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Vitamin retention during blanching of vegetables

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The role of vegetables as sources of vitamins in the diet is highlighted and the UK consumption of processed vegetables is summarised. The average vitamin contents of nine vegetables are given, together with typical losses incurred during boiling in water. The influence of the different types of blanching on vitamin losses is discussed, with reference to some of the many studies done since the 1940s. The main mechanisms of loss, namely thermal destruction, enzymic oxidation and primarily leaching, are discussed using the examples of thiamin, folic acid and vitamin C, and the main factors influencing these mechanisms are summarised. The determination of diffusion coefficients and the calculation of mass transfer of vitamin C are included to demonstrate how leaching losses from vegetables can be predicted for a given set of conditions. It is concluded that well-controlled blanch systems can contribute to the overall retention of vitamins within frozen vegetable products.

INTRODUCTION

Vegetables have a role as an indispensable part of a properly balanced nutritious diet. Potatoes still remain central to the UK diet; however, during the last 40 years consumption has declined to just under half the total vegetable consumption of around 80 oz per person per week (1 oz ≈ 28 g). Also, there has been some move away from traditional vegetables such as cabbage, Brussels sprouts and root vegetables. The 1960s saw technology enable a surge in the consumption of frozen vegetables. In recent years the trend has been towards other fresh green and leafy salad vegetables, with an increasing range of new and exotic varieties. Hence, while the total weight of vegetables, excluding potatoes, has increased only slowly, the proportion of total household food expenditure has increased from around 7% in the mid-1960s to nearly 12% today (MAFF, 1991).

The average UK household consumption of processed vegetables during 1990 is shown in Table 1 and, as such, this provided almost half the reference nutrient intakes for vitamin C, and substantial contributions of vitamin A, folate and thiamin (DoH, 1991). For most processed vegetable products, blanching will have been one of the key processing operations which will have influenced the vitamin content of the final products.

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VITAMINS IN VEGETABLES

Many factors affect the amount of vitamins in vegetables. These include cultivar and maturity, and light may also have some effect. For example, crops which mature during winter are often poorer in vitamin A than those which mature during the autumn months. Vegetables contain some vitamin E and, although vitamin K is present in green vegetables such as peas and cabbage, these are not important sources because sufficient is usually supplied by the bacterial flora of the human intestine. The richest vegetable sources of thiamin are green leafy vegetables and legumes. The vitamin is present in greatest quantities in the leaves of plants until full maturity, after which it passes to the seed or root. Thiamin content of peas and potatoes has been shown to increase as plants ripen. In peas the thiamin content remained constant after a tenderometer reading of 100 had been reached, but in potatoes thiamin increased to full maturity.

Only small quantities of riboflavin are present in green leafy vegetables, but vegetables are reasonable sources of niacin and folate, and very good sources of vitamin C. As with thiamin and other vitamins, the concentration of vitamin C in various parts of the vegetable tissue can vary significantly, and especially with maturity (Arthey, 1975). The influence of agricultural practices on nutritional composition is reviewed elsewhere (Karmas & Harris, 1988).

Table 1. UK household consumption of processed vegetables, annual national averages 1990[a]

	Consumption (oz[b] per person per week, except where otherwise stated)					Percentage of all households purchasing each type of food during survey week
	Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec	Yearly Average	
Tomatoes, canned or bottled	1·60	1·56	1·38	1·45	1·50	19
Canned peas	1·61	1·71	1·41	1·47	1·55	19
Canned beans	4·84	4·32	3·98	4·33	4·37	40
Canned vegetables, other than pulses, potatoes or tomatoes	1·02	1·16	1·05	1·03	1·06	15
Dried pulses, other than air-dried	0·29	0·19	0·17	0·31	0·24	5
Air-dried vegetables	0·01	—	—	0·01	—	—
Vegetable juices (fl oz)	0·17	0·25	0·20	0·19	0·20	4
Chips, excluding frozen	0·69	0·64	0·84	0·59	0·69	17
Instant potato	0·05	0·06	0·04	0·04	0·05	1
Canned potato	0·19	0·28	0·22	0·17	0·22	2
Crisps and other products, not frozen	1·21	1·24	1·18	1·29	1·23	34
Other vegetable products	0·76	1·15	1·13	0·91	0·99	21
Frozen peas	2·02	1·73	1·57	1·72	1·76	14
Frozen beans	0·49	0·53	0·30	0·29	0·40	4
Frozen chips and other frozen convenience potato products	2·75	2·71	2·40	2·45	2·58	15
All frozen vegetables and frozen vegetable products, not specified elsewhere	2·05	1·91	1·67	1·59	1·80	14
Total processed vegetables	19·75	19·44	17·54	17·84	18·64	80
Total vegetables (fresh and processed)	80·10	79·63	76·70	82·78	79·79	94

[a] From MAFF (1991), reproduced by permission of the Controller of HMSO.

[b] 1 oz ≈ 28 g.

Table 2. Average vitamin contents of some fresh and boiled vegetables (per 100 g)[a]

	Carotene (μg)	Vitamin E (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Vitamin B_6 (mg)	Folate (μg)	Pantothenate (mg)	Biotin (μg)	Vitamin C (mg)
New potatoes										
Raw	Trace	0·06	0·15	0·02	0·4	0·44	25	0·37	0·3	16
Boiled[b]	Trace	0·06	0·13	0·02	0·4	0·33	19	0·38	0·3	9
Old potatoes										
Raw	Trace	0·06	0·21	0·02	0·6	0·44	35	0·37	0·3	11
Boiled[b]	Trace	0·06	0·18	0·01	0·5	0·33	26	0·38	0·3	6
Green beans/French beans										
Raw	330	0·20	0·05	0·07	0·9	0·05	80	0·09	1·0	12
Frozen/boiled[b]	180	0·12	0·05	0·09	0·4	0·06	56	N[c]	N[c]	7
Peas										
Raw	300	0·21	0·74	0·02	2·5	0·12	62	0·15	0·5	24
Boiled[b]	250	0·21	0·70	0·03	1·8	0·09	27	0·15	0·4	16
Broccoli										
Raw	575	1·30	0·10	0·06	0·9	0·14	90	N[c]	N[c]	87
Boiled[b]	475	1·10	0·05	0·05	0·7	0·11	64	N[c]	N[c]	44
Brussels sprouts										
Raw	215	1·00	0·15	0·11	0·2	0·37	135	1·00	0·4	115
Boiled[b]	320	0·90	0·07	0·09	Trace	0·19	110	0·28	0·3	60
Cauliflower										
Raw	50	0·22	0·17	0·05	0·6	0·28	66	0·60	1·5	43
Boiled[b]	60	0·11	0·07	0·04	0·4	0·15	51	0·42	1·0	27
Old carrots										
Raw	8 115	0·56	0·10	0·01	0·2	0·14	12	0·25	0·6	6
Boiled[b]	7 560	0·56	0·09	Trace	Trace	0·10	16	0·18	0·4	2
Young carrots										
Raw	5 330	0·56	0·04	0·02	0·2	0·07	28	0·25	0·6	4
Boiled[b]	4 425	0·56	0·05	0·01	0·1	0·05	17	0·18	0·4	2

[a] From Holland *et al.* (1991), reproduced by permission of the Royal Society and the Controller of HMSO.

[b] Boiled in unsalted water.

[c] N—nutrient is present in significant quantities, but no reliable information on the amount.

Table 3. Typical percentage losses of vitamins in vegetables during cooking[a]

	Root vegetables	Leafy vegetables
Carotene	0	0
Thiamin	25	40
Riboflavin	30	40
Nicotinic acid	30	40
Vitamin C	40	70
Vitamin E	0	0
Vitamin B_6	40	40
Folic acid (total)	50	20–40
Pantothenic acid	30	30
Biotin	30	30

[a] From Paul & Southgate (1978), reproduced by permission of the Royal Society of Chemistry and the Controller of HMSO.

The average vitamin content per 100 g of some fresh and boiled vegetables is shown in Table 2 (Holland *et al.*, 1991). As well as indicating typical levels of the vitamins in these raw vegetables, the data represent the most recent to indicate the effect on vitamin content resulting from heating the vegetables in water at around 100°C. For example, the levels of water-soluble and heat-sensitive vitamins such as thiamin, folate and vitamin C tend to be reduced. In fact, data from previous surveys had suggested typical vitamin losses are in the range of 25–50% from root vegetables and 20–70% from leafy vegetables during cooking, as shown in Table 3 (Paul & Southgate, 1978). Effects similar to these would be expected as a result of industrial blanching operations.

INFLUENCE OF TYPE OF BLANCH ON VITAMIN LOSSES

In addition to the intrinsic factors affecting the vitamin content of vegetables, other factors may reduce vitamin content prior to blanching. These may include damage, such as bruising, caused by the harvesting method, delay time and ambient temperature during transport and storage prior to pre-blanch operations, and any further damage or leaching caused by pre-blanch operations such as washing and cleaning (Rutledge, 1991).

The various types of blanching operations have been reviewed by several workers (e.g. Lee, 1958; Lund, 1988; Selman, 1992). These comprise water blanching, steam blanching including the individual quick blanch (IQB) concept, vacuum steam blanching, in-can blanching, microwave blanching and hot-gas blanching. The most common system is still water blanching, where capital and running costs are relatively low, despite the significant loss of vitamins by leaching. To address this loss, much attention has been given to the use of steam blanching. Despite the improved performance of such blancher designs regarding energy and leaching losses, capital and other variable costs have continued to give conventional water blanching the competitive edge (Poulsen, 1986). The use of water may also enable the addition of processing aids to control, for example, the pH of the blanch water. Such aids could have both positive and detrimental effects on the stability of vitamins. For example, sulphite destroys thiamin, whereas acidification of blanch water to control vegetable colour may improve vitamin C stability.

Typically, the blanching process utilizes temperatures around 75–95°C for times of about 1–10 min, depending on the product requirements. A blanching process may be needed if there is likely to be a delay in reaching enzyme inactivation temperatures or, as in freezing preservation, if such temperatures are never achieved. The process should ensure the required reduction of enzyme activity that otherwise might cause undesirable changes in odour, flavour, colour, texture, and nutritive value during frozen storage. Another major effect is the removal of intercellular gases. This reduces the potential for oxidative changes in the food and allows the achievement of suitable headspace vacua in cans. As a heat process, blanching may result in some reduction in microbial load, and texture may be improved. Vegetable matter tends to shrink because of loss of turgor, which can aid the achievement of fill weight. Undesirable losses of heat-sensitive nutrients may be caused and, in water blanching, soluble constituents may be leached, resulting in large volumes of effluent (Selman, 1987).

A number of wide-ranging studies on the effects of blanching on vitamin loss from several vegetables were done in the late 1940s (Wagner *et al.*, 1947). Some of the subsequent studies have been summarised by Lund (1988) and are shown in Table 4. As expected, for water blanching the loss of water-soluble vitamins increases with contact time, and fat-soluble vitamins are relatively unaffected. Steam blanching did result in greater retention of water-soluble vitamins. The IQB method, designed to reduce effluent, appears to result in further ascorbic acid retention. The study by Dietrich *et al.* (1970), comparing microwave, steam and water blanching, verified better ascorbic acid retention in Brussels sprouts using microwaves. However, from a total quality point, the best product was achieved with a combination process of microwave and water blanching. Ralls *et al.* (1973) concluded that there was no significant difference between nutrient retention in spinach blanched in water or hot gas. It might normally be expected that the use of hot air would contribute significantly to the oxidation of nutrients. Lee *et al.* (1982) studied the vitamin changes in peas sampled from several points in four different canneries over four seasons, and identified differences in vitamin retention arising from the use of different equipment and different operating conditions. These examples show that, in general, blanching can significantly reduce the nutrient content of foods, the extent depending upon the blanching method and the product.

Table 4. Effects of blanching on nutrients[a]

References	Product	Nutrient	Blanch process[b]	Loss (%)	Comment
Bomben *et al.* (1973)	Green beans	Vitamin C	S, 2·5 min	8 mg/100 g	No initial content available; content after blanching
			IQB	11 mg/100 g	
			IQB predry	7 mg/100 g	
	Lima beans		S, 3·0 min	16 mg/100 g	
			IQB	24 mg/100 g	
			IQB predry	22 mg/100 g	
	Brussels sprouts		S	47 mg/100 g	
			IQB	46 mg/100 g	
			IQB predry	43 mg/100 g	
	Peas		S	21 mg/100 g	
			IQB	18 mg/100 g	
			IQB predry	20 mg/100 g	
Dietrich & Neumann (1965)	Brussels sprouts	Vitamin C	W, 9 min/88°C	24	
			S, 11 min/88°C	16	
			W, 6 min/93°C	16	
			S, 7 min/93°C	16	
			W, 5 min/100°C	19	
			W, 6 min/100°C	20	
Dietrich *et al.* (1970)	Brussels sprouts	Vitamin C	W, 6 min/100°C	43	
			M, 1 min + W 4 min/100°C	29	
			M, 3 min + W2 min/100°C	35	
Guerrant *et al.* (1947)	Peas	Ascorbic acid	W, 3 min/93°C	33	Other temperature–time combinations were done on other vegetables: green beans, lima beans, spinach
			W, 6 min/93°C	46	
			W, 9 min/93°C	58	
		Riboflavin	W, 3 min/93°C	30	
			W, 6 min/93°C	30	
			W, 9 min/93°C	50	
		Thiamin	W, 3 min/93°C	16	
			W, 6 min/93°C	16	
			W, 9 min/93°C	34	
		Carotene	W, 3 min/93°C	2	
			W, 6 min/93°C	0	
			W, 9 min/93°C	0	
	Lima beans	Niacin	W, 2 min/93°C	32	
			W, 4 min/93°C	32	
			W, 6 min/93°C	37	
Holmquist *et al.* (1954)	Peas	Vitamin C	S	12·3	
			W	25·8	
Raab *et al.* (1973)	Lima beans	Vitamin B_6	W, 10 min/100°C	21	
			S, 10 min/100°C	14	
Ralls *et al.* (1973)	Spinach	Carotene	W	5·4 mg/100 g	Evaluation after canning and processing; initial level not reported
			Hot gas	3·9 mg/100 g	
		Riboflavin	W	0·12 mg/100 g	
			Hot gas	0·10 mg/100 g	
		Vitamin C	W	20·8 mg/200 g	
			Hot gas	34·2 mg/100 g	

[a] From Lund (1988), permission requested.

[b] Process to blanch adequately. Generally determined by peroxidase inactivation. W, water; S, steam; IQB, individual quick blanch; hot gas, hot gas blanching; M, microwave.

MECHANISMS OF VITAMIN LOSS

The general effects of blanching on nutrient content of vegetables are fairly clear from the data referred to so far. However, a more detailed look at the various research studies reveals a significant lack of control over key parameters affecting vitamin losses. For example, in the case of ascorbic acid loss from peas, a review of 14 studies highlighted the differences in cultivar, harvesting method, maturity index, size of peas, initial ascorbic acid content, the analytical method, the type of blanching equipment, and the product to water ratios used (Selman, 1978). In several instances some of this information was not recorded. This renders the task of critically comparing results very difficult, especially when trying to understand the mechanisms of vitamin loss. As a further example, there is also a need to study the location and distribution of nutrients within various tissues, and to study how concentrations vary with maturity. In one blanching study, large ascorbic acid losses were noted for peas and broccoli, but not green beans. An analysis of the beans showed that ascorbic acid was concentrated in the seeds (38 mg/100 g fresh weight), which were protected by the pod (8·4 mg/100 g fresh weight) (Cumming *et al.*, 1981).

The effect of heat is common to all types of blanching operation and, as with all types of heating process, the effects of heating on vitamins, enzymes and sensory quality will be a function of their relative kinetics of heat destruction. Priestley (1979) reviewed the effects of heat on vitamins, and although some work has been done on a number of vegetables in this respect, most has been concerned with the effects of temperatures

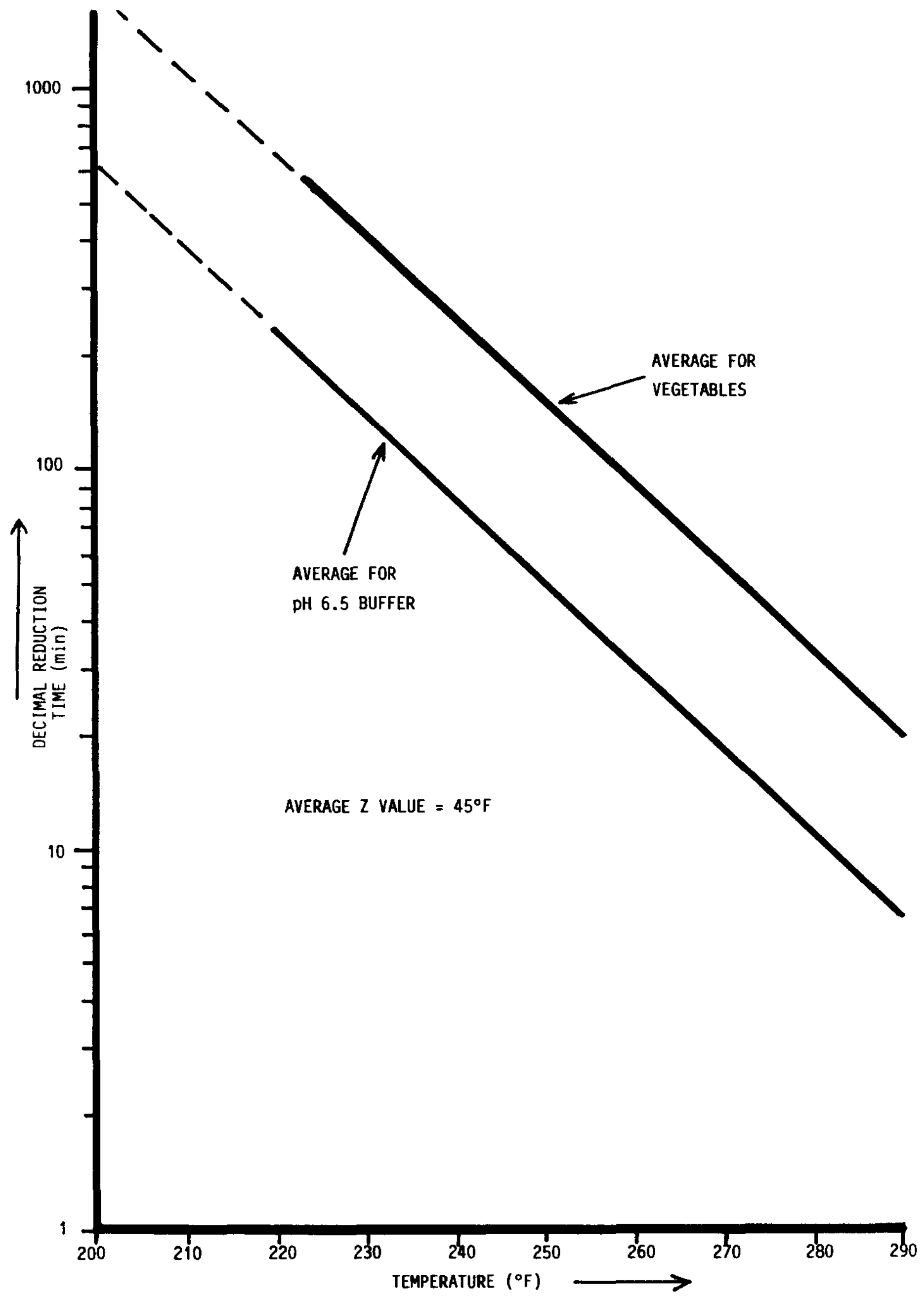


Fig. 1. Time for 90% destruction of thiamin (*D* value) in phosphate buffer at pH 6·5, and vegetables of similar pH at various temperatures. (Adapted from Feliciotti & Esselen (1957).)

above 100°C on thiamin destruction. Other vitamins have received far less attention (Holdsworth, 1990).

In the same way that experimental variations were recorded for many studies on vitamin C losses, much contradictory information was noted for the early work on the effects on blanching on thiamin retention (Farrer, 1955). Kinetic data are available for several vegetables including carrots, green beans, spinach and peas. At a given temperature, the time required for the thiamin (or other vitamin) content to be thermally reduced 10-fold is known as the decimal reduction time (*D* value). The temperature range over which the *D* value itself reduces tenfold is defined as *z* (*z* value). *z* values are typically 22°C, and activation energies around 117 kJ/mol (Feliciotti & Esselen, 1957). They demonstrated that the rate of thiamin destruction in phosphate-buffered solutions in the pH range of 4·5–7·0 increased with increasing pH. The most pronounced change occurred between pH 6·0 and 6·5. In foods, however, thiamin appears to be more resistant to thermal breakdown than the pure vitamin *in vitro*, and may be related to the relative proportions of the free and combined forms of the vitamin (see Fig. 1). The rate of destruction increased with increasing content of the combined form. Paulus *et al.* (1975) studied the effects of heating spinach on thiamin retention, and also noted that the loss of both ascorbic acid and thiamin could be represented by equations indicating first order reactions. *D* values reduced with increasing temperature of the heating medium, and *z* values were calculated at about 18°C for both vitamins. The effects of a wide range of conditions on thiamin destruction, including temperature and pH, were reviewed by Mauri *et al.* (1989) and they concluded that in most cases thiamin destruction follows first-order kinetics. In order to draw some simple conclusion about the loss of thiamin during blanching, the classical data of Feliciotti and Esselen (1957) were examined further. The equation for the graphs in Fig. 1 is given by the following relationship:

$$\log \frac{D}{D_\theta} = -\frac{T-\theta}{z}$$

where θ is the reference temperature of 121°C, T is any other temperature (°C), D_θ is the decimal reduction time (min) for thiamin content at 121°C, D is the decimal reduction time (min) for thiamin at the temperature T(°C), and z is the temperature range in °C over which the decimal reduction time is reduced 10-fold.

From the data given in Fig. 1 it can be calculated, either by extrapolation or by using the equation, that the averaged D value for thiamin at 212°F is 1052 min for the vegetables. Taking an idealised example of peas with a thiamin content of 0·74 mg/100 g, if after 5 min blanching at 100°C the total loss of thiamin was, say, 5·4% (0·70 mg/100 g retained), then the proportion of thiamin destroyed by heat can be calculated thus. If the time at 100°C required to reduce the initial thiamin content by 90% (D value) is 1052 min, then after this time the thiamin destroyed would be 0·74–0·074 mg/100 g. After only 5 mins at this temperature, the thiamin destroyed would be

$$\frac{0{\cdot}74 - 0{\cdot}074}{1052} \times 5 = 0{\cdot}003\,165 \text{ mg}$$

Hence, where the total loss is 0·040 mg, the proportion lost due to thermal destruction would be

$$\frac{0{\cdot}003\,165}{0{\cdot}040} \times 100 = 7{\cdot}9\%$$

and by difference, 92·1% would have been lost due to leaching.

The term ‘folacin’ is used to denote a heterogeneous group of derivatives with a similar basic structure and biological function. Pteroylglutamic acid, or folic acid, is the basic structural unit in these compounds. The existence of these forms and the difficulty of differentiating between them has led to complications in characterising the vitamin, and hence the folacin content, of foods. Some of these forms are subject to greater deterioration than other forms. For example, tetrahydrofolic acid and 5-methyl tetrahydrofolic acid have been shown to be moderately labile derivatives, and the presence of oxygen has been implicated as a factor in the degradation of folates during heating.

Pteroylglutamic acid has been shown to be stable for up to 1 h when heated at 100°C in solutions with pH above 5. Destruction occurred slowly at lower pH, and it seems unlikely that it would be significant under the typical blanching times and temperatures. Chen and Cooper (1979) studied the thermal lability of tetrahydrofolic acid and 5-methyl tetrahydrofolic acid *in vitro*, and found that at 100°C the half-life of the former was 2·25 min and that of the latter 21·4 min. The stability of both forms of the vitamin drastically increased in the presence of ascorbate or under nitrogen atmosphere, and indicated the oxidative nature of the degradation reactions (see Fig. 2). The rate of destruction of 5-methyl tetrahydrofolic acid followed first order kinetics and exhibited an activation energy of 39·8 kJ/mol. Ruddick *et al.* (1980) studied the thermal degradation of methyl tetrahydrofolic acid in a 0·1 M phosphate buffer (pH 7·3) and found that in the presence of an unlimited supply of oxygen, the degradation reaction could be described as pseudo-first-order. Reaction rate constants were found to increase with increasing reaction temperature, and the activation energy was estimated as 29·7 kJ/mol. In the presence of a limited oxygen supply, the overall reaction appeared to be second order.

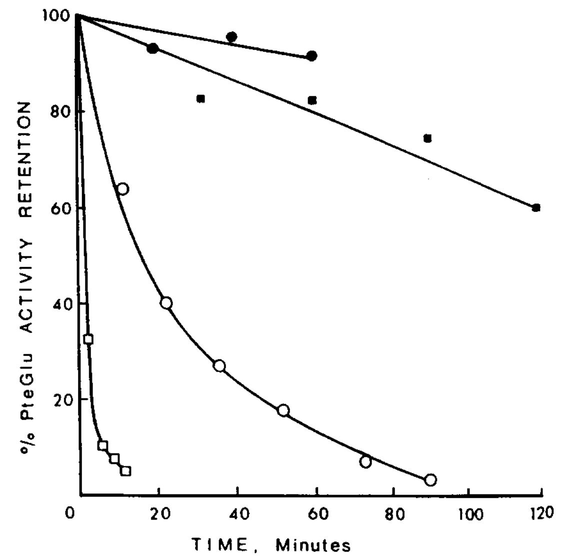
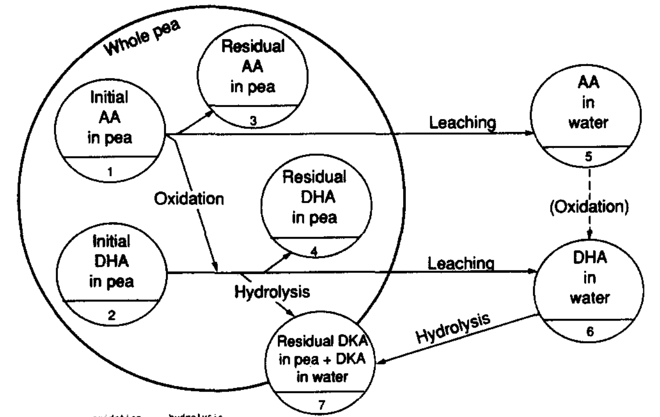


Fig. 2. Stability of tetrahydrofolic acid (■) with, and (□) without nitrogen, and 5-methyl tetrahydrofolic acid (expressed as pterpylglutamic acid activity) (●) with, and (○) without nitrogen when heated at 100°C. (Adapted from Chen & Cooper (1979).)

Hawkes and Villota (1989) have reviewed the information available on folate stability in food processing. In most studies of blanching or cooking of vegetables in water, the water was found to contain higher quantities of folate than the cooked vegetables themselves. Brussels sprouts and asparagus were exceptions, probably due to their lower surface to weight ratio of all the vegetables analysed. Losses of folate ranged from 22% in asparagus to 84% in cauliflower. Mass balances with respect to total folate contents before and after cooking indicated that most losses were caused by leaching of the folate into the cooking water rather than by actual destruction of the vitamin. Malin (1977) examined the effects of water blanching on Brussels sprouts and found relatively small losses. He attributed this stability in part to the presence of relatively high concentrations of endogenous antioxidative ascorbic acid, in addition to its physical geometry (low surface area to volume ratio). The major loss of folacin during blanching will



Basic reaction: AA $\underset{}{\overset{\text{oxidation}}{\rightleftharpoons}}$ DHA $\xrightarrow{\text{hydrolysis}}$ 2,3-diketogulonic acid (DKA) and further breakdown products. Where initial total vitamin C (AA + DHA) in pea is taken to be 100%, then initial total vitamin C in pea before blanching 1+2=3+4+5+6+7 in pea and water after blanching. The proportion of DHA hydrolyzed to DKA (and further breakdown products) was calculated thus: 7=(1+2)-(1+4+5+6) and the proportion of AA oxidized to DHA was similarly calculated thus: 1-(3+5)=(4+6+7)-2.

Fig. 3. Net changes in the ascorbic acid (AA) and dehydroascorbic acid (DHA) contents of whole peas after blanching in water. (Adapted from Selman & Rolfe (1982).)

thus be due to leaching, with less than 5% being destroyed by heat.

In the case of vitamin C, a summary of the apparent net changes in the ascorbic acid and dehydroascorbic acid contents of peas and blanch water has been proposed and is shown in Fig. 3 (Selman & Rolfe, 1982). Ascorbic acid is essentially stable to the heating conditions during pea blanching, although a small proportion may be enzymically oxidised during the heating-up period. Dehydroascorbic acid, which exhibits equal antiscorbutic activity, is not stable to heat and is rapidly hydrolysed to 2,3-diketogulonic acid and further breakdown products. The thermal half-life of dehydroascorbic acid at pH 6 has been shown to decrease from 35 min at 40°C to 2 min at 70°C irrespective of oxygen concentration (Huelin, 1949).

In a controlled study of water blanching of Dark Skinned Perfection peas (total vitamin C content 32·9 mg, ascorbic acid content 30·6 mg per 100 g wet weight basis), a 1 min blanch at 97°C resulted in a loss of 28% of the initial ascorbic acid (see Fig. 4). At temperatures of 97°C and 85°C, the sum of the ascorbic acid remaining in the peas and the ascorbic acid in the water virtually equalled the initial ascorbic acid content of the peas. But at a demonstration blanch temperature of 70°C, the total loss was not accounted for solely in the water. This demonstrated that at the two higher temperatures, virtually no oxidation had occurred, whereas some 20% of the initial ascorbic acid was oxidised in the first 2 min at 70°C (Birch *et al.*, 1974). It is most likely that the enzyme ascorbic acid oxidase was responsible for this during the heating-up period prior to reaching enzyme inactivation temperature. Maximum ascorbic acid oxidase activity *in vitro* occurs at 40°C, and at 60°C the activity is half that at 20°C. Above 65°C the activity is negligible, and this emphasises the need for rapid heating to reach 65°C as quickly as possible, hence minimising enzymic oxidation.

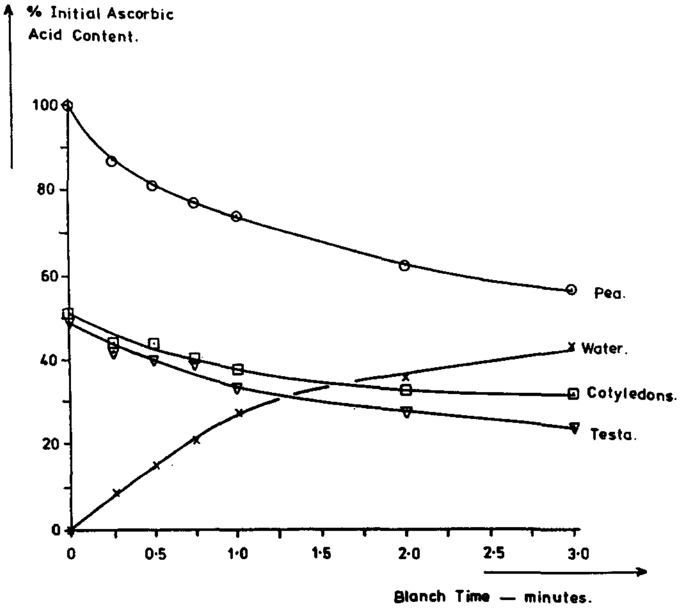


Fig. 4. Percentage of the original ascorbic acid content of dark skinned perfection peas remaining in the whole peas, the cotyledons, the testa, and in the blanch water after blanching in distilled water at 97°C. (Adapted from Birch *et al.* (1974).)

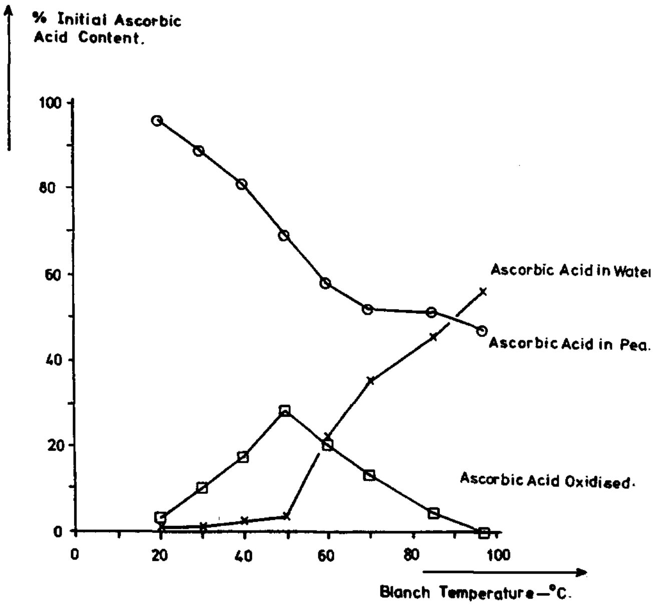


Fig. 5. Percentage ascorbic acid remaining in dark skinned perfection peas and lost into the blanch water after blanching for 10 min at the given temperature, and showing by difference the ascorbic acid oxidized. (Adapted from Birch *et al.* (1974).)

In the organised structure of intact pea tissue, the enzyme and substrate would not be as freely in contact until the cell structure broke down due to the action of heat. Therefore, it might be expected that the fastest rate of oxidation would occur at the point of maximum cell disruption with minimum enzyme denaturation. Figure 5 shows that this optimum point occurs at about 50°C. Here, the leaching losses increase rapidly as the cells die and the cell membranes become permeable. It also suggests that a significant change in the mode of vitamin C loss during blanching might occur if the peas were cut or bruised prior to blanching, which is the case in commercial operations as a result of the mechanical shelling of peas (Birch *et al.*, 1974).

Apart from thermal destruction and enzymic oxidation, the major loss of these three vitamins occurs by leaching losses due to water solubility. This is

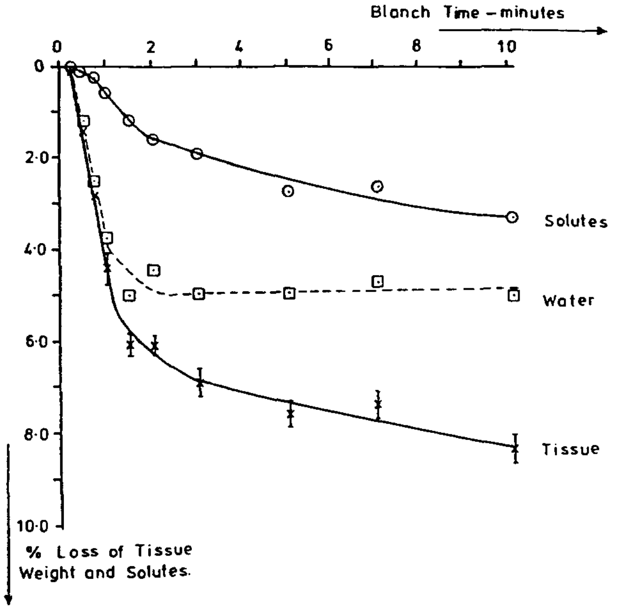


Fig. 6. Percentage loss of tissue weight, solutes and water (by difference) from carrot samples after the given blanch time at 70°C. (Adapted from Selman & Rolfe (1979).)

influenced firstly by the contraction of turgid vegetable tissue at around 55°C, and then by further mass diffusional loss. What appears to be a typical pattern was demonstrated for carrot tissue (see Fig. 6). The initial loss of turgor during the first 2 min at the demonstration temperature of 70°C resulted in an expulsive loss of cell sap, thereafter a steady diffusional loss of water soluble constituents was recorded (Selman & Rolfe, 1979). Further methodology was developed to measure diffusion coefficients of water soluble constituents during vegetable blanching (Selman *et al.*, 1983; Nicolas *et al.*, 1987), and using this type of approach, the apparent diffusion coefficient of, for example, ascorbic acid during pea blanching has been calculated (Rice & Selman, 1984; Abdel-Kader, 1991). One approach to the calculation of diffusion coefficients for water soluble vitamins is based upon the two contributions to the total resistance to mass transfer in the blanching of vegetables, which are the surface resistance due to convection and the 'internal' resistance due to mass diffusion. These two can be represented by Fick's second and first laws together with a mass balance at the interface (surface):

$$\frac{\partial C}{\partial t} = D_a \times \frac{\partial^2 C}{\partial x^2}$$

and

$$-D_a \times \frac{\partial C}{\partial x} = k(C - C_0) = \frac{1}{A} \times \frac{\partial N}{\partial t}$$

at $x = a$ (surface), where A is the total surface area for mass transfer (m^2), C is the solute concentration at any point in the sample (%), C_0 is the concentration in the (blanch) medium (%), k is the surface mass transfer coefficient (kg/m^2 s), N is mass diffusing (kg), t is (blanch) time (s), and x is the distance from the surface of any position in the sample where the concentration is C(m).

The solution to these equations is given by Newman (1931) for the three geometric shapes of a slab of infinite extent, a cylinder of infinite length, and a sphere. The average concentration is obtained after integration with respect to position, as a function of time for given values of surface mass transfer coefficient, all in non-dimensionalised form. Newman also showed how the results for a slab of infinite extent can be used to obtain the solution for a strip of infinite length, a rhomboid (in particular a cube) and a cylinder of finite length.

If there is sufficient agitation of the blanching liquid, then the surface resistance becomes small and it can be assumed that the total resistance is due to only the 'internal' resistance. We then require only the solution to Fick's second law. This is given by Newman (1931) for the geometrical shapes slab of infinite extent, cylinder of infinite length, and sphere, with the average concentration obtained after integration with respect to position as a function of time, again in non-dimensionalised form as follows:

Slab:

$$E = \frac{\overline{C} - C_0}{C_1 - C_0} \text{ (non-dimensionalised concentration)}$$

$$= \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \left(\frac{D_a t}{a^2}\right)\left(\frac{\pi}{2}\right)^2\right]$$

Sphere:

$$E = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-n^2 \left(\frac{D_a t}{a^2}\right) \pi^2\right]$$

Cylinder:

$$E = 4 \sum_{n=1}^{\infty} \frac{1}{R_n^2} \exp\left[-\left(\frac{D_a t}{a^2}\right) R_n^2\right]$$

where R_n is the root of

$$J_0(x) = 1 + \sum_{n=1}^{\infty} (-1)n \frac{x^{2n}}{(2n)^2!} = 0$$

where the first 10 values are

n	1	2	3	4	5
R_n	2·4048	5·5201	8·654	11·792	14·931
n	6	7	8	9	10
R_n	18·071	21·212	24·352	27·493	30·635

and here a is the characteristic linear dimension: half the diameter for a cylinder and sphere, half the thickness for a slab (m), $\overline{C}$ is the average solute concentration in the (blanched) sample at time t (%), C_1 is the uniform initial (cell sap) solute concentration in the fresh (unblanched) sample (%), J_0 is the Bessel function of order zero, n = number of roots and $D_a t/a^2 = \bar{t}$, a non-dimensional time.

Newman (1931) developed these solutions for drying applications over a wide range of concentrations and presented the results as a set of tables. In the case of blanching vegetables, the concentrations are much smaller and near to zero, and the solutions have been recalculated for smaller increments in this range of concentrations, using the first 10 terms for the three series (Selman *et al.*, 1983). Values of D_a for the solute in the vegetable were calculated by first estimating $E = (\overline{C} - C_0/C_1 - C_0)$ from the experimental data, and then finding the corresponding value for $\bar{t}$ from the graph of $\bar{t}$ versus E for a cylinder. D_a can be finally determined by solving $\bar{t} = D_a t/a^2$.

Knowing the diffusion coefficients of water-soluble vitamins and the blanching conditions thus permits the prediction of nutrient loss under those given conditions (Thompson, 1982; Alzamora *et al.*, 1985). Hough *et al.* (1988) used a mathematical model based on heat and mass transfer and enzyme destruction to predict the effect of piece shape and size on vitamin C retention during water blanching in forced convection at 100°C of potato pieces (0·95 cm × 0·95 cm × variable dimension). The model predicted that increasing the variable dimension from 0·32 to 1·59 cm would increase the vitamin C retention. Experimental verification confirmed that vitamin retention was increased from around 40 to 60% over this range of piece size. Hough *et al.* (1990) verified their model for predicting leaching losses of ascorbic acid from peas with different radii and at different temperatures, and confirmed that at higher temperatures vitamin retention was increased due to the larger value of activation energy for enzymic inactivation than for vitamin diffusion (see Fig. 7). Previously, they had also concluded that leaching losses from peas would be lower in static than in agitated water blanching, and that leaching losses would be lower when pea size is increased (Alzamora *et al.*, 1985).

OPTIMIZATION OF VEGETABLE BLANCHING

Heating vegetables during blanching will affect a number of quality parameters, including vitamin and colour retention, enzyme activity, texture and flavour. High-temperature short-time (HTST) processes for sterilisation have been demonstrated to maximise microbial destruction and minimise quality loss due to the differing destruction kinetics of microorganisms and quality parameters. However, where the blanching objective is to inactivate enzymes, the benefit of such HTST processes is less obvious due to the similarity of destruction kinetics of many enzymes and nutrients (Holdsworth, 1990).

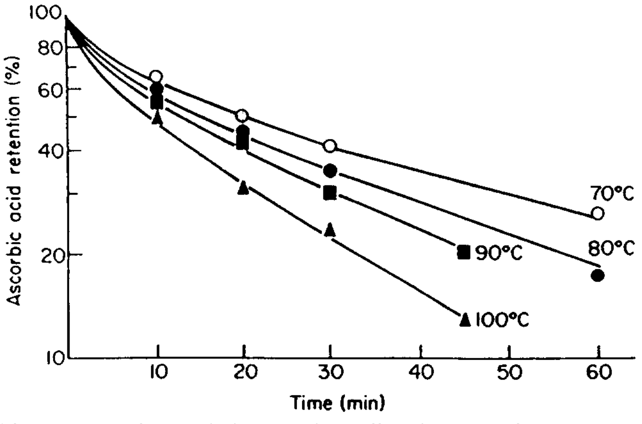


Fig. 7. Experimental data and predicted curves for ascorbic acid retention versus time for finale variety peas at different temperatures. (Adapated from Hough *et al.* (1990).)

Blanching is also energy intensive, and rapid heating with short holding times are required using a minimum of water and energy. This will minimise thermal destruction and leaching, and achieve the objectives efficiently. Close control of blanch time and temperature influences uniformity of product quality as well as energy consumption. For example, where a vegetable does require blanching prior to freezing, it is now being established that the blanch treatment required depends largely on the thermal stability of those enzymes directly responsible for the main deteriorative changes in a given product during frozen storage. Hence, energy may be wasted if the blanching conditions are loosely controlled to inactivate peroxidase enzymes, if the less heat stable lipoxygenases are the relevant enzymes to inactivate.

Therefore, there is a need to optimise the blanching process, including the minimisation of nutrient losses during any subsequent post-blanch cooling step. Poulsen (1986) discusses these issues with reference to modern energy efficient steam blanchers and integrated water blancher–coolers.

VITAMINS IN FROZEN VEGETABLES

The process of freezing itself does not alter the nutritive value of the product being frozen. It is during the preparative steps prior to freezing, particularly blanching, and during subsequent frozen storage that losses of the more labile vitamins occur. During frozen storage, vitamin C is generally fairly stable over a period of 1 year at temperatures below −20 to −25°C. A 10% loss might be expected. At temperatures of −25 to −30°C and below, practically no losses can be observed. However, at elevated temperatures of around −10°C, losses of 80–90% can occur after storage for 1 year. The vitamins of the B group are more stable than vitamin C during the storage time, except for folic acid, which on the basis of limited experimental information has been found to show similar sensitivity to degradation as vitamin C (IIR, 1986).

During storage at −18°C over one year, the loss in thiamin in vegetables like asparagus, broccoli, green beans and peas is about 20%. Spinach and cauliflower seem to be more sensitive; losses are increased up to 50%. The losses of the other vitamins of the B group are less than those of thiamin and folic acid. The losses of carotene during frozen storage of vegetables at −18°C over 1 year varied, with minor exceptions, between 5 and 20%.

In conventionally frozen peas, a significant loss occurs during processing primarily due to blanching. The result is that when frozen peas are purchased, they have a lower vitamin C content than the unfrozen peas.

However, this is offset by a smaller loss during home preparation. The result is that the product, when eaten, may have practically the same ascorbic acid content regardless of whether the product was frozen or not (Jul, 1984). Recent work has confirmed that vitamin levels in frozen vegetables may often be higher than the fresh stored produce, as well as the canned product, when comparing the three products at the point of consumption (Hall *et al.*, 1989; Pither & Hall, 1991).

CONCLUSIONS

From the general observations it is seen that some of the B vitamins and vitamin C are the most susceptible to loss. In addition to being water soluble, vitamin C is readily destroyed by heat under alkaline or neutral conditions. Of the B group complex, thiamin and folic acid are the most sensitive. Thiamin is most heat labile at pH 7. Vitamin C is lost more easily than either thiamin or folic acid due to its very high water solubility and concentration in vegetables. For these reasons vitamin C, and more recently thiamin and folic acid, are frequently used as research indicators of the severity of food processing—it being assumed that if these nutrients are well retained in food, the percentage retention of all other nutrients is as high or higher. In terms of cooking, there is a clear benefit in using cooking water in gravy and sauces to recover the leached vitamins.

It can be concluded that the main mechanisms of vitamin loss are due to water solubility and mass transfer, heat sensitivity and heat transfer and enzymic oxidation. These mechanisms will therefore be influenced by such gross factors as:

- Botanical structure
- Location of vitamin
- Concentration of vitamin
- Intercellular oxygen
- Oxidative enzyme activity
- Piece size and surface area
- Product/water ratio
- Soluble solids content of blanch water
- Chemical quality of blanch water, e.g. pH
- Blanch temperature
- Blanch time
- Post-blanch water cooling

The growing consumer awareness of the effect of diet on susceptibility to disease, and the increasing popularity of convenience foods and meals, are both likely to result in greater consumption of vegetables. For example, recognition that the intake of antioxidant vitamins C and E may have a protective role against cancer will mean that vegetables will be in demand, but in a form that protects the vitamin content. There will also be a widening diversity of forms in which the vegetables may be eaten. During the period from January to October 1991, 48 new products were launched in the UK that contained green beans (Stanley & Bond, 1992). Of these 22 were frozen, 11 were chilled and 15 were ambient stable types. A similar number of new products containing cauliflower were launched during the same period, of which 22 were frozen, 20 were chilled and 11 ambient stable (Bedford & Bond, 1992). It is likely, therefore, that the market for frozen vegetables may outpace other forms of processing in the short term. Well designed and controlled blanching processes will therefore contribute to this protection of vitamins in conjunction with preservation operations such as freezing.

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