may improve the bioaccessibility of β carotene and the loosening of food matrices facilitates carotenoid absorption.^[11,32,33] Sun *et al.*^[17] found a 16% reduction of total phenolic concentration in sweet potato leaves due to the breakdown of phenolic compounds during processing. Frying also decreased phenolic compounds in spinach by 17%, bush sorrel by 29-39%, and tatsoi by 4% likely due to decomposition and liberation of phenolic compounds.^[69,73,74] On the contrary, frying has been found to increase considerably the total polyphenol and flavonoid contents in drumstick leaves, spinach, water spinach, and Chinese mustard and, to a lesser degree, increased ascorbic acid availability. Previous studies suggested that the apparent increase of these phytochemical compounds can be related to the breakdown of the cell wall and softening vegetable tissues, thus liberating the phytochemical compounds and making it more accessible. Other mechanisms include inactivation of oxidative enzymes, thus minimizing the risk of the enzyme rendering phytochemicals into, e.g. its inactive form.^[33,68,73,114,116]

Conclusion

Changes of phytochemical compounds in vegetables during cooking/processing are influenced by various factors such as characteristics of the compounds, type of vegetables, and processing methods. Loss of phytochemical compounds during blanching, boiling, microwave cooking, and pressure cooking of green leafy vegetables are often found related to leaching and thermal degradation. Significant losses during frying and drying could be due to the thermal degradation, oxidation reaction, and isomerization of phytochemical structures. Steaming can be the most suitable method to retain phytochemical compounds because of the low impact on thermal degradation, oxidation reaction, and leaching of water-soluble phytochemical compounds, such as polyphenols and ascorbic acid. Increase the bioavailability of phytochemical compounds in vegetables during processing is due to the breakdown of complex bound, cell wall disruption, and inactivation of oxidation enzymes. Processing should therefore be optimized to minimize the loss of phytochemical compounds.



Table 5. The effect of microwave cooking, pressure cooking, and frying on the phytochemical compounds of green leafy vegetables.

Phytochemical compounds	Method	Vegetables	Power (W)	Times (minutes)	Amount of water (mL)	Mass (g)	Phytochemical retention (%) ^a	References
Total polyphenol	Microwave cooking	Drumstick leaves (<i>Moringa oleifera</i>)	-	5	60	100	88	[113]
		Drumstick leaves (<i>Moringa oleifera</i>)	1000	5	250	50	165	[71]
		Drumstick leaves (<i>Moringa oleifera</i>)	1000	10	250	50	153	[71]
		Drumstick leaves (<i>Moringa oleifera</i>)	1000	20	250	50	166	[71]
		Sweet potato leaves (<i>Ipomea batatas</i>)	1000	2	-	100	74	[17]
		Chinese mustard (<i>Brassica juncea</i>)	550	5	150	100	81	[72]
		Chinese mustard (<i>Brassica juncea</i>)	-	5	10	200	107	[31]
		Bush Sorrel (<i>Hibiscus surattensis</i>)	300	3	50	5	116	[74]
				5			70	
				10			112	
				5			96	
				5			87	
		Water soluble phenolic	Microwave cooking	Tatsoi (<i>Brassica narinosa</i>)	450	5	10	300
Water spinach (<i>Ipomoea aquatica</i>)	1000			5	100	150	87	[67]
Spinach (<i>Spinacea oleracea</i>)	500			5	12	200	110	[69]
Drumstick leaves (<i>Moringa oleifera</i>)	-			5	60	100	105	[113]
Chinese mustard (<i>Brassica juncea</i>)	550			5	150	100	90	[72]
Bush Sorrel (<i>Hibiscus surattensis</i>)	300			3	50	5	127	[74]
				5			102	
				10			106	
				5			70	
				5			82	
Carotenoid	Microwave cooking	Chinese mustard (<i>Brassica juncea</i>)	-	5	10	200	70	[31]
		Spinach (<i>Spinacea oleracea</i>)	700	1	-	50	82	[46]
				9			39	
				5			70	
Chlorophyll	Microwave cooking	Tatsoi (<i>Brassica narinosa</i>)	450	5	10	300	70	[73]
		Spinach (<i>Spinacea oleracea</i>)	750	2.5	-	240	106	[80]
		Chinese mustard (<i>Brassica juncea</i>)	-	5	10	200	27	[31]
		Tatsoi (<i>Brassica narinosa</i>)	450	5	10	300	78	[73]
Ascorbic acid	Microwave cooking	Water spinach (<i>Ipomoea aquatica</i>)	121°C, 2 mPa	20	100	150	101	[67]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	-	1000	-	128	[115]
		Chinese mustard (<i>Brassica juncea</i>)	-	4	150	200	135	[31]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	7	80	100	120	[113]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	-	1000	-	92	[115]
Phytochemical compounds	Pressure cooking	Water spinach (<i>Ipomoea aquatica</i>)	121°C, 2 mPa	20	100	150	101	[67]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	-	1000	-	128	[115]
		Chinese mustard (<i>Brassica juncea</i>)	-	4	150	200	135	[31]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	7	80	100	120	[113]
		Drumstick leaves (<i>Moringa oleifera</i>)	-	-	1000	-	92	[115]

Table 5. (Continued).

Phytochemical compounds	Method	Vegetables	Power (W)	Times (minutes)	Amount of water (mL)	Mass (g)	Phytochemical retention (%) ^a	References
		Basil (<i>Ocimum bacillicum</i>)	190	1	-	10	51	[78]
		Drumstick leaves (<i>Moringa oleifera</i>)	100	10	185 mg groundnut oil	2	58	[33]
		Drumstick leaves (<i>Moringa oleifera</i>)	180	3	-	2	21	[79]
		Coriander leaves (<i>Coriander sativum</i>)	100	10	185 mg groundnut oil	2	61	[33]
		Coriander leaves (<i>Coriander sativum</i>)	190	1	-	10	53	[78]
		Sweet potato leaves (<i>Ipomea batatas</i>)	190	1	-	10	42	[78]
		Pak choy (<i>Brassica rapa</i> var <i>parachinensis</i>)	190	1	-	10	48	[78]
Chlorophyll		Tatsoi (<i>Brassica narinosa</i>)	130	5	10 mL blend oil	300	63	[73]
Ascorbic acid		Tatsoi (<i>Brassica narinosa</i>)	130	5	10 mL blend oil	300	75	[73]

^aThe retention level is calculated from the concentration of the phytochemicals both in the raw and the processed green leafy vegetables.

^bNumbers are estimated from the data reported in the graphs.

Declarations of Interest

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