学位論文

Iron, zinc and ascorbic acid enrichments of whole potato tubers by vacuum impregnation

生物資源科学専攻

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真空含浸処理によるジャガイモ塊茎の鉄，亜鉛及びアスコルビン酸含量増強

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Chapter 1

General introduction

1.1. Functional foods

In the last decades consumer demands in the field of food production has changed considerably. Consumers more and more believe that foods contribute directly to their health (Mollet and Rowland, 2002). Today foods are not intended to only satisfy hunger and to provide necessary nutrients for humans but also to prevent nutrition-related diseases and improve physical and mental well-being of the consumers (Menrad, 2003). The development of functional foods is currently one of the most intensive areas of food products development worldwide. The functional foods have been defined as foods that provide an additional physiological benefit that may prevent disease or promote health and well-being (Hasler, 1996; Stauffer, 1999). The functional food products have been mainly launched in the dairy-, confectionery-, soft-drinks-, bakery- and baby-food market (Kotilainen et al, 2006; Menrad, 2003). Experts like Sloan (2000, 2002) have reckoned the global functional food market to be 47.6 billion US$; the United States is the largest market segment, followed by Europe and Japan. Moreover, the functional food industry is currently striving to functional new products to the rapidly growing

markets (Bistrom and Nordstrom, 2002).

1.2. Overview of iron, zinc and ascorbic acid deficiencies

In functional ingredients, iron is required for hemoglobin production in the cell precursors, and thus insufficient iron delivery to the red cell precursor's results in impaired erythropoiesis and an iron-deficient anemia (Domanski et al., 2011). Iron is not actively excreted from the body in urine or in the intestines. Iron is only lost with cells from the skin and interior surfaces of the body-intestines, urinary tract, and airways. The total amount lost is estimated at 14 µg/kg body weight/day (Green, 1968). Iron deficiency is the most widely distributed nutrient deficiency state, affecting some 2 billion people worldwide (DeMaeyer and Adiels-Tegman, 1985) and impairing the function of iron-dependent enzymes and proteins (Beard and Dawson, 1997). USDA (2000) reports that 62% of women aged 20 and older are iron deficiency. FAO/WHO indicated that the recommended daily allowance (RDA) of iron for adult men and women amounted to 9.1 and 19.6 mg/day, respectively (Schümann et al., 2007).

Moreover, zinc is involved in many biochemical processes supporting life. The most important of these processes are cellular respiration, cellular utilization of oxygen, DNA and RNA, reproduction, maintenance of cell membrane integrity, and

sequestration of free radicals (Chan et al., 1998). However, conservative estimates suggest that more than 25% of the world's population is at risk of zinc deficiency (Maret and Sandstead, 2006). Especially, zinc deficiency may increase oxidative stress, which may directly cause DNA damage. Moreover, zinc deficiency may impair DNA damage repair responses (Ho, 2004). It leads to several chronic degenerative diseases, such as cancer (Castro and Freeman, 2001). The Food and Nutrition Board (FNB, 2001) indicated that the recommended daily allowance of zinc for adult men and women amounted to 11 and 8 mg/day, respectively.

In addition, ascorbic acid is an essential component of most living tissues. As an antioxidant, it plays an important role in protection against oxidative stress. Ascorbic acid is an important scavenger of free radical species, such as reactive oxygen species that can cause tissue damage resulting from lipid peroxidation, DNA breakage or base alterations, and may contribute to degenerative diseases, such as heart disease or cancer (Bates, 1997). Due to its participation in the oxidation of transition metal ions, ascorbic acid also plays an important role in enhancing the bioavailability of non-haem iron (Teucher et al., 2004). The UK Low Income Diet and Nutrition Survey carried out between 2003 and 2005 found evidence of vitamin C deficiency in an estimated 25% of men and 16% of women. Another 20% of the population had vitamin C levels in the

depleted range (Mosdøl et al., 2008). The Food and Agriculture Organization (FAO) indicated that the recommended nutrient intake of vitamin C ranges from 25 to 45 mg/day, depending on age. However, based on available biochemical, clinical and epidemiological studies, the current recommended daily allowance for ascorbic acid is suggested to be 100 mg/day for adults to achieve cellular saturation and reduce risk of heart disease, stroke and cancer, in healthy individuals (Naidu, 2003).

1.3. Overview of potato consumption

Potatoes (*Solanum tuberosum L.*) are an essential food crop all around the world and are the first non-grain food product (FAOSTAT, 2012). It is ranked fifth in terms of human consumption and fourth in worldwide production (Burlingame et al., 2009). Apart from supply of energy and high quality protein, the potato has also been known to be an important source of vitamins and minerals (Abong et al., 2009).

1.4. Vacuum impregnation and its application

One of the alternatives for the development of new products in the food industry is the use of vacuum impregnation (VI) (Igual et al., 2008). VI is the application of low pressure to a solid-liquid system, followed by the restoration of atmospheric pressure

(Fito 1994; Fito and Chiralt, 1997). In VI process, Fito (1994) report the in-flow of the external liquid throughout the capillary pores, controlled by the expansion/compression of the internal gas. This is responsible for the VI processes of porous products when reduced pressures are imposed in a solid liquid system (vacuum step) followed by the restoration of atmospheric pressure. During the vacuum step (t_1), the internal gas in the product pores is expanded and partially flows out. All of the steps are coupled with the capillary penetration as a function of the interfacial tension of the liquid and the diameter of pores. In the atmospheric step (t_2), the residual gas is compressed and the external liquid flows into the pores as a function of the compression ratio. Different applications of food VI have been developed recently in numerous studies (Gras et al., 2002; Chiralt et al., 1999; Fito and Chiralt, 2000; Fito et al., 2000). These studies have validated a model which describes the coupling of the hydrodynamic mechanism (HDM) and the deformation-relaxation phenomena (DRP) of viscoelastic products (Fito et al., 1996) when they are immersed in an external liquid phase and submitted to pressure changes.

In the last years, several uses of VI on vegetable food have been studied with particular attention on dewatering processes. A wide range of literature is available about the use of VI for osmotic dehydration (Shi and Fito, 1993; Fito and Chiralt, 1995;

Paes et al., 2007) and salting processes (Chiralt et al., 2001; Mujica-Paz et al., 2006). Some authors proposed the use of VI to enrich food (fruits and vegetables) with nutritional and functional ingredients (Fito et al., 2001; Betoret et al., 2003; Xie and Zhao, 2003). Fito et al. (2001) first evaluated the feasibility of using VI for mineral fortification of fruits and vegetables from an engineering point of view. At first, mathematical models were developed to determine the concentration of different minerals in VI solutions required to achieve a 20-25% dietary reference intake (DRI) fortification in 200 g of samples. Following the modeling predication, experimental validation confirmed that VI could be an effective method for the enrichment of fruits and vegetables with minerals, vitamins or other physiologically active compounds (PAC).

VI of porous food matrices with adequate solutions/suspensions of physiologically active compounds has been claimed as a useful way to obtain this kind of products, without destroying the initial food matrix, but only occupying its initial porous fraction with a liquid phase (Fito et al., 2001). Gras et al. (2002) studied the response of several sliced vegetables (beetroot, carrot, eggplant, zucchini, mushroom and oyster mushroom) to VI treatments, in terms of sample volume deformation and impregnation levels. They evaluated changes in the microstructure of different vegetables by cryo-scanning

electron microscopy observation, and found that VI could be used to fill intercellular spaces (ICS) in the vegetable matrix. In addition, Sanzana et al. (2011) studied Aloe vera fortification of endives, cauliflower, broccoli and carrots using VI technique with sucrose solutions. The result showed that VI made it possible to incorporate up to 7 g of Aloe vera in 100 g (dry matter) of broccoli, about 4 g of Aloe vera in 100 g (dry matter) of cauliflower and endive, and about 3 g of Aloe vera in 100 g (dry matter) of carrots.

Regarding VI operation, Zhao and Xie (2004) reported that the qualities of finished products by VI are determined by processing conditions such as vacuum pressure, vacuum time and restoration time. Schulze et al. (2012) reported that the quercetin content of vacuum-impregnated apples increased with vacuum pressure. Also, concerning vacuum time and restoration time of VI treatment for vegetables and fruits, Mújica-Paz et al. (2003) used a 13.5–67.4 kPa of vacuum pressure for 10 min, and 10-min restoration time for VI of the sucrose solution (41–60 Brix) for slices (3.5 × 2.5 × 1.2 cm) of mango, apple and melon. Gras et al. (2003) used a vacuum pressure of 5 kPa for 10min, and a 10-min restoration time for impregnation of isotonic solutions of sucrose and calcium lactate mixtures for eggplants, carrots and oyster mushroom. Salvatori et al. (1998) reported that in plant tissue samples of about 2 cm in diameter, with relatively large intercellular spaces and elastic cellular arrangement, the necessary

length of vacuum period in VI operations is in the order of 5 min and impregnation times with sugar syrups are in the order of the time required to achieve a stationary pressure in the tank after the valve is opened to restore atmospheric pressure.

In addition to the above-mentioned vacuum pressure, vacuum time and restoration time, changes in nutritional value mainly occur during storage and cooking such as steaming for potato tubers (Murniece et al., 2011). Faller and Fialho (2009) reported that steaming led to reduction in the antioxidant activity of vegetables.

Morphologically, potato tuber structure is non-homogenous; the elements of tuber are: skin with lenticels, the eyes, the bud and stem ends, the cortex, the ring of vascular bundles, the perimedullary zone and the pith with medullary rays (Rastovski and van Es, 1981). Thus, it would be interesting to examine the distribution of nutrients incorporated by VI treatment within potatoes.

In addition, potatoes for domestic consumption are stored at 5 ℃ in order to avoid serious sprout growth (Burton et al., 1991). Järvinen et al. (2011) reported that the amount (thickness) of potato skin increased with storage, which may affect the amount of nutrition incorporated by VI treatment. Therefore, it would also be interesting to investigate the effect of storage time on the amount of nutrition of VI whole potatoes.

In the present study, I attempted to enrich zinc content of whole potato tubers by

VI treatment in order to supply nutritious whole potatoes to consumers.

Concerning VI of potato, only one report was found regarding enrichment of ascorbic acid content of whole potatoes (Hironaka et al., 2011). However, no studies exist on vacuum impregnation of iron and zinc. In addition, there are no studies concerning the distribution of ascorbic acid content within VI whole potatoes, and the effect of storage time on the ascorbic acid content of VI whole potatoes.

1.5. Research objectives

Objectives of this research were summarized as follows:

1) To evaluate the effect of vacuum pressure, vacuum time and restoration time on the iron and zinc contents of VI whole potatoes, and to investigate the effects of steam-cooking and storage at 4 ℃ on the iron and zinc contents of VI whole potatoes (Chapter 2).

2) To examine the longitudinal or transverse distribution of the iron, zinc and ascorbic acid contents within VI whole potatoes (Chapter 3).

3) To evaluate the effect of VI treatment time on the iron, zinc and ascorbic acid contents of stored VI-whole potatoes (Chapter 4).

Chapter 2

Effect of vacuum pressure, vacuum time, restoration time, cooking and storage on

iron and zinc contents of vacuum-impregnated whole potatoes

2.1. Introduction

Increased consumer interests in the health benefits of foods have led to the significant development of nutraceuticals and functional foods (Zhao and Xie, 2004; Sibbel, 2007). The global functional foods markets are estimated to be $47.6 billion in 2001 in comparison with $30 billion in 1995 (Anon, 2001). The functional food industry is currently striving to provide new functional products to rapidly growing markets (Bistrom and Nordstrom, 2002).

One of the alternatives for the development of new products in the food industry is the use of vacuum impregnation (VI) (Igual et al., 2008). VI is the application of low pressure to a solid-liquid system, followed by the restoration of atmospheric pressure (Fito, 1994; Fito and Chiralt, 1997). In a VI operation, a porous food is immersed in a liquid and submitted to a vacuum step (first step) for a time period (t_1), followed by a second step at atmospheric pressure (restoration step), as mentioned in Chapter 1. The compression second step forces the liquid to flow into the solid food structure after the

initial gas is partially released during the first expansion step (Fig. 2-1).
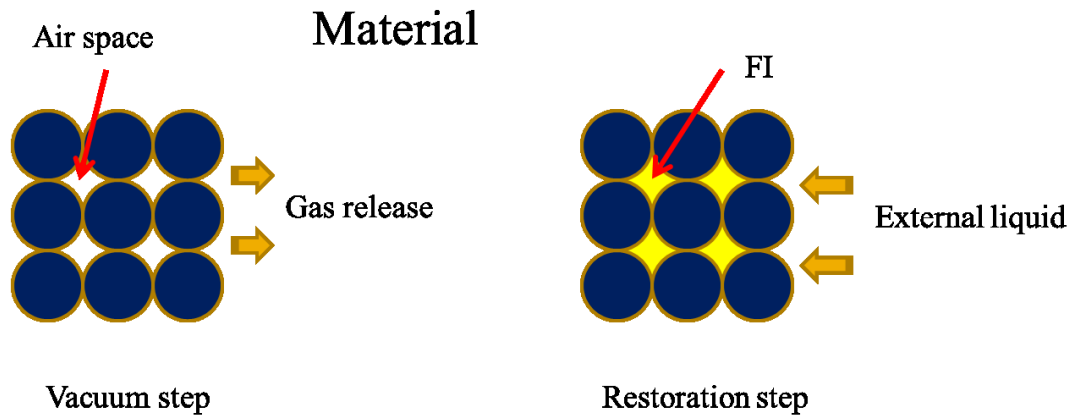
Fig. 2-1. Scheme of vacuum impregnation operation on vacuum step and restoration step. FI: functional ingredient.

To achieve a better efficient impregnation in VI process, it is required to know the suitable VI conditions. VI efficiency has been reported to depend on process parameters, including vacuum pressure, vacuum time and restoration time (Hoover and Miller, 1975). Concerning vacuum pressure, vacuum time, and restoration time of VI treatment for vegetables or fruits, Mújica-Paz et al. (2003) used a 13.5-67.4 kPa of vacuum pressure for 10 min, and 10-min restoration time for VI of the sucrose solution (41-60 Brix) for slices (3.5 × 2.5 × 1.2 cm) of mango, apple and melon. Gras et al. (2003) used

a vacuum pressure of 5 kPa for 10 min, and a 10-min restoration time for impregnation

of isotonic solutions of sucrose and calcium lactate mixtures for eggplants, carrots and

oyster mushroom. Salvatori et al. (1998) reported that in plant tissue samples of about 2

cm in diameter, with relatively large intercellular spaces and elastic cellular arrangement,

the necessary length of vacuum period in VI operations is in the order of 5 min and

impregnation times with sugar syrups are in the order of the time required to achieve a

stationary pressure in the tank after the valve is opened to restore atmospheric pressure.

In the present study, the effects of vacuum pressure, vacuum time (t_1) and

restoration time (t_2) on the iron and zinc contents of VI whole potato tubers were

evaluated. The effects of steam-cooking and storage at 4 ℃ on iron and zinc contents of

VI whole potato tubers were also evaluated. Moreover, the effect of VI treatment on cell

structures of potatoes was investigated.

2.2. Materials and methods

2.2.1. Materials

Three cultivars of potatoes were used: Toyoshiro, Snowden and Dejima. Toyoshiro

and Snowden potatoes were harvested in September 2010 and 2011, in Hokkaido, Japan.

Dejima potatoes were harvested in March 2013 in Kyushu, Japan. After harvesting,

tubers approximately 150-200 g in size, and with three characteristic diameters, 7.4-8.8, 5.1-6.8 and 3.8-4.7 cm, respectively, were selected, and then washed with tap water to remove the attached soil. Tubers were then dried with tissue papers, and provided for the VI treatment of iron and zinc.

Ferric pyrophosphate and zinc gluconate were purchased from Kanto Chemical Co., Inc. (Tokyo, Japan).

2.2.2. Vacuum impregnation treatment of potatoes

Ferric pyrophosphate was used for iron fortification; it can be used as a food additive to prevent iron deficiency in humans without colour and palatability changes (Navas-Carretero et al., 2009; Hurrell, 2002; Zimmermann and Hurrell, 2007; IMNA, 2004). However, as this salt is hardly soluble in water (Navas-Carretero et al., 2009), a maximum concentration at 0.4 g/100 g (Kishi, 1972) was used in this study.

Zinc gluconate was used for zinc fortification in this study; it is recognized as a food additive by the US food and drug administration (FDA) (Whittaker, 1998). The zinc VI treatment was carried out in a saturated concentration of 9 g/100 g of zinc gluconate solution.

A mass ratio, of potato to the solutions, of 1/33 (W/W) was used to ensure adequate

immersion and minimize the dilution effect (leaching of intercellular sap) on the concentration of the VI solution (Sormani et al., 1999). Also, a vacuum meter (PM-32A, Shimadzu, Kyoto, Japan) placed between the dessicator and vacuum pump (GDH-362, Shimadzu, Kyoto, Japan) was used to measure pressure values (Fig. 2-2).

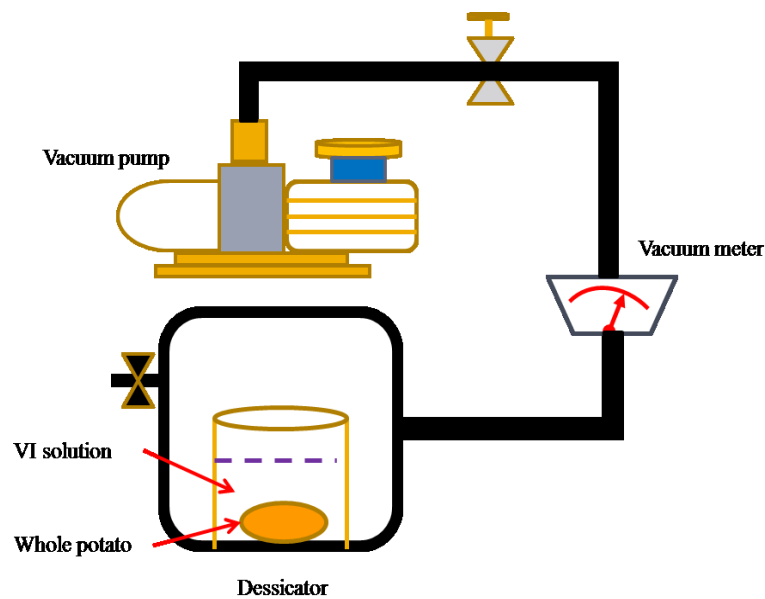**Fig. 2-2. Schematic representation of the vacuum impregnation system**

The experimental designs of VI treatment for vacuum pressure, vacuum time and restoration time experiments were expressed in Tables 2-1, 2-2 and 2-3, respectively. For design of vacuum pressure, a vacuum pressure of 10, 15, 20 and 30 hPa was applied in the VI system for 1 h (t_1) and after which atmospheric pressure was restored while

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samples remained immersed in the solution for 3 h (t_2) (Table 2-1). For design of vacuum time, a vacuum pressure of 10 hPa was applied to the system for 0, 15, 30, 60 and 120 min (t_1). After the vacuum period, the atmospheric pressure was restored, and the potato tuber was maintained in the VI solution for a restoration time (t_2) of 3 h (Table 2-2). For design of restoration time, a vacuum pressure of 10 hPa was applied for 1 h (t_1), and afterwards the atmospheric pressure was restored and the system remained at this pressure condition for 0, 1, 2, 3 and 4 h (t_2) (Table 2-3).

Table 2-1

Experimental design for vacuum pressure

Vacuum levels (hPa)	Vacuum period t_1 (min)	Restoration period t_2 (h)
10	60	3
15	60	3
20	60	3
30	60	3

Table 2-2

Experimental design for vacuum time

Vacuum levels (hPa)	Vacuum period t_1 (min)	Restoration period t_2 (h)
10	0	3
10	15	3
10	30	3
10	60	3
10	120	3

Table 2-3

Experimental design for restoration time

Vacuum levels (hPa)	Vacuum period t_1 (min)	Restoration period t_2 (h)
10	60	0
10	60	1
10	60	2
10	60	3
10	60	4

VI-treated whole potatoes were drained, rinsed with distilled water to remove the attached solution, and gently wiped with tissue papers. Iron and zinc contents of VI-treated samples, and non-vacuum (NV) treated samples (control; immersion in the VI solution without vacuum treatment) were analyzed immediately.

2.2.3. Cooking

Cooking experiments were done to investigate the effect of steam-cooking on iron and zinc contents of VI whole potatoes. VI whole potatoes were divided into two sections: (1) unpeeled, and (2) peeled. Peeled potatoes were obtained by peeling to a depth of 0.5 mm using a hand peeler (Mondy et al., 1992). Unpeeled or peeled whole potatoes were placed in a stainless steam cooker, which was covered with a lid and

steamed over boiling water at atmospheric pressure until a fork can be easily penetrated

(Faller and Fialho, 2009; Weaver et al., 1983).

2.2.4. Storage

Wustman and Struik (2007) reported that proper storage temperature is 4-5 ℃ for

table stock potato. Thus, the VI-treatment whole potatoes in the present study were

stored also at 4 ℃ and 90% relative humidity for up to 30 days. The iron and zinc

contents of the samples were measured at 0, 5, 10, 20 and 30 days.

2.2.5. Determination of iron and zinc

Potato skin is considered to be inedible (Fierens et al., 2012). Thus, iron or zinc

determination in this study was performed after removal of the potato skin; one potato

tuber was washed, peeled (except already peeled) and diced into approximately 5-mm

cubes. After mixing well whole cubes, approximately 10 g of potato cubes was placed

in a drying oven (DPS-41, Yamato Scientific Co., Ltd., Tokyo, Japan) at 70 ℃ for 18 h

and then put in a vacuum drying oven (DPS-48, Yamato Scientific Co., Ltd., Tokyo,

Japan) under 54 kPa vacuum at 70 ℃ for 2 h (AOAC, 1970). The dried sample was

powdered with a mortar and pestle. The powdered sample of 1 g was put into a crucible,

and then incinerated at 550 ºC in a muffle furnace (ETR-17K, Shibata Scientific Technology Ltd., Tokyo, Japan) system for 24 h (Ruerez, 2002). Subsequently, the incinerated sample was dissolved to 5 ml of 2 mol/L of hydrochloric acid at 60 ºC with a hotplate. Then, the dissolved solution was diluted to 100 ml in a volumetric flask with distilled water. The iron and zinc contents were determined with an atomic absorption spectrometer (AA-6300, Shimadzu, Kyoto, Japan) system at a wavelengths of 248.3 nm and 213.8 nm, respectively (Brandão et al., 2007; Tompkins et al., 2007). Two calibration curves for iron and zinc contents were established, using iron and zinc solutions containing 0, 1, 2, 5 and 10 μg/ml and 0, 0.1, 0.5, 1 and 3 μg/ml, respectively.

2.2.6. Cryo-SEM (low temperature scanning electron microscope)

Structural analysis was carried out by the method of Gras et al. (2003); rectangular pieces (4 × 1.5 × 5 mm) were cut from raw and VI treated potatoes, frozen by immersion in slush nitrogen, freeze-fractured (at -94.5 ºC, 10^{-3} Pa for 15 min) and viewed using a JEOL JSM-6510 microscope.

2.2.7. Statistical analysis

One tuber was used per treatment. Each treatment condition was assayed 6 times.

Results were averaged to obtain mean values. Duncan's multiple range test of SPSS 9.0 (SPSS Inc., Chicago, USA) was used to determine differences between means of vacuum pressure, vacuum time, restoration time, cooking treatment or storage time.

2.3. Results and discussion

2.3.1. Effect of vacuum pressure

Fig. 2-3 shows the relation between the iron content of VI whole potatoes of the Dejima and vacuum pressure. As shown in this figure, the iron content increased with vacuum level; especially, the VI potatoes at 10 hPa had 9.5 times higher ($p<0.05$) iron contents than that of the raw potatoes, and contained a 5.9 mg iron content per 100 g.
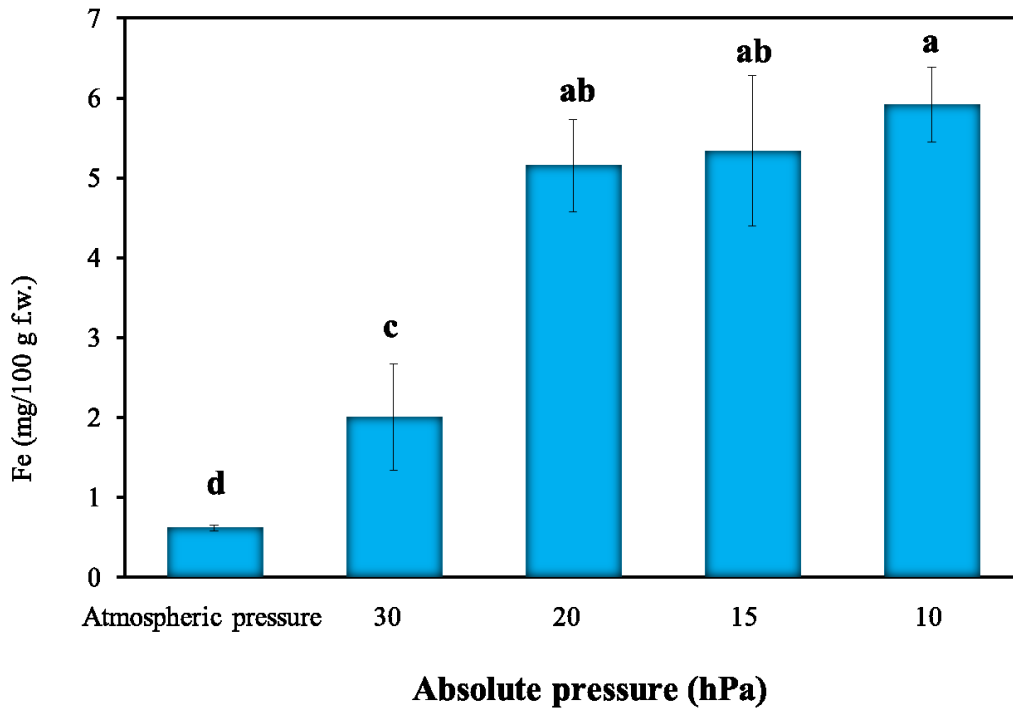
Fig. 2-3. Effect of vacuum levels on iron contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g iron concentration; vacuum time for 60 min; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

A similar result has been obtained by Schulze et al. (2012). They reported that the quercetin and quercetin glycosides contents of vacuum-impregnated apple slices increased with vacuum level.

Hydrodynamic mechanism is associated with the pressure gradient between the vacuum and the atmospheric phase. According to Fito (1994), capillary forces increase as the system pressure decreases. Depending on the pressure of the vacuum phase, air

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occluded and liquid penetration occurred. The capillary pressure has an impact on the impregnation result, because it is a function of the capillary forces, which influence the hydrodynamic mechanism.

In this figure, high values of iron content of vacuum impregnated potatoes were obtained at a pressure of 20 hPa or less. Thus, VI experiments in later studies were carried out at a maximum pressure level, 10 hPa of this equipment.

2.3.2. Effect of vacuum time and restoration time

Fig. 2-4 shows the relation between the iron content of VI whole potatoes and vacuum time (t_1). As shown in this figure, the iron content increased with t_1; especially, the 60 min VI potatoes of the Toyoshiro had a 6.4 times higher ($p<0.05$) iron content than that of the control (non-vacuum 60 min-immersion in the iron solution) potatoes and contained a 4.1 mg iron content per 100 g (fresh weight). For the Snowden, the 60 min VI whole potatoes had 6.6 times higher ($p<0.05$) iron contents than that of the control potatoes and possessed a 4.4 mg iron content per 100 g (fresh weight).
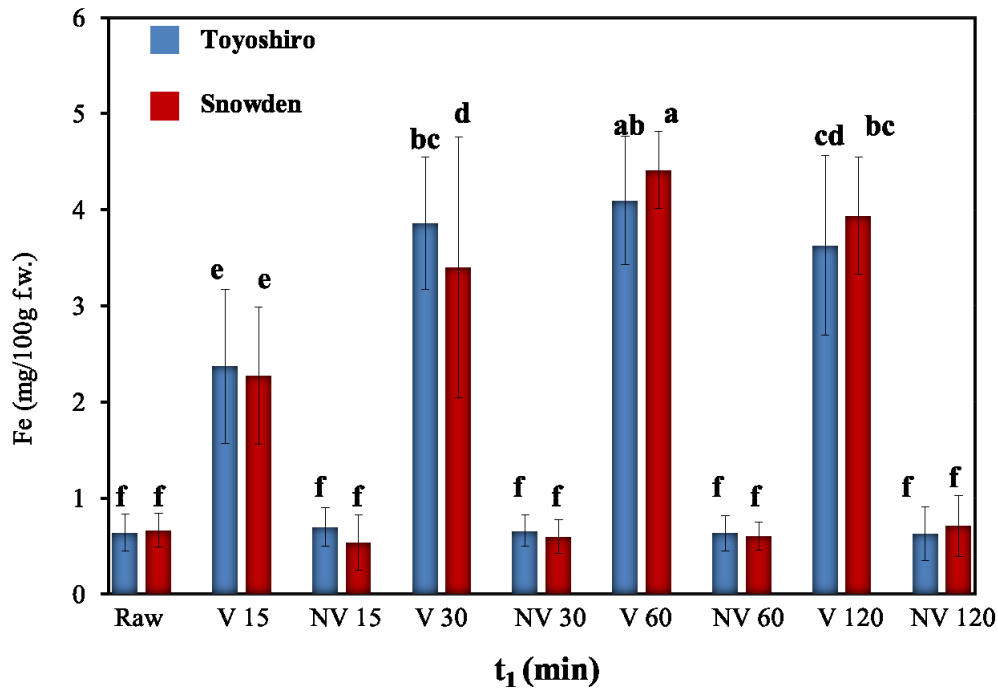
Fig. 2-4. Effect of vacuum time (t_1) on iron contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g iron concentration; vacuum pressure at 10 hPa; restoration time for 3 h. Abbreviations: V 15: t_1, 15 min; NV 15: non-vacuum (NV) 15 min-immersion in the iron solution; V 30: t_1, 30 min; NV 30: non-vacuum (NV) 30 min-immersion in the iron solution; V 60: t_1, 60 min; NV 60: non-vacuum (NV) 60 min-immersion in the iron solution; V 120: t_1, 120 min; NV 120: non-vacuum (NV) 120 min-immersion in the iron solution. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 2-5 shows the relation between the zinc content of VI whole potatoes and vacuum time (t_1). As shown in this figure, the zinc content increased with t_1; especially, the 60 min VI whole potato of the Toyoshiro had 61 times higher ($p<0.05$) zinc contents than that of the control (non-vacuum 60 min) potatoes, and contained a 17.3 mg zinc content per 100 g (fresh weight). In addition, the 60 min VI whole potatoes (per 100 g)

could provide adult men and women more than 100% of the RDA values. Even the 15 min VI whole potatoes (per 100 g) could exceed RDA values (11 mg/day of adult man and 8 mg/day of women) (FNB, 2001). For the Snowden, the 60 min VI whole potatoes had 45 times higher ($p<0.05$) zinc contents than that of the control potatoes and had a 16.7 mg zinc content per 100 g. In addition, the VI whole potatoes (per 100 g of fresh weight), beyond 15 min of t_1, had zinc contents higher than the RDA values for adult men (11 mg/day) and women (8 mg/day). Especially, 60 min VI whole potatoes (100 g) could provide adult men and women with 152 and 210% of the RDA values (FNB, 2001), respectively.
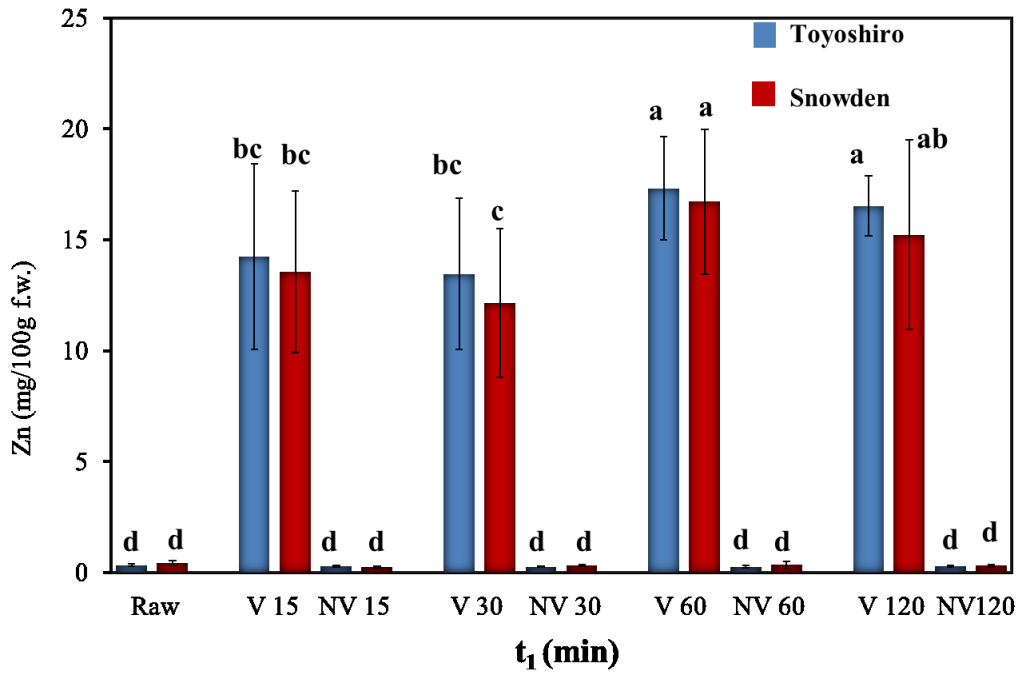
Fig. 2-5. Effect of vacuum time (t_1) on zinc contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; restoration time for 3 h. Abbreviations: V 15: t_1, 15 min; NV 15: non-vacuum (NV) 15 min-immersion in the zinc solution; V 30: t_1, 30 min; NV 30: non-vacuum (NV) 30 min-immersion in the zinc solution; V 60: t_1, 60 min; NV 60: non-vacuum (NV) 60 min-immersion in the zinc solution; V 120: t_1, 120 min; NV 120: non-vacuum (NV) 120 min-immersion in the zinc solution. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

The iron content of VI whole potatoes increased during restoration time (t_2) (Fig. 2-6). The 3 h VI whole potatoes (Toyoshiro) had 6.4 times higher ($p<0.05$) iron contents than that of the raw potatoes, and reached a 4.1 mg iron content per 100 g. Similarly, the VI whole potatoes of Snowden with the maximum iron content were obtained beyond 3 h of t_2, and reached a 4.4 mg iron content per 100 g. The 3 h restoration potatoes had 6.6

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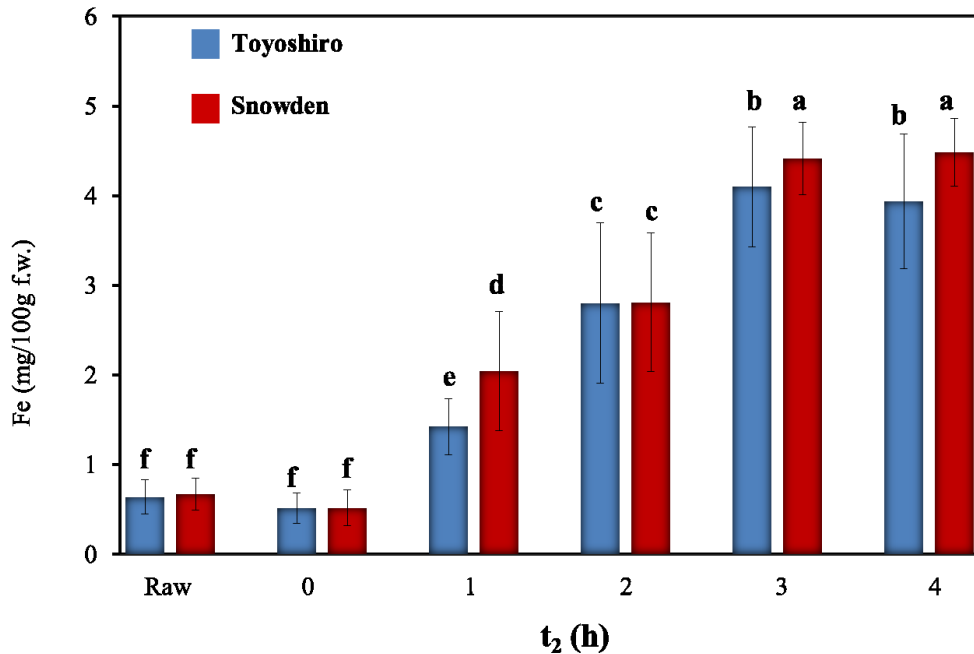times higher ($p<0.05$) iron contents than that of the raw potatoes.

Fig. 2-6. Effect of restoration time (t_2) on iron contents of vacuum-impregnated

whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Zinc content of the VI whole potatoes increased during restoration time (t_2) (Fig. 2-7). The 3 h VI-treatment whole potatoes (Toyoshiro) had 53 times higher ($p<0.05$) zinc contents than that of the raw potatoes, and reached a 17.3 mg zinc content per 100 g. Similarly, the maximum zinc content of the Snowden VI potatoes was obtained beyond 4 h of t_2, and led to 19.3 mg zinc content per 100 g.
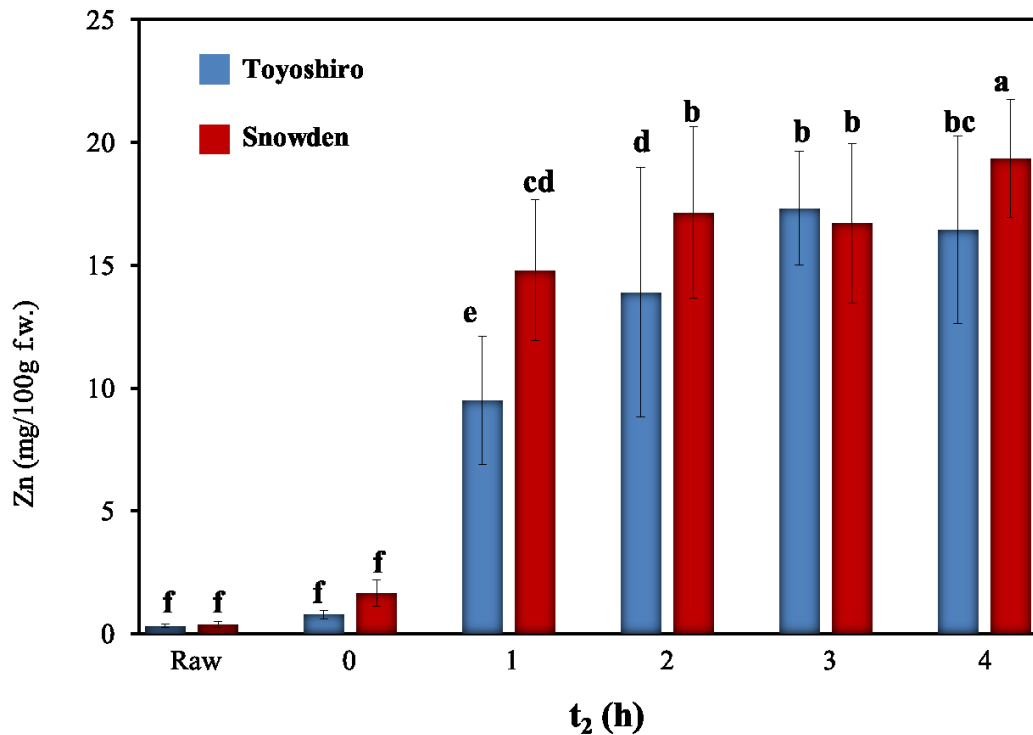
Fig. 2-7. Effect of restoration time (t_2) on zinc contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Concerning the VI system, Fito (1994) report the in-flow of the external liquid throughout the capillary pores, controlled by the expansion/compression of the internal gas. This is responsible for the VI processes of porous products when reduced pressures are imposed in a solid liquid system (vacuum step) followed by the restoration of atmospheric pressure. During the vacuum step (t_1) the internal gas in the product pores

is expanded and partially flows out (gas release). All of the steps are coupled with the capillary penetration as a function of the interfacial tension of the liquid and the diameter of pores. In the atmospheric step (t_2), the residual gas is compressed and the external liquid flows into the pores as a function of the compression ratio. Plant tissue has intercellular spaces that may contain a gas or liquid phase and are susceptible to impregnation with an external solution (Zhao and Xie, 2004). Sun and Li (2003) observed that the intact cells of fresh potato tissue are in perfect contact, although some small intercellular voids exist. Their voids are intercellular spaces which are common in parenchymous tissue. The intercellular spaces volumes in potatoes are estimated as 1% of the total volume of potatoes (Aguilera and Stanley, 1990). Therefore, in the present study, the external solution with high iron or zinc contents may gradually penetrate into the intercellular spaces within the potato in the atmospheric step (restoration step).

In the present study, a long vacuum time (1 h) and a long restoration time (3 or 4 h) were needed for whole potatoes. As mentioned previously (Chapter 1), Salvatori et al. (1998) reported that in plant tissue samples of about 2 cm in characteristic dimension, with the relatively large intercellular spaces and elastic cellular arrangement, the necessary lengths of vacuum time and restoration time are within 5 min, respectively. Nevertheless, in big pieces with small pores, much more time could be necessary to

complete sample equilibration in mechanical terms because of difficulties for gas release. Likewise, impregnation times can be prolonged due to the greater pressure drops (Chiralt et al., 2001). In the present study, potatoes have characteristic dimension larger than 2 cm. In addition, the intercellular space of potatoes is very small (1%) compared with that of apple (25%), peach (15%) and mushroom (37-45%) (Alzamora et al., 2000). Also, whole potatoes have thick periderm, which is less permeable to water and gas (Peterson et al., 1985). Thus, these long vacuum and restoration times in the present study may be due to the above reasons.

2.3.3. Effect of steam-cooking

Fig. 2-8 shows the decrease in iron content of VI whole potatoes by steam-cooking. As shown in the figure, the iron content of Toyoshiro VI-cooked unpeeled potatoes decreased by 11% while the VI-cooked peeled potatoes declined to a greater extent (43%). In addition, the VI-cooked unpeeled potatoes had 6 times higher ($p<0.05$) iron contents than that of the raw-cooked unpeeled potatoes. Also, the VI-cooked peeled potatoes had 5 times more ($p<0.05$) iron contents than that of the raw-cooked peeled potatoes. In addition, iron content of the VI-cooked unpeeled and peeled potatoes of Snowden variety decreased by around 30%. However, VI-cooked unpeeled potatoes had

10 times higher ($p<0.05$) iron contents than that of raw-cooked unpeeled potatoes. Moreover, VI-cooked peeled potatoes had 13 times higher ($p<0.05$) iron contents than that of raw-cooked peeled potatoes.
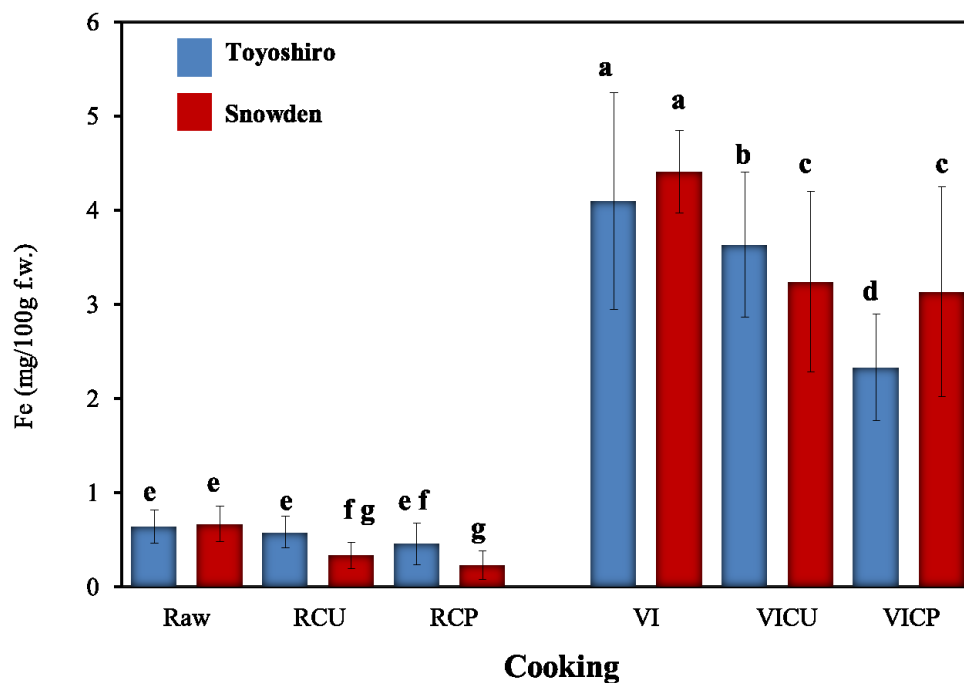

Fig. 2-8. Effect of steam-cooking on iron contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Abbreviations: RCU, raw-cooking (unpeeled); RCP, raw-cooking (peeled); VICU, VI-cooking (unpeeled); VICP, VI-cooking (peeled). Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

The International Year of Potato (IYP, 2008) and Keijbets (2008) reported that potato consumption per capita in 2005 was the highest in Europe, followed by North America. In addition, it is also well known large fractions of populations in the industrialized world can be affect by iron deficiency, although it is a problem mainly in developing countries. In Europe, iron deficiency is considered to be one of the main nutritional deficiency disorders (Hallberg, 1995). Epidemiological surveys performed in European countries showed that iron depletion affects 10-30% of menstruating women and iron deficiency anaemia for 1.5 to 14% (Hercberg et al., 2001). In Europe, daily potato intake per capita, in 2005, was 260 g (IYP, 2008). Thus, European daily potato consumption of two cultivars of VI-cooked unpeeled and peeled potatoes can provide adult men with 93-104 and 67-90% of the RDA of iron, respectively. In addition, that of the unpeeled and peeled of VI-cooked potatoes can provide adult women 43-48 and 31-41% of the RDA level (Schümann et al., 2007), respectively. Thus, the VI whole potatoes had an advantage in providing foods enriched with iron content.

Fig. 2-9 shows the decrease in zinc content of VI whole potatoes by steam-cooking. As shown in the figure, the zinc content of Toyoshiro VI-cooked unpeeled potatoes decreased by 4% while VI-cooked peeled potatoes declined to a greater extent (26%). Moreover, VI-cooked unpeeled potatoes had 63 times higher ($p<0.05$) zinc contents

than that of raw-cooked unpeeled potatoes. Also, VI-cooked peeled potatoes had 47

times more ($p<0.05$) zinc contents than that of raw-cooked peeled potatoes. In addition,

the zinc content of VI-cooked unpeeled and peeled potatoes of Snowden variety

decreased by 2 and 11%, respectively. However, VI-cooked unpeeled whole potatoes

had 94 times higher ($p<0.05$) zinc contents than that of raw-cooked unpeeled potatoes.

Moreover, VI-cooked peeled whole potatoes had 75 times higher ($p<0.05$) zinc contents

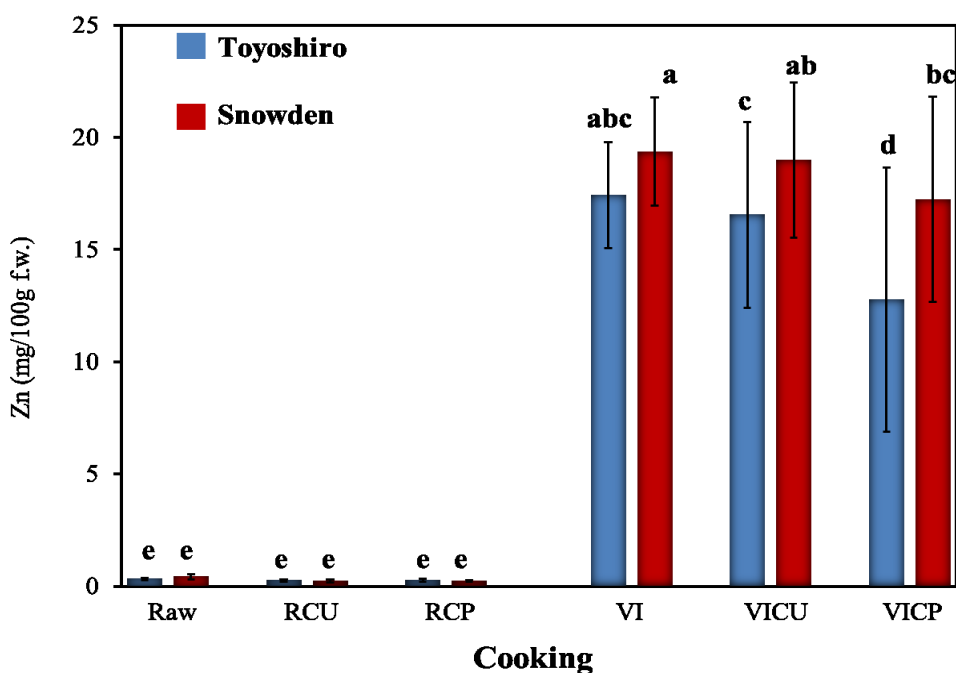than that of raw-cooked peeled potatoes.

Fig. 2-9. Effect of steam-cooking on zinc contents of vacuum-impregnated whole potato tubers.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Abbreviations: RCU, raw-cooking (unpeeled); RCP, raw-cooking (peeled); VICU, VI-cooking (unpeeled); VICP, VI-cooking (peeled). Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Worldwide daily potato intake per capita was 86 g in 2005 (IYP, 2008). Thus, daily potato consumptions of VI-cooked unpeeled and peeled potatoes could provide adult men with 130-148 and 100-135% of the zinc RDA values, respectively. In addition, those of the unpeeled and peeled of VI-cooked potatoes could give adult women 178-203 and 137-185% of the zinc RDA levels (FNB, 2001), respectively. Thus,

the VI potatoes had a health advantage in providing foods enriched with zinc content.

As for calcium distribution in tissues of calcium VI products (eggplant, carrot and oyster mushroom), Gras et al. (2003) showed that calcium incorporation mainly occurred in the intercellular spaces using an energy dispersive X-ray microanalysis. Thus, the iron or zinc may be also located in intercellular space in the present study. Peterson et al. (1985) indicated that the lenticels of potatoes allow excess water loss from the internal tissues of the tuber. Heat by steam-cooking may cause an expansion of gas in the intercellular space of the potato, which might lead to pushing of iron or zinc solution out of the intercellular space. Therefore, larger losses of iron or zinc by steam cooking in the present study might be due to a direct loss from the intercellular spaces for peeled VI-potatoes. Then, the cooking losses in iron and zinc of the whole unpeeled potato are much smaller than those of the peeled potato. This may be due to the thick periderm of whole potatoes, which is less permeable to water and gas (Peterson et al., 1985). Moreover, a difference in iron or zinc content of unpeeled and peeled VI potatoes for Snowden variety was small in Figs 2-8 and 2-9. Less permeable surfaces due to starch gelatinization might be formed on the surface of peeled whole potato by heating. Further study is needed on iron or zinc distribution in the tissue of VI potatoes.

2.3.4. Effect of storage

Iron content of VI whole potatoes was kept during the storage at 4 ℃ for 30 days (Fig. 2-10). As shown in this figure, there was no significant difference in iron content of the VI potato tubers for Toyoshiro or Snowden variety between 0 and 30 days of storage. Thus, VI potatoes of Toyoshiro and Snowden also retained 6 times higher ($p<0.05$) iron contents during storage compared with that of the raw potatoes.
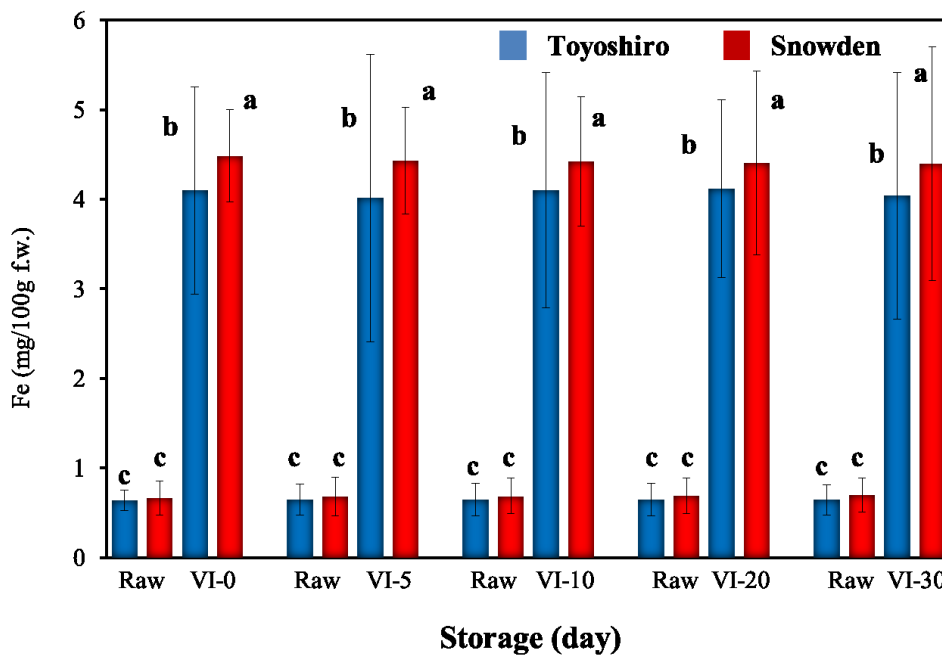

Fig. 2-10. Change in iron contents of vacuum-impregnated whole potato tubers during storage at 4 ℃.

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g of iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Abbreviations: VI-0, 0 day storage of VI potato; VI-5, 5 days storage of VI potato; VI-10, 10 days storage of VI potato; VI-20, 20 days storage of VI potato; VI-30, 30 days storage of VI potato. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 2-11 shows the change in zinc content of VI whole potatoes during storage at 4 ℃. As shown in this figure, there was no significant difference in zinc content of the VI whole potato tubers for Toyoshiro or Snowden variety between 0 and 30 days of storage. Thus, VI whole potatoes of Toyoshiro retained 50 times higher ($p<0.05$) zinc contents during storage compared with that of raw potatoes. In addition, for Snowden variety, VI whole potatoes also kept 40 times higher ($p<0.05$) levels during storage compared with that of raw potatoes.
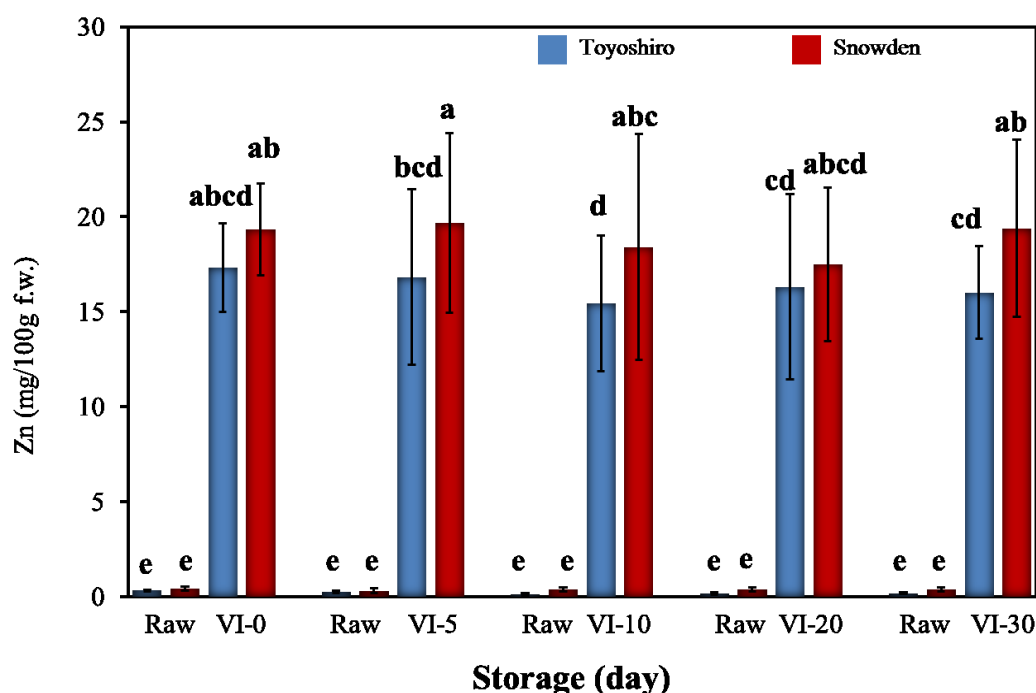
Fig. 2-11. Change in zinc contents of vacuum-impregnated whole potato tubers

during storage at 4 °C.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure 10 hPa; vacuum time for 1 h; restoration time for 3 h. Abbreviations: VI-0, 0 day storage of VI potato; VI-5, 5 days storage of VI potato; VI-10, 10 days storage of VI potato; VI-20, 20 days storage of VI potato; VI-30, 30 days storage of VI potato. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

VI can be considered as a tool in the development of fruit and vegetable products without disrupting their cellular structure, while conveniently modifying their original composition (Chiralt et al., 1999). Moreover, Gras et al. (2003) showed that many calcium ions of VI products existed only in the intercellular space, not inside of cells. In the present study, the zinc solution may be also kept in the intercellular space without

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disrupting internal cells, and thus, leaching of the zinc solution occurred from the tuber during storage.

2.3.5. Microstructure of vacuum-impregnated whole potato

Fig. 2-12 shows the microstructure of potatoes. As shown in this figure, there were no failures of cell walls of VI whole potatoes (Fig. 2-12 (b) and (d)) similar to raw potatoes (Fig. 2-12 (a) and (c)). This result was in agreement with that reported in earlier study on vacuum-impregnated carrot slices (Gras et al., 2002). This figure proved the VI treatment as a useful way to introduce desirable solutes into the internal tissues of whole potato tubers without disrupting internal cells.

Finally, this study indicates that VI treatment with iron and zinc solutions of whole potatoes was useful for enriching iron and zinc contents.
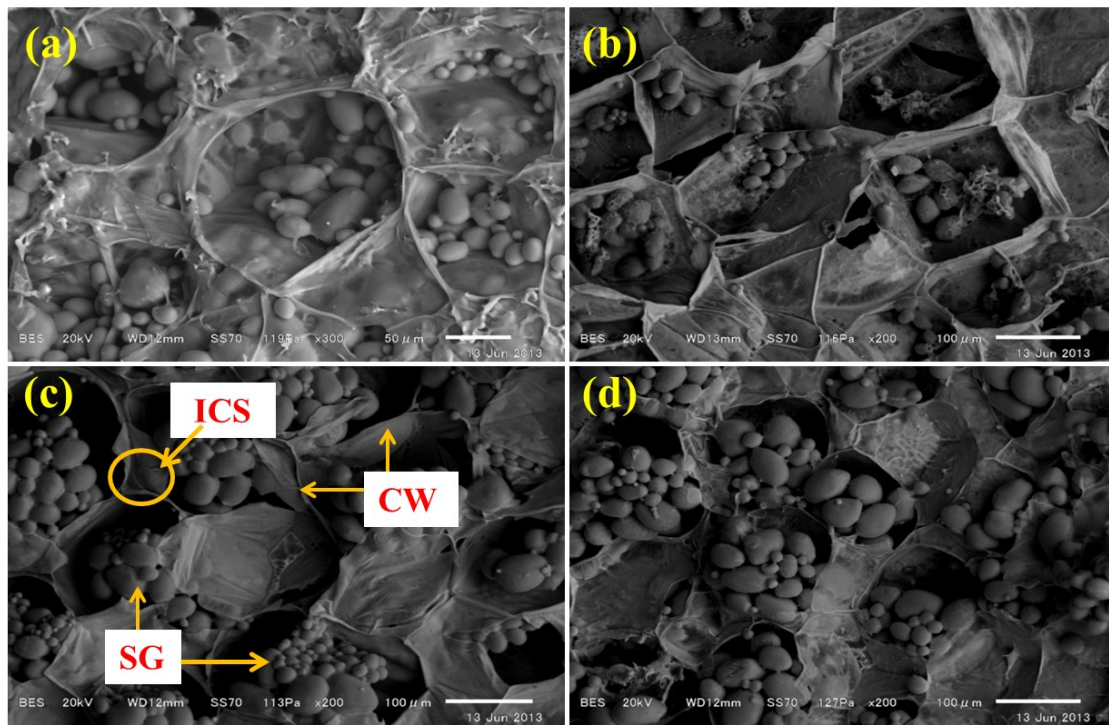
Fig. 2-12. Cryo-SME micrographs of potato tissues: (a) raw potato (Toyoshiro);

(b) vacuum-impregnated potato (Toyoshiro); (c) raw potato (Snowden) (d)

vacuum-impregnated potato (Snowden).

Vacuum impregnation (VI) conditions: VI solution at 0.4 g/100 g of iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Abbreviations: CW, cell wall; SG, starch grain; ICS, intercellular space.

2.4. Conclusions

The results of the present study indicate that the iron content of VI whole potatoes increased with vacuum level (pressure). Also, iron and zinc contents of VI whole potatoes increased with vacuum time and restoration time.

Moreover, VI-cooked unpeeled and peeled potatoes had 6 times higher iron contents than that of raw-cooked unpeeled and peeled potatoes. European daily potato consumption is around 260 g and when these amounts of VI-cooked unpeeled and peeled potatoes are taken by adult men with 93-104% and 67-90% of the RDA of iron can be supplied, respectively. Also, same amount of the VI-cooked unpeeled and peeled potatoes can supply adult women with 43-48% and 31-41% of the RDA level, respectively. Moreover, the VI whole potatoes had 6 times higher iron contents (>4 mg/100 g fr.wt.) through 30 days of storage at 4 ℃, compared with that of raw potatoes.

In addition, VI-cooked unpeeled or peeled potatoes had 63-94 times and 47-75 times higher zinc contents than that of raw-cooked unpeeled or peeled potatoes, respectively. Daily potato consumption on the world average is 86 g when these amounts of the VI-cooked unpeeled and peeled potatoes can provide adult men with 130-148 and 100-135% of the RDA of zinc, respectively. Also, same amount of the VI-cooked unpeeled and peeled potatoes can supply adult women with 178-203% and 137-185% of the RDA levels, respectively. The high zinc content of VI whole potatoes was kept during 4 ℃-storage for 30 days.

This study therefore indicated that VI treatment of whole potatoes with iron and zinc solutions was useful for enriching iron and zinc contents of peeled or unpeeled

cooked potatoes.

Microstructure analysis showed that VI occurred without disrupturing internal cells of whole potato tubers.

Chapter 3

Distribution of iron, zinc and ascorbic acid contents within vacuum-impregnated whole potatoes

3.1. Introduction

In recent years vacuum impregnation (VI) has become a popular method to enrich food products, such as fruits and vegetables, with beneficial food ingredients for human health (Schulze et al., 2012). Structured foods (porous foods) such as fruits and vegetables have a great number of pores (intercellular space) which are occupied by gas, or native liquid to quite an extent, which offer the possibility of being impregnated by a determined solution thereby improving composition by adding specific/selected solutes: incorporation of acids, preservatives, sugars or other water activity depressors, special nutrients, etc. In this sense, VI can be considered as a tool in the development of fruit or vegetable products without disrupting their cellular structure, while conveniently modifying their original composition (Chiralt et al., 1999).

The net mass flow is transferred by the vacuum operations between porous foods and a liquid in which they are immersed, and it is the result of the contribution of several mechanisms such as osmotic and diffusion etc.. Among them, hydrodynamic

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mechanism may play an important role in terms of total amount of transferred mass (Fito, 1994), because the changes in pressure in the system produce strong driving forces responsible for mass transfer (Fito et al., 1994; Fito and Chiralt, 1995). VI mass transfer caused by pressure change is affected by several factors, including mechanical properties and pore sizes samples (Zhao and Xie, 2004). Tissue structure also plays a very important role, not only due to the total porosity, but also to the size and shape distribution of pores and the communications (interactions) between themselves and with the external liquid (Fito et al., 1996).

Potato has a complex structure of morphological elements: skin with lenticels, eyes, bud and stem ends, cortex, a ring of vascular bundles, perimedullary zone and pith with medullary rays (Fig. 3-1) (Rastowski and van Es, 1981; Sadowska et al., 2008). Thus, the nutrients incorporated by VI may distribute non-homogeneously within the VI whole potatoes.

However, no studies have been found on the distribution of nutrients within VI whole potatoes. Thus, the longitudinal or transverse distribution of iron, zinc and ascorbic acid contents within VI whole potatoes was evaluated in this Chapter.
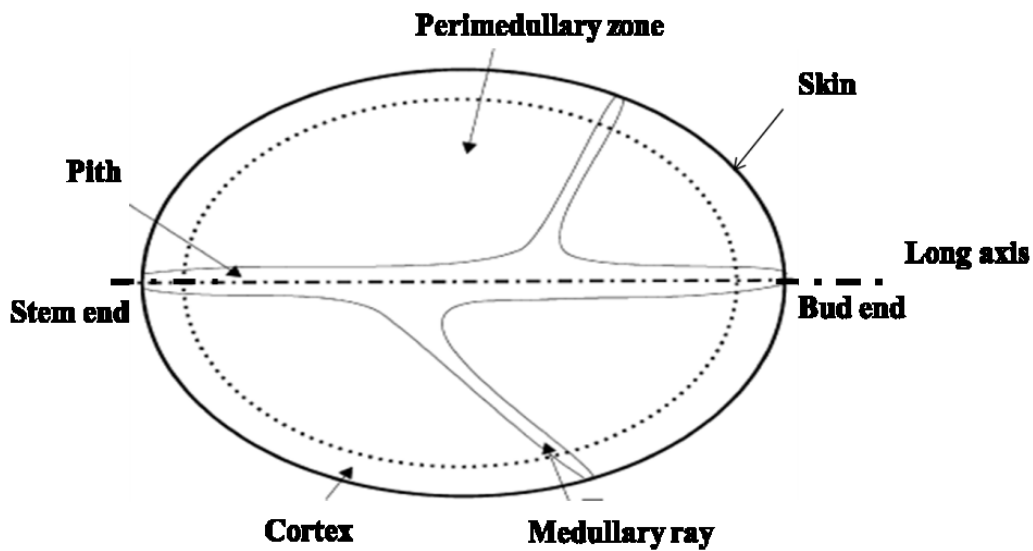
Fig. 3-1. Anatomy of potato tuber (Sadowska et al., 2008)

3.2. Materials and methods

3.2.1. Materials

Potatoes used in this study were the same as those described in Chapter 2. These potatoes were washed with tap water to remove the attached soil. Tubers were then dried the surface water with tissue papers, and provided for the VI treatment.

Ferric pyrophosphate and zinc gluconate were also the same as those described in Chapter 2.

Ascorbic acid and metaphosphoric acid were purchased from Kanto Chemical Co., Inc. (Tokyo, Japan).

3.2.2. Red ink treatment of whole potatoes

Red ink immersion test was done to investigate impregnation progress within potato by VI treatment. Red ink (Kokuyo, IP-540r) was distilled 300 times using ion-exchanged water as described by Hironaka et al. (2011). Whole potatoes of Toyoshiro variety were immersed in the red ink solution placed inside a desiccator at room temperature. The VI apparatus used in this experiment was the same as that described in Chapter 2. A vacuum pressure of 10 hPa was applied to the system for 1 h, then atmospheric pressure restoration for 0, 1, 2 or 3 h. The whole potato tubers were cut longitudinally after vacuum or restoration. Then cut sections were photographed by a digital camera (EX-Z400, Casio, Tokyo, Japan).

3.2.3. Vacuum impregnation treatment of potatoes

VI treatments of iron or zinc were performed in the saturated solution of ferric pyrophosphate or zinc gluconate as mentioned in Chapter 2. VI treatment of ascorbic acid was carried out in a concentration of 10 g/100 g (Hironaka et al., 2011). Mass ratio of potato to solutions was the same as that described in Chapter 2. A vacuum pressure of 10 hPa was applied for 1 h, and atmospheric pressure restoration for 3 h. VI-treated whole potatoes were drained, rinsed with distilled water to remove the attached solution,

and gently wiped with tissue papers. Iron, zinc and ascorbic acid contents of VI-treated samples were analyzed immediately.

3.2.4. Cooking

The cooking method was as same as that described in Chapter 2 except only that unpeeled potatoes were used.

3.2.5. Sample preparation

After removal of potato skin, whole potatoes were divided longitudinally into 3 fractions (bud end, middle and stem end sections) (Fig. 3-2 (a)), or transversely into 3 fractions (outer, middle and center sections) (Fig. 3-2 (b)).
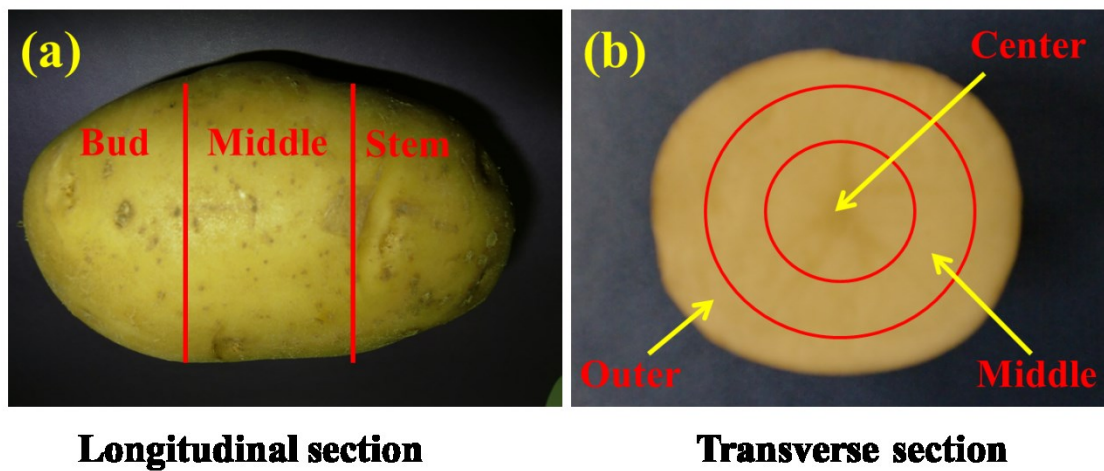

Fig. 3-2. Zones of tuber sample for analysis.

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3.2.6. Determination of iron, zinc and ascorbic acid contents

Each fraction was diced into approximately 5-mm cubes. After mixing cubes well, approximately 10 g of cubes were prepared for determination of iron and zinc contents. Determination of iron and zinc was carried out by the atomic absorption spectrometry method as described in Chapter 2.

The concentration of ascorbic acid was determined using the HPLC technique reported by Sapers et al. (1990) with slight modification. Potato tissues (10 g) were blended with a solution containing 10 ml of 2.5% metaphosphoric acid and 20 ml of acetonitrile: 0.05 M KH_2PO_4 (75:25). The homogenate was filtered and then passed through a C_{18} Sep-Pak cartridge (Waters Associates, Milford, MA) and a 0.45-μm HPLC disk (Paul Corp., Japan). The filtrate was injected into the HPLC system, equipped with a pump (LC-20AD, Shimadzu, Kyoto, Japan), a column oven (CTO-20A, Shimadzu, Kyoto, Japan) and a UV detector (SPD-M20A, Shimadzu, Kyoto, Japan) set at 254 nm wavelength. The chromatographic column was a 7.8×300 mm i.d. of Gelpack C_{18} (GL-C610H-S, Hitachi, Tokyo, Japan). A 0.3% metaphosphoric acid solution was used as mobile phase. An ascorbic acid standard curve was prepared, using solutions containing 0, 25, 50, 75, and 100 mg/ml. The standard solution was injected into the HPLC system and the corresponding peak area was obtained (Diamante et al.,

2002).

3.2.7. Statistical analysis

All analyses were performed six times, and results were averaged to obtain mean values. Duncan's multiple range test of SPSS 9.0 (SPSS Inc., Chicago, USA) was used to determine differences between means of longitudinal or transverse sections.

3.3. Results and discussion

3.3.1. Distribution of red ink within VI whole potato

Fig. 3-3 shows the impregnation of red ink into a whole potato during restoration. No impregnations occurred in the potato without restoration (Fig. 3-3 (a)). Thus, vacuum treatment alone could not cause impregnation into the potato. However, red ink impregnated into areas between the vascular ring and the periderm within restoration time of 2 h (Fig. 3-3 (b) and (c)), and at restoration for 3 h, the impregnation occurred also at the central pith (Fig. 3-3 (d)).

Artschwager (1924) reported that the pith forms the narrow central core of the tuber, but is continuous with eyes by means of lateral branches, and the vascular ring (as it appears to the naked eye) constitutes a narrow band of tissue that contains xylem and secondary phloem.

While whole potatoes have a thick periderm to prevent rapid water loss from the thin-walled parenchyma of the tuber (Peterson et al., 1985), they have 74–141 lenticels per tuber (Wigginton, 1973). Lenticels provide permeable regions (Cutter, 1991). For example, Burton (1965) found an O_2 permeability value of 2.5 mm^3 cm^{-2} h^{-1} kPa^{-1} for mature tubers.

When a potato is immersed in a concentrated solution of physiologically active compound under vacuum, air might be extracted from eyes and lenticels and then, when atmospheric pressure is restored, impregnation occurs at the intercellular spaces of porous tissues through eyes and lenticels by capillary action and by pressure gradients (i.e., hydrodynamic mechanism) that are imposed on the system, helping incorporation of physiologically active compounds (Fito, 1994). So, the strong impregnation of red ink in the tuber was found at the central pith and the areas between the vascular ring and the periderm, as shown in Fig. 3-3.
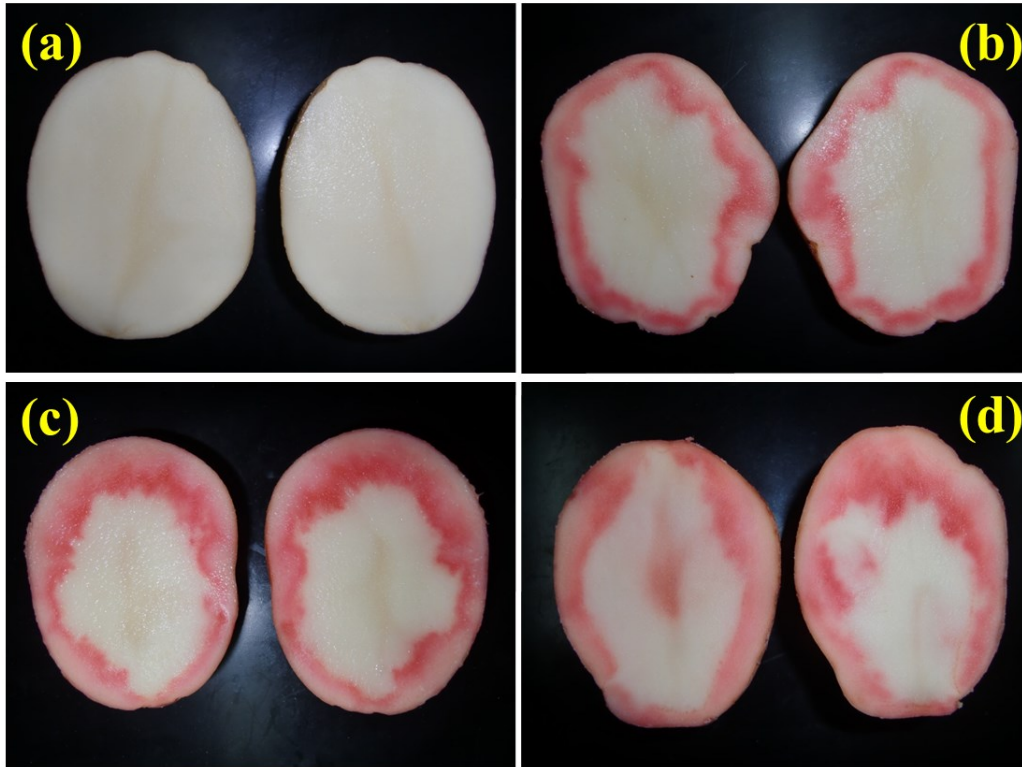
Fig. 3-3. Impregnation of red ink into whole potato tuber of Toyoshiro variety during restoration.

Vacuum impregnation (VI) conditions: vacuum pressure at 10 hPa, vacuum time for 1 h; restoration time for 0 (a), 1 (b), 2 (c) and 3 h (d).

3.3.2. Distribution of iron, zinc and ascorbic acid contents in longitudinal sections

Fig. 3-4 shows the distribution of iron content in longitudinal sections of VI whole potatoes of Toyoshiro. As shown in this figure, the bud end of uncooked and cooked VI potatoes had a higher ($p<0.05$) iron content than that of the middle and stem end of uncooked and cooked VI potatoes. In addition, the iron contents of the bud end, middle

and stem end of VI potatoes decreased by steam-cooking, but the bud end, middle part

and stem end of VI-cooked potatoes had 7, 4.6 and 3.4 times higher ($p<0.05$) iron

content than that of the bud end, middle part and stem end of the raw-cooked potatoes,
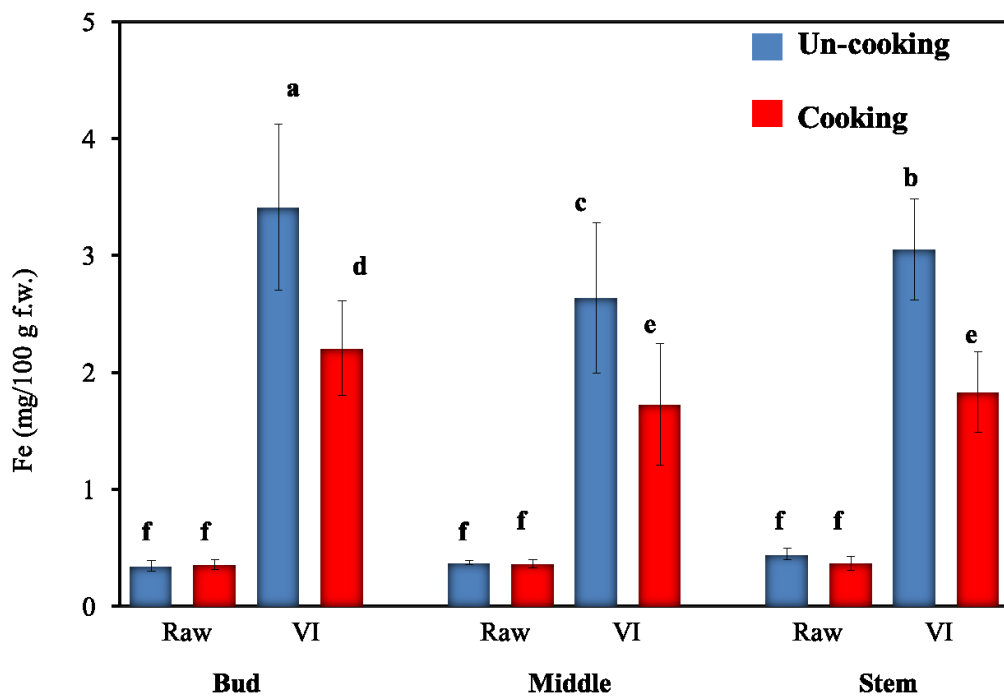
respectively.

Fig. 3-4. Distribution of iron content in longitudinal sections of the vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-5 shows the distribution of iron content in longitudinal sections of the VI

whole potatoes of Snowden. As shown in this figure, the bud end of uncooked or cooked VI potatoes had a higher ($p<0.05$) iron content than that of the middle part and stem end of uncooked and cooked VI potatoes. In addition, steam-cooking decreased iron content of each section of VI potatoes, but the bud end, middle part and stem end of VI-cooked potatoes had 6.2, 4.8 and 5 times higher ($p<0.05$) iron content than that of the bud end, middle part and stem end of raw-cooked potatoes, respectively.
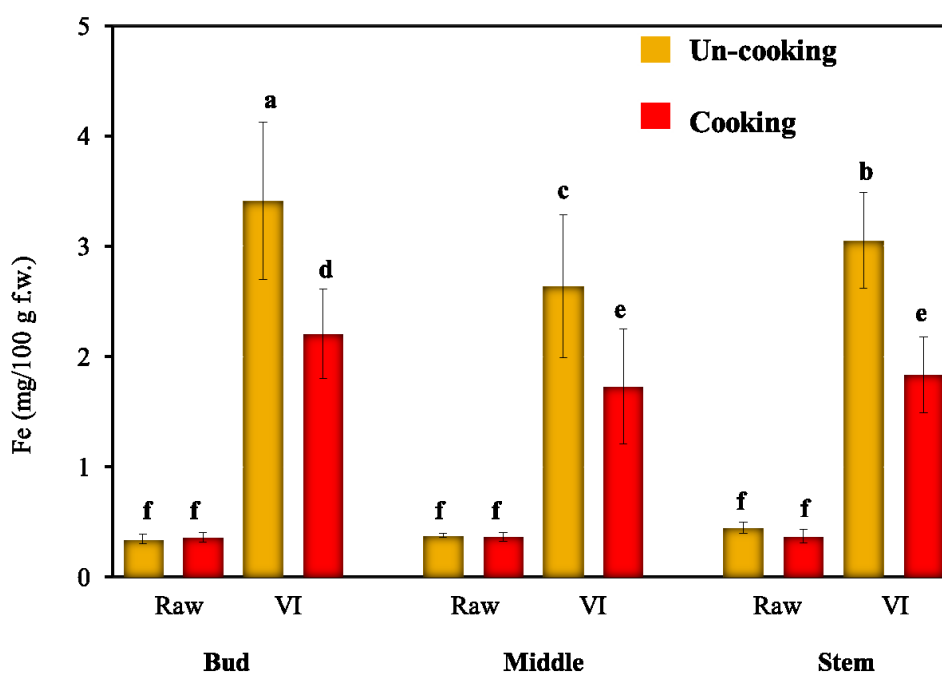

Fig. 3-5. Distribution of iron content in longitudinal sections of the vacuum-impregnated whole potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-6 shows the distribution of zinc content in longitudinal sections of VI whole potatoes of Toyoshiro. As shown in this figure, the bud end of un-cooked and cooked VI potatoes had a higher ($p<0.05$) zinc content than that of the middle part and stem end of un-cooked and cooked VI potatoes. Moreover, the bud end, middle part and stem end of VI-cooked potatoes had 28, 17 and 16 times higher ($p<0.05$) zinc contents than that of the bud end, middle part and stem end of raw-cooked potatoes, respectively.
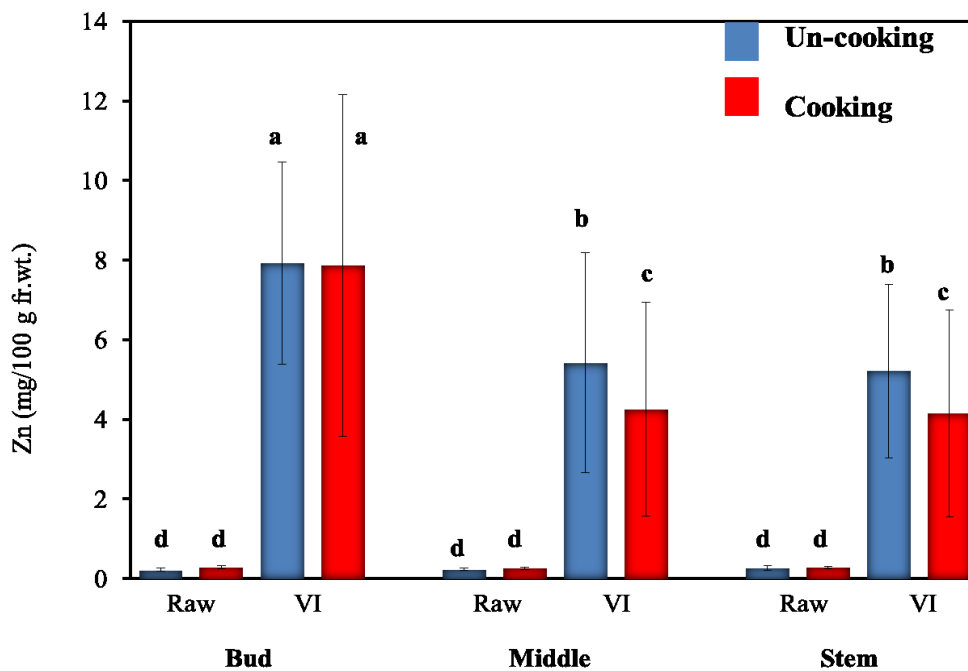

Fig. 3-6. Distribution of zinc content in longitudinal sections of vacuum-impregnated whole potatoes of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

The distribution of zinc content in longitudinal sections of VI whole potatoes of Snowden was shown in Fig. 3-7. The zinc content of the middle part of VI-uncooked potatoes in this figure was lower ($p<0.05$) than that of the bud and stem ends of VI-uncooked potatoes. However, the bud end, middle part and stem end of VI-cooked potatoes had 56, 28 and 47 times higher ($p<0.05$) zinc contents than that of the bud end, middle part and stem end of raw-cooked potatoes, respectively.
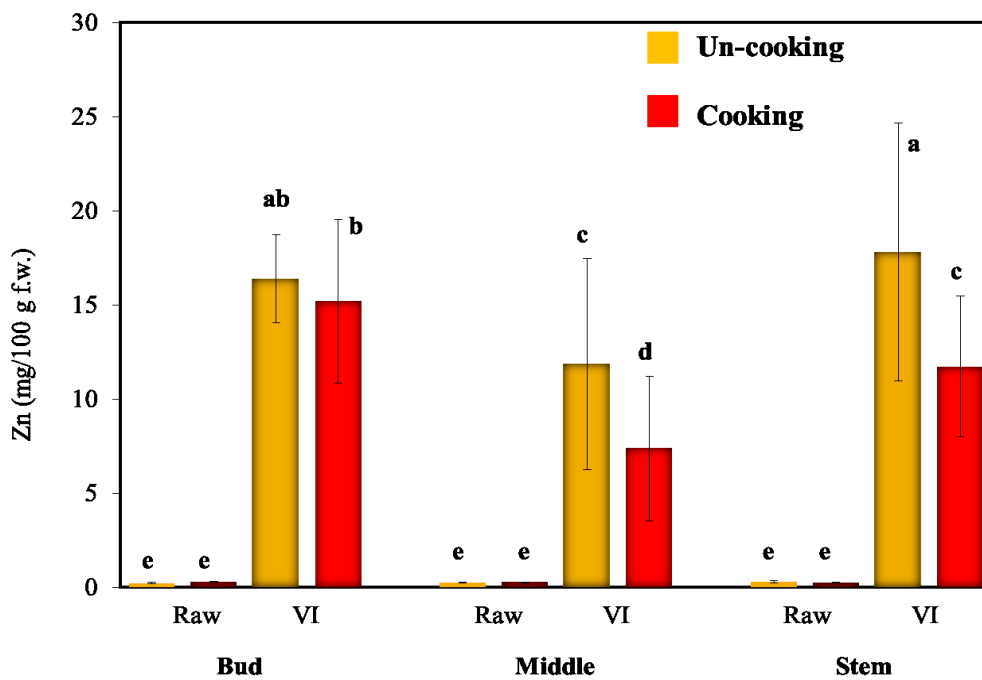

Fig. 3-7. Distribution of zinc content in longitudinal sections of the vacuum-impregnated whole potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD (n = 6). Different letters show significant differences at 0.05 probability.

Fig. 3-8 shows the distribution of ascorbic acid content in longitudinal sections of the VI whole potatoes of Toyoshiro. There were no significant differences ($p<0.05$) in ascorbic acid content among three sections. However, the bud end, middle part and stem end of VI-cooked potatoes had 7.4, 7.4 and 9.1 times higher ($p<0.05$) ascorbic acid contents than that of the bud end, middle part and stem end of raw-cooked potatoes, respectively.
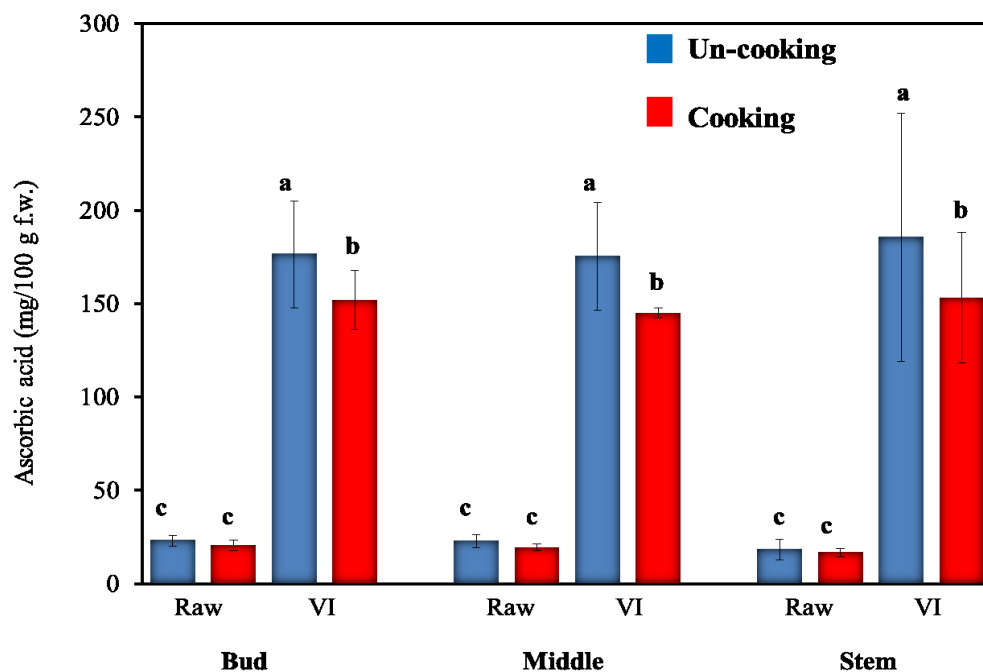

Fig. 3-8. Distribution of ascorbic acid content in longitudinal sections of the vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-9 shows distribution of ascorbic acid contents in longitudinal sections of the VI whole potatoes of Dejima. In this figure, the middle section of un-cooked VI potatoes had a lower ($p<0.05$) ascorbic acid content than that of the bud and stem ends of raw-uncooked potatoes. However, ascorbic acid contents of the bud end, middle part and stem end of VI-cooked potatoes were 6.4, 6.3 and 5.3 times higher ($p<0.05$) than those of the bud end, middle part and stem end of un-VI-cooked potatoes, respectively.

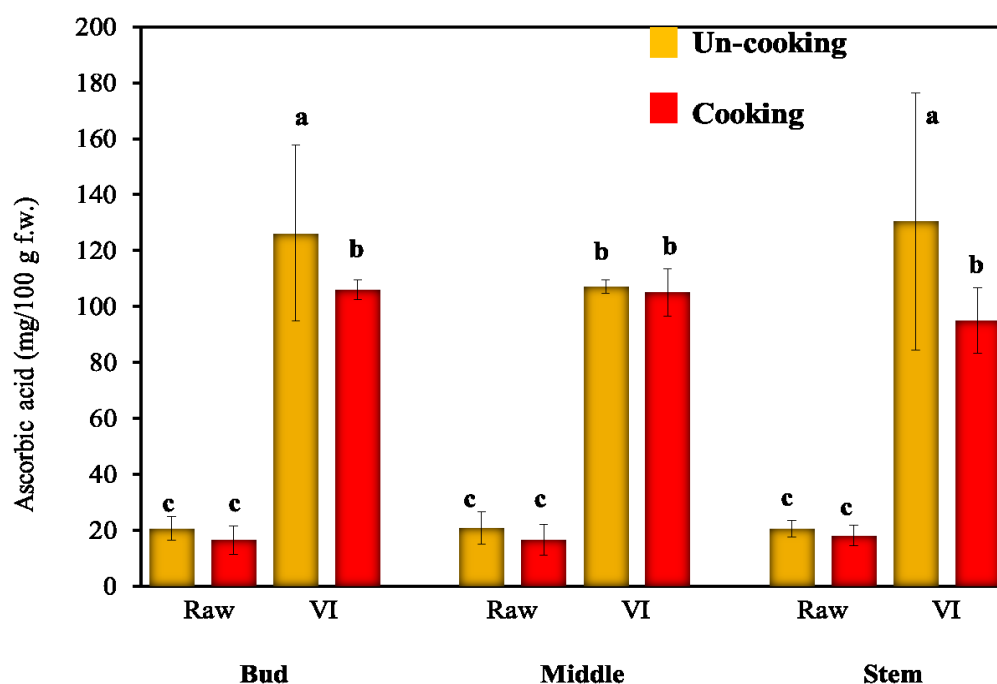**Fig. 3-9. Distribution of ascorbic acid content in longitudinal sections of the vacuum-impregnated whole potato tubers of Dejima variety.**

Vacuum impregnation (VI) conditions: VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Huamán (1986) reported that many potatoes eyes are spirally arranged on the tuber surface and concentrated toward the apical (bud) end. As mentioned previously, potatoes have a thick periderm, impermeable to water and gases (Peterson et al., 1985). When a potato is immersed in a concentrated solution of physiological active compound under vacuum conditions, air might be extracted from the eyes and lenticels and then, when atmospheric pressure is restored, impregnation occurred at the intercellular spaces of porous tissues though the eyes and lenticels by capillary action and by the pressure gradients (i.e., the hydrodynamic mechanism) that are imposed on the system, helping incorporation of physiological active compounds (Fito, 1994). So, strong impregnation of iron, zinc and ascorbic acid occurred at the bud end of potatoes as shown in Figs. 3-4~3-9.

3.3.3. Distribution of iron, zinc and ascorbic acid contents in transverse sections

Fig. 3-10 showed the distribution of iron content in transverse sections of the VI whole potatoes of Toyoshiro. As shown in this figure, the outer section of the VI-uncooked and VI-cooked potatoes had a higher ($p<0.05$) iron content than that of the middle and center sections of the VI-uncooked and VI-cooked potatoes. The outer, middle and center sections of VI-cooked potatoes had 8.6, 6.0 and 2.0 times higher

($p<0.05$) iron content than that of the outer, middle and center sections of raw-cooked potatoes, respectively.

Fig. 3-10. Distribution of iron content in transverse sections of the vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-11 shows the distribution of iron contents in transverse sections of the VI whole potatoes of Snowden. As shown in this figure, the outer section of the uncooked and cooked potatoes also had a higher ($p<0.05$) iron content than that of the middle and

center sections of the VI-uncooked and VI-cooked potatoes. The outer, middle and center sections of the VI-cooked potatoes had 9.3, 3.6 and 1.5 times higher ($p<0.05$) iron contents than that of the outer, middle and center sections of raw-cooked potatoes, respectively.
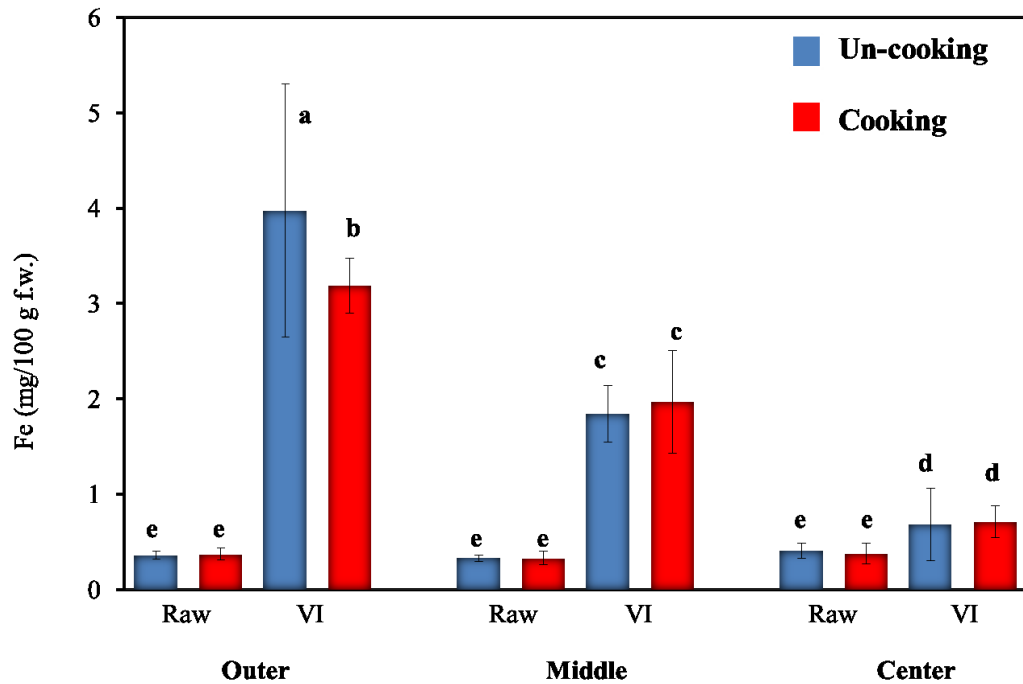

Fig. 3-11. Distribution of iron content in transverse sections of the vacuum-impregnated whole potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

The distribution of zinc contents in transverse sections of the VI whole potatoes of

Toyoshiro of was shown in Fig. 3-12. The outer section of the uncooked or cooked potatoes in this figure had also a higher ($p<0.05$) iron content than that of the middle and center sections of the VI-uncooked and VI-cooked potatoes. The outer, middle and center sections of the VI-cooked potatoes had 38, 10 and 4.7 times higher ($p<0.05$) iron contents than that of the outer, middle and center sections of raw-cooked potatoes, respectively.
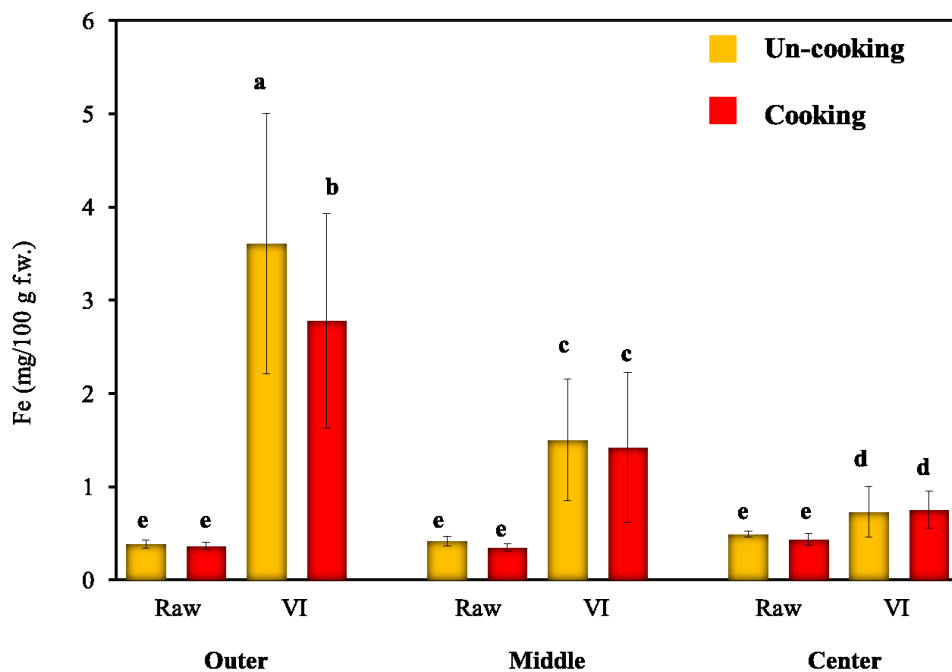

Fig. 3-12. Distribution of zinc content in transverse sections of the vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-13 shows the distribution of zinc contents in transverse sections of the VI whole potatoes of Snowden. The outer section of the un-cooked and cooked potatoes in this figure had also a higher ($p<0.05$) zinc content than that of the middle and center sections of the VI-uncooked and VI-cooked potatoes. The outer, middle and center sections of the VI-cooked potatoes had 86, 31 and 8 times higher ($p<0.05$) zinc contents than that of the outer, middle and center sections of raw-cooked potatoes, respectively.
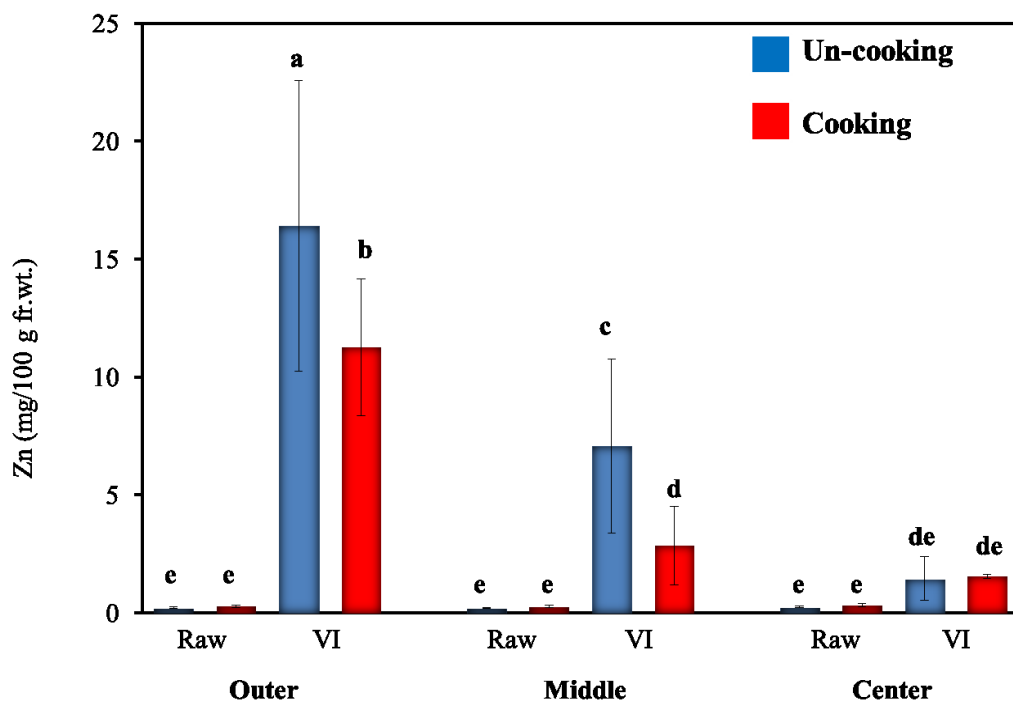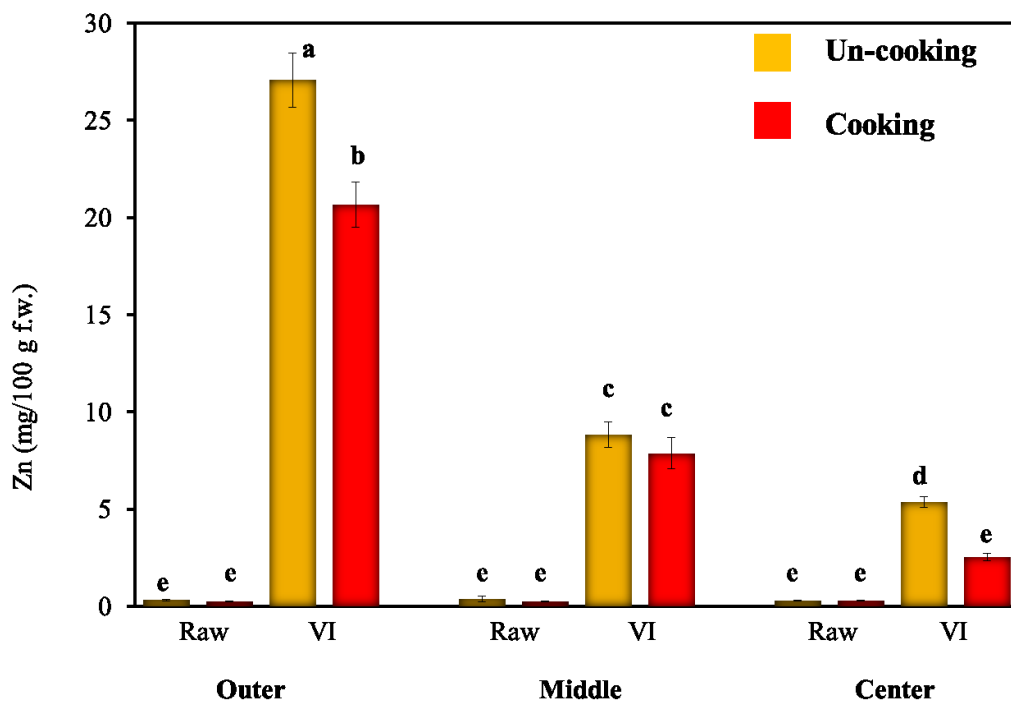

Fig. 3-13. Distribution of zinc content in transverse sections of the vacuum-impregnated whole potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 3-14 shows the distribution of ascorbic acid contents in transverse sections of the VI whole potatoes of Toyoshiro. The outer section of the uncooked and cooked potatoes in this figure had a higher ($p<0.05$) ascorbic acid content than that of the middle and center sections of the VI-uncooked and VI-cooked potatoes. Also, the outer, middle and center sections of the VI-cooked potatoes had 7, 5 and 2.5 times higher ($p<0.05$) ascorbic acid contents than that of the outer, middle and center sections of raw-cooked potatoes, respectively.

Fig. 3-14. Distribution of ascorbic acid content in transverse sections of the

vacuum-impregnated whole potato tubes of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

The distribution of ascorbic acid contents in transverse sections of the VI whole potatoes of Dejima was shown in Fig. 3-15. As shown in this figure, the outer section of the VI-uncooked and VI-cooked potatoes had a higher ($p<0.05$) ascorbic acid content than that of the middle and center sections of the VI-uncooked and VI-cooked potatoes. Also, the outer and middle sections of the VI-cooked potatoes had 7.3 and 4.6 times higher ($p<0.05$) ascorbic acid contents than that of the outer and middle sections of raw-cooked potatoes, respectively.
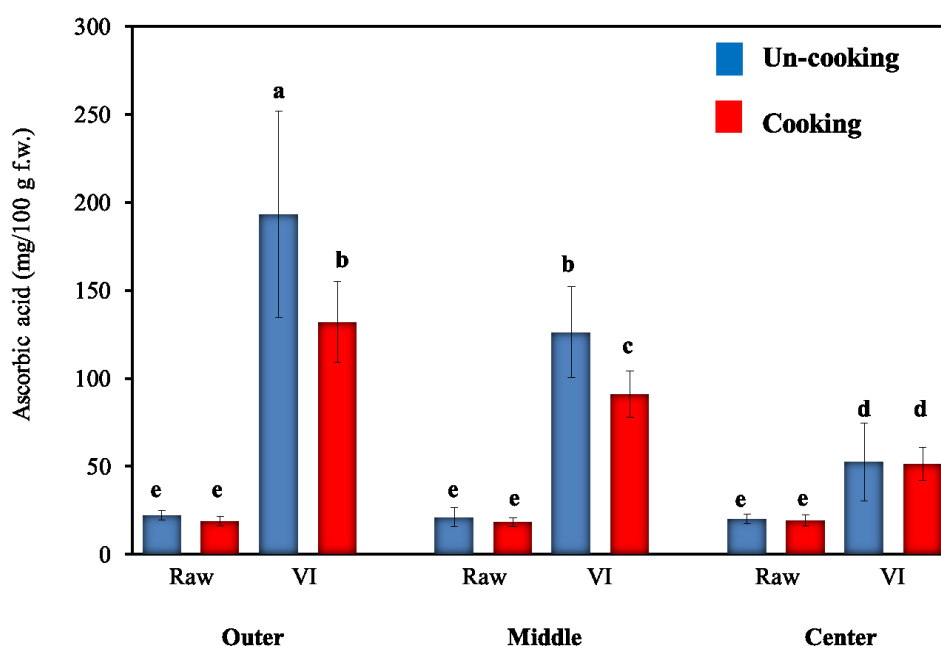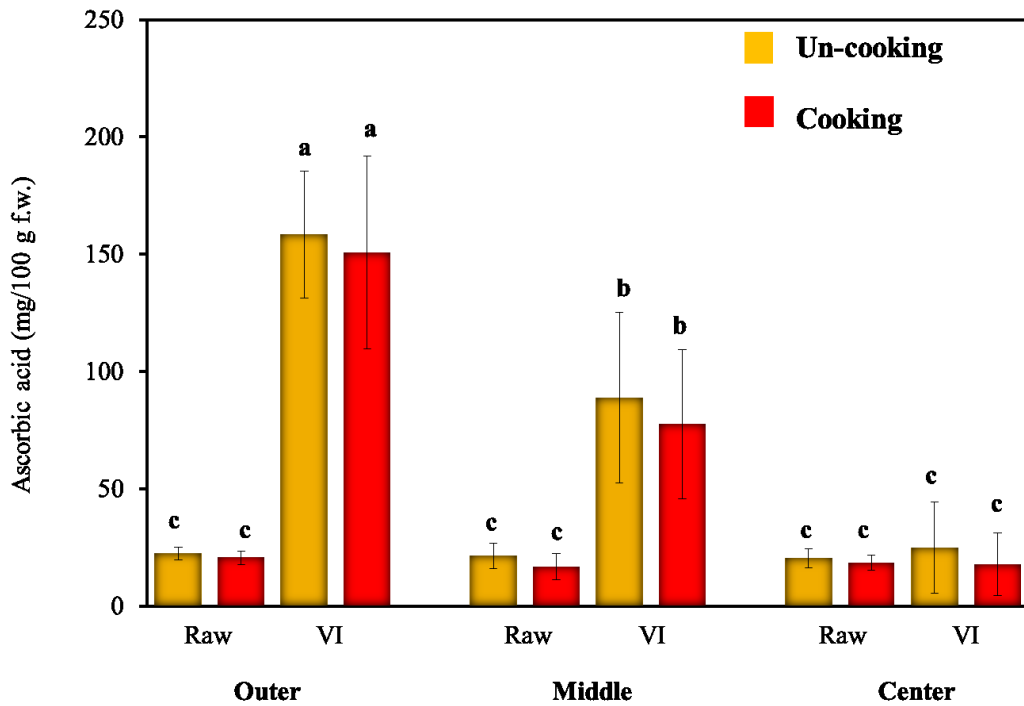
Fig. 3-15. Distribution of ascorbic acid content in transverse sections of the vacuum-impregnated whole potato tubers of Dejima variety.

Vacuum impregnation (VI): VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

In connection with the impregnation level in VI process, Gras et al. (2003) examined calcium fortification of vegetables using VI technique with sucrose solutions, and found that the final impregnation level of carrot slices (10, 15 and 25 mm) depended on the slice thicknesses; the thinner the slice, the greater the impregnation level. As for the VI mechanism, as previously described, Fito and Pastor (1994) reported that the net mass flows transferred in the vacuum operations between porous

foods and the liquid in which they are immersed were the result of the contribution of several mechanisms (osmotic, diffusion, etc.). Among them, the hydrodynamic mechanism may play an important role in terms of the total amount of transferred mass; the changes of pressure (pressure gradient) in the system produce strong driving forces responsible for mass transfer (Fito, 1994). In the transverse sections of the VI whole potato in the present study, vacuum pressure may be higher at the outer section compared with those at inner sections (middle and center), because the outer section is closer to the potato surface. So, VI whole potatoes had higher iron, zinc and ascorbic acid contents at the outer section compared with those at inner sections as shown in Figs. 3-10~3-15.

This study clarified the distribution of iron, zinc and ascorbic acid within longitudinal and transverse sections of VI whole potatoes. The results will provide useful information for school lunches and hospital foods where cut pieces are supplied instead of whole potatoes.

3.4. Conclusions

This study described the distribution of iron, zinc and ascorbic acid contents within VI whole potatoes. The results of the present research indicated that the bud end of

VI-uncooked and VI-cooked potatoes had higher ($p<0.05$) iron and zinc contents compared with that of the middle and stem sections of VI-uncooked and VI-cooked potatoes. Moreover, the outer section within VI-uncooked and VI-cooked potatoes had higher ($p<0.05$) iron, zinc and ascorbic acid contents than that of the middle and center sections of VI-uncooked and VI-cooked potatoes.

This information will be useful for school lunches and hospital foods where cut pieces are supplied instead of VI whole potatoes.

Chapter 4

Effect of storage time on iron, zinc and ascorbic acid contents of

vacuum-impregnated whole potatoes

4.1. Introduction

Potato storage can have a dominant effect on the product quality depending on the storage environment (Herrman et al., 1996; Lozano and Ibarz, 1997). Appropriate storage environment should maintain tubers in their edible and marketable conditions by preventing large moisture losses, spoilage by pathogens, quality deterioration and sprout growth (Nourian et al., 2003). Potatoes for domestic consumption are stored at 5 ºC for several months in order to avoid serious sprout growth (Burton et al., 1991; Weaver et al., 1972).

From potato harvest to consumption, the changes in nutritional value of potatoes mainly occur during storage (Burton et al., 1992); increased reducing sugar content (Cottrell et al., 1993), and decreased starch content during low temperature storage (Hironaka et al., 2001). With respect to changes in physical properties of stored potatoes, Bentini et al. (2009) reported that the Young's modulus declined with storage time. In addition, Järvinen et al. (2011) reported that the amount (thickness) of potato skin

increased with storage. Fito et al. (1996) indicated that tissue structures and mechanical properties of the material play a very important role in vacuum impregnation (VI). Therefore, changes in the above mentioned physical properties such as skin thickness and tissue hardness of potatoes during storage may affect the amount of nutritious incorporated by VI treatment into whole potatoes. Thus, it is interesting to investigate the effect of storage time on the amount of nutritious incorporated by VI into whole potatoes.

However, no studies exist on the effect of storage time on the iron, zinc and ascorbic acid contents of VI whole potatoes. Therefore, this study was initiated to investigate the effect of storage time at 4 ℃ on iron, zinc and ascorbic acid contents of VI whole potatoes.

4.2. Materials and methods

4.2.1. Materials, storage and VI treatment of iron, zinc and ascorbic acid

Two cultivar potatoes of Toyoshiro and Snowden were used. These potatoes were the same as those described in Chapter 2. Tubers were stored at 4 ℃ and 90% RH for 0, 1, 2, 3 or 4 months. At each storage time, tubers were vacuum-impregnated by the methods described in Chapters 2 and 3.

4.2.2. Cooking

The cooking experiment of whole unpeeled potatoes was carried out by the method described in Chapter 2.

4.2.3. Determination of iron, zinc and ascorbic acid

The iron, zinc and ascorbic acid contents of potatoes were determined by the method described in Chapters 2 and 3.

4.2.4. Statistical analysis

One tuber was used per treatment. Each treatment condition was assayed 6 times. Results were averaged to obtain mean values. Duncan's multiple range test of SPSS 9.0 (SPSS Inc., Chicago, USA) was used to determine differences between means of storage time.

4.3. Results and discussion

Fig. 4-1 shows the iron contents of VI whole potatoes of Toyoshiro variety during storage. Although the uncooked-potatoes which was VI-treated at one month of storage, resulted in a 20% reduction in iron contents in comparison with that of the VI treated at

the beginning of the storage, afterwords those of the VI-treated potatoes retained 7.5 times higher ($p<0.05$) iron contents compared with that of the raw-uncooked potatoes. Moreover, VI-cooked potatoes also had 8 times higher ($p<0.05$) iron contents compared with that of the raw-cooked potatoes at each storage time.
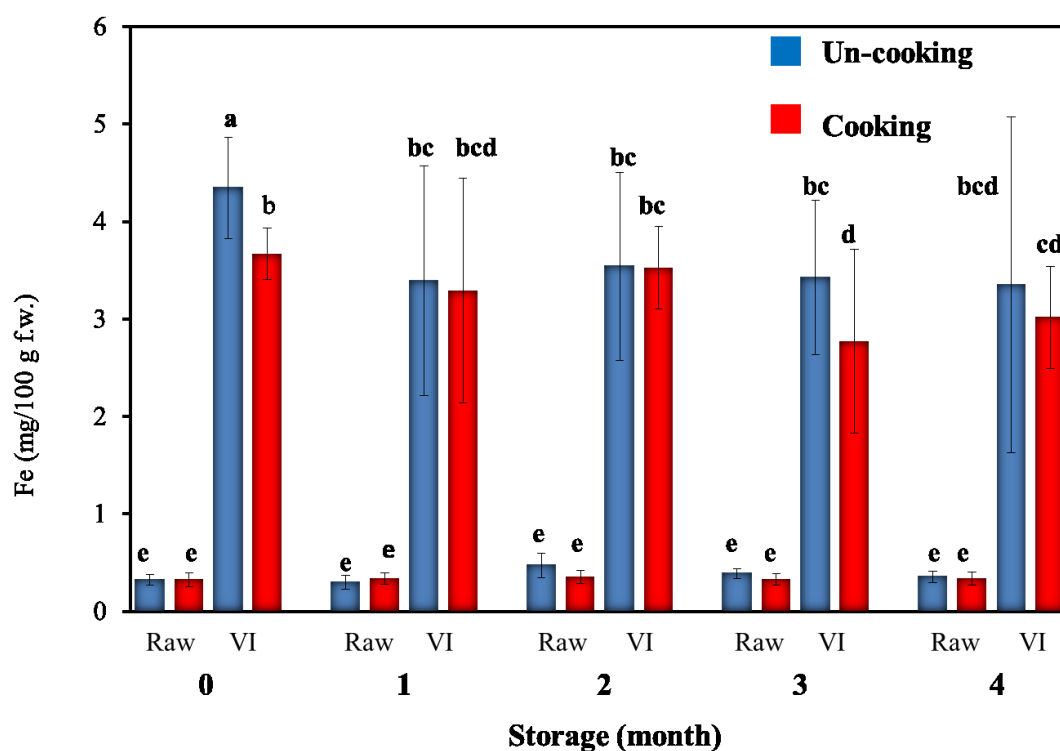

Fig. 4-1. Effect of storage time on iron contents of vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Iron contents of VI whole potatoes of Snowden variety during storage time were shown in Fig. 4-2. There were no significant differences in the iron contents of the VI-uncooked potatoes between 0 and 4 months of storage; the VI-uncooked potatoes had 4.4 times or higher ($p<0.05$) iron contents compared with that of the raw-uncooked potatoes. In addition, the VI-cooked potatoes also had 3.7 times or higher ($p<0.05$) iron contents compared with that of the raw-cooked potatoes.

Fig. 4-2. Effect of storage time on iron contents of vacuum-impregnated whole

potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution at 0.4% iron concentration; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 4-3 shows zinc contents of VI whole potatoes of Toyoshiro variety during

storage. As shown in this figure, the zinc content of the uncooked-potatoes with

VI-treatment at storage of 2 months decreased by 15% comparison with that of the

VI-treatment at storage of 0 month, and declined markedly afterwords. However, even

the VI-uncooked-potatoes VI-treated at 4 months of storage had 71 times higher

($p<0.05$) zinc contents than that of the raw-uncooked potatoes. Also, the

VI-cooked-potatoes VI-treated at 4 months of storage contained 66 times higher

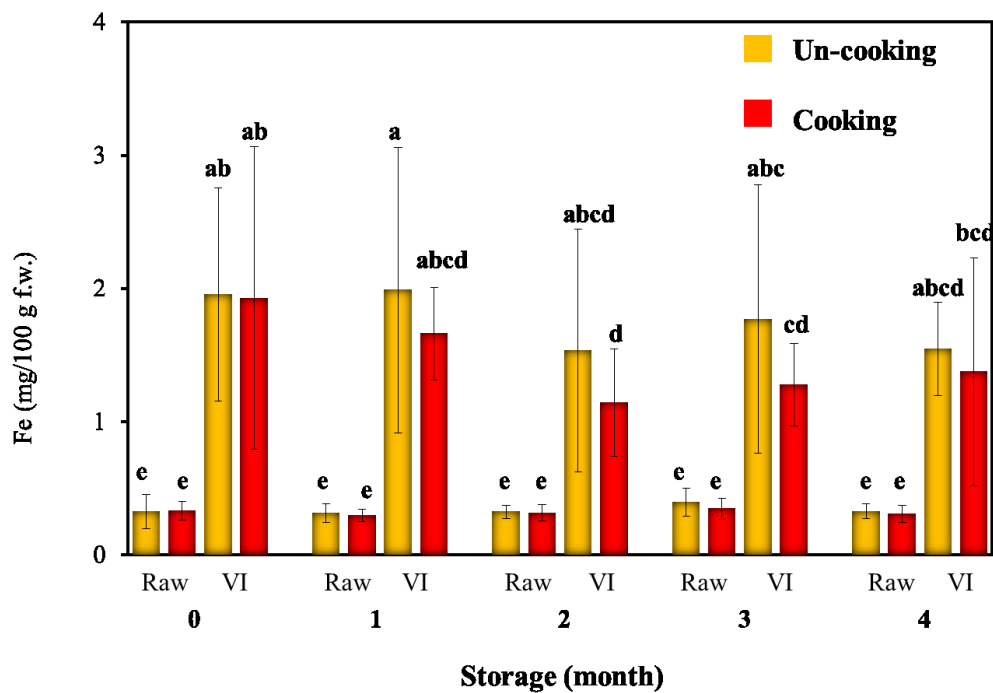($p<0.05$) zinc contents compared with that of the raw-cooked potatoes.

Fig. 4-3. Effect of storage time on zinc contents of vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means $\pm$ SD ($n = 6$). Different letters show significant differences at 0.05 probability.

For Snowden variety (Fig. 4-4), no significant differences in zinc contents of the VI-uncooked whole potatoes were observed within 4 months of storage. Thus, the VI-uncooked potatoes during storage had 140 times higher ($p<0.05$) zinc contents compared with that of the raw-uncooked potatoes. Moreover, the VI-cooked potatoes also had 128-189 times higher zinc contents than that of the raw-cooked potatoes.
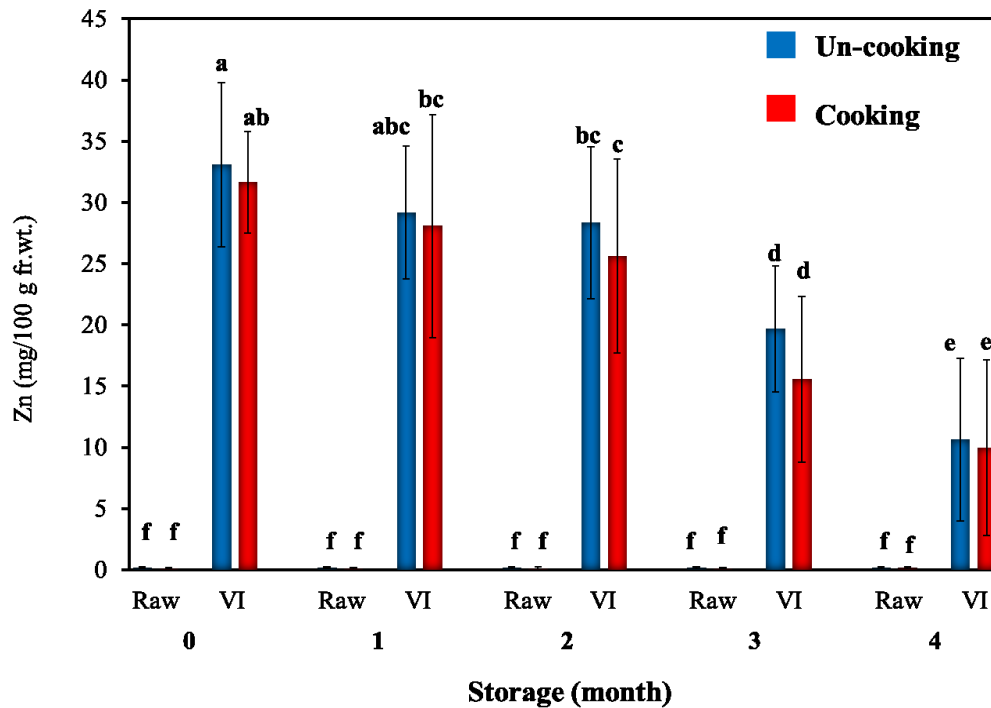
Fig. 4-4. Effect of storage time on zinc contents of vacuum-impregnated whole potato tubers of Snowden variety.

Vacuum impregnation (VI) conditions: VI solution saturated with zinc gluconate; vacuum pressure of 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

Fig. 4-5 shows ascorbic acid contents of VI whole potatoes of Toyoshiro variety during storage. In terms of ascorbic acid content of the VI whole potatoes, there are no significant differences ($p<0.05$) between VI-treatment at storage of 2 months and VI-treatment at storage of 0 month potatoes, but afterwords there was a marked reduction in ascorbic acid contents of the VI-cooked potatoes. Also, a marked reduction in ascorbic acid contents of the VI-cooked potatoes was observed after 2 months of
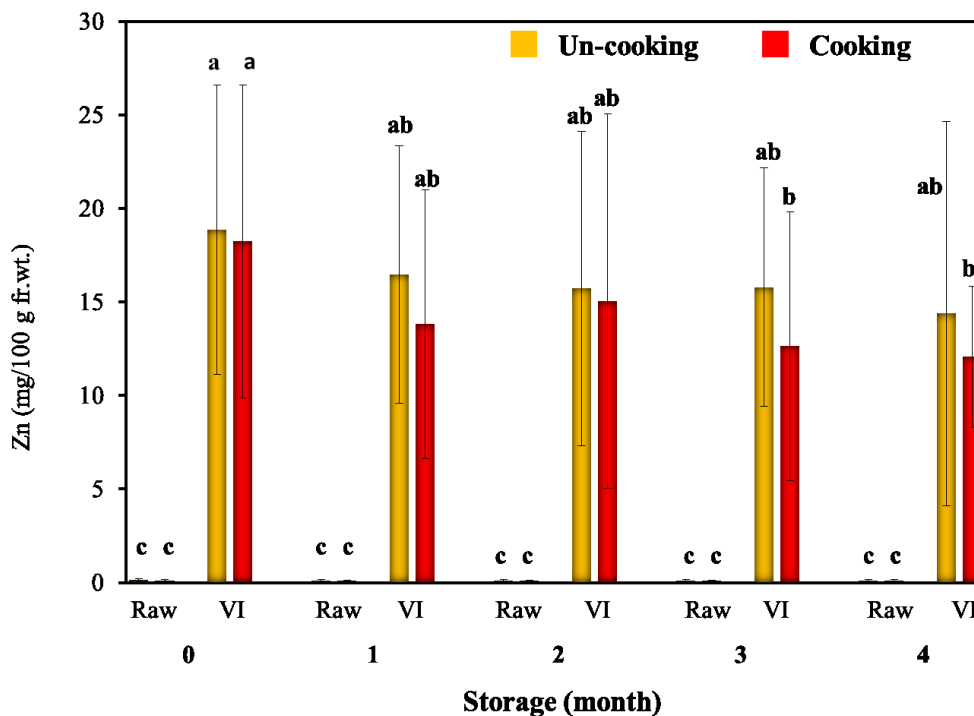
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storage.

Fig. 4-5. Effect of storage time on ascorbic acid contents of vacuum-impregnated whole potato tubers of Toyoshiro variety.

Vacuum impregnation (VI) conditions: VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means ± SD ($n = 6$). Different letters show significant differences at 0.05 probability.

For Dejima variety (Fig. 4-6), VI-uncooked or VI-cooked potatoes showed a similar reduction to that observed in Fig. 4-5.
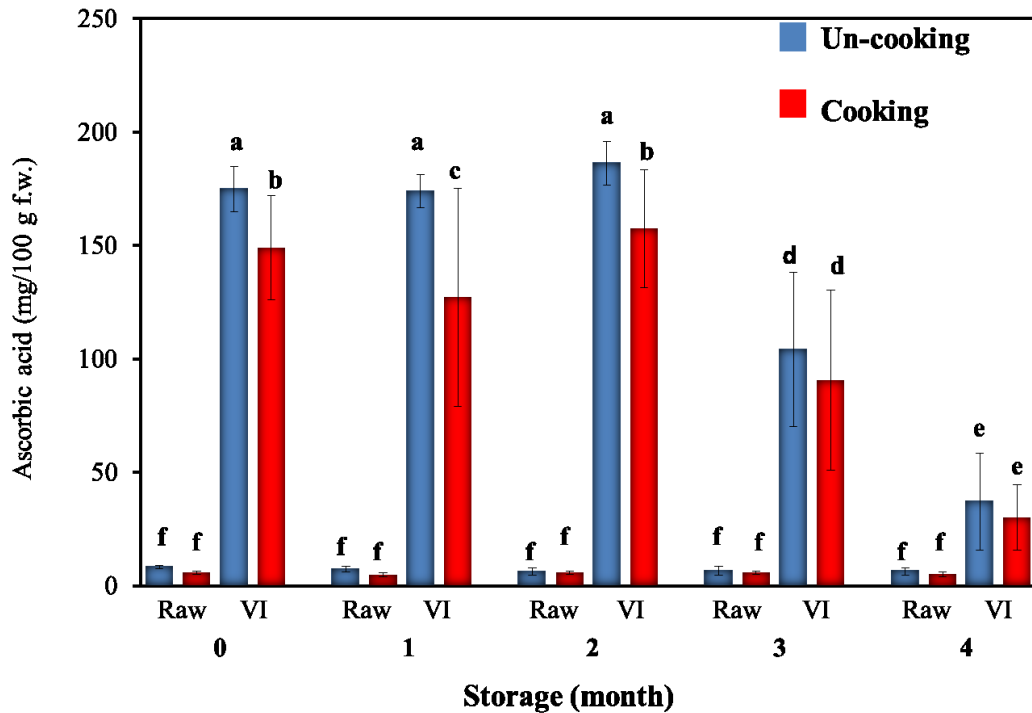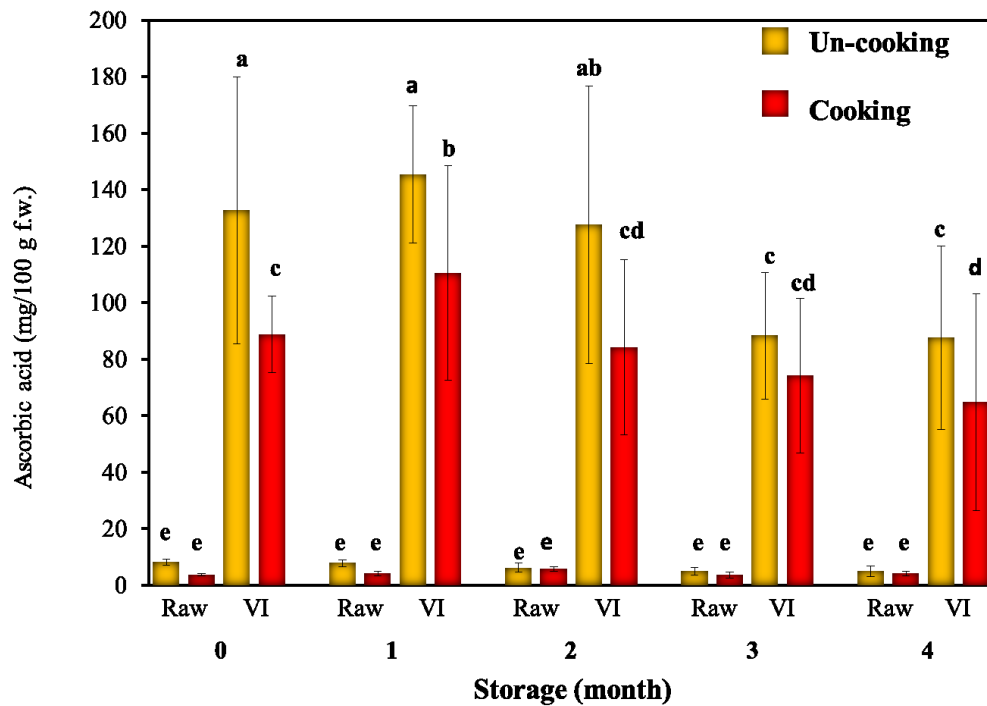
Fig. 4-6. Effect of storage time on ascorbic acid contents of vacuum-impregnated whole potato tubers of Dejima variety.

Vacuum impregnation (VI) conditions: VI solution at 10% concentration of ascorbic acid; vacuum pressure at 10 hPa; vacuum time for 1 h; restoration time for 3 h. Values are the means $\pm$ SD ($n = 6$). Different letters show significant differences at 0.05 probability.

As shown in Figs. 4-1~4-6, iron, zinc and ascorbic acid contents of VI-uncooked or VI-cooked potatoes decreased during storage. Fito and Pastor (1994) point out that intercellular space (ICS) is important for sample behaviour during VI processing because it determines the volume that can be occupied by the external liquid in the product tissue. Davis (1962) reported that stored potato intercellular space decreased from 1.45% to 1.14% during storage of 3 months. In addition, potatoes have a thick

periderm, which is less permeable to water and gas (Peterson et al., 1985). As mentioned previously, Järvinen et al. (2011) reported that the thickness of potato skin increased with storage. Thus, the decrease in iron, zinc and ascorbic acid contents of the VI-uncooked or VI-cooked potatoes during storage may be due to the decrease in intercellular space, and increase in skin thickness.

Finally, this study indicates that the VI treatment was particularly effective for potatoes within one month storage at 4 $^\circ$C.

4.4. Conclusions

The results of this study indicated that VI treatment was particularly effective for potatoes within one month storage at 4 $^\circ$C. This study provides useful information for potato processors to determine the optimal VI treatment time of stored potatoes.

Chapter 5

Summary

In the last decades consumer demands in the field of food production has changed considerably. Today foods are not intended to only satisfy hunger and to provide necessary nutrients for humans but also to prevent nutrition-related diseases and to improve physical and mental well-being of the consumers. The development of functional foods is currently one of the most important areas of food product development worldwide.

Potatoes are an essential food crop in the world. It is ranked fifth in terms of human consumption and fourth in world production.

One of the alternatives for the development of new products in the food industry is the use of vacuum impregnation (VI). VI is the application of low pressure to a solid-liquid system, followed by the restoration of atmospheric pressure. To achieve a better efficient impregnation in VI process, it is required to know the suitable VI conditions. VI efficiency depends mainly on vacuum pressure, vacuum time and restoration time.

This study was carried out to evaluate the effect of vacuum pressure, vacuum time

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and restoration time on the iron and zinc contents of VI treatments on whole potatoes. The effects of steam-cooking and storage at 4 ºC on iron and zinc contents of VI whole potatoes were also evaluated. Further, the effect of VI treatment on cell structures of potatoes was investigated. In addition, the longitudinal or transverse distribution of the iron, zinc and ascorbic acid contents within VI whole potatoes was evaluated. The effect of VI treatment time on the iron, zinc and ascorbic acid contents of VI stored-potatoes was also investigated.

The following conclusions were obtained from the studies:

1) The iron content of VI whole potatoes increased with vacuum level (pressure). Also, iron and zinc contents of VI whole potatoes increased with vacuum time and restoration time.

2) VI-cooked unpeeled and peeled potatoes had 6 times higher iron contents than that of the raw-cooked unpeeled and peeled potatoes. In Europe, daily potato intake per capita, in 2005, was 260 g. Thus, European daily potato consumption of the VI-cooked unpeeled and peeled potatoes can provide adult men with 93-104% and 67-90% of the RDA of iron, respectively. Also, the daily potato consumption of the unpeeled and peeled potatoes supplied adult women with 43-48% and 31-41% of the RDA level, respectively. Moreover, the VI whole potatoes had 6 times higher iron contents (>4

mg/100 g fr.wt.) through 30 days of storage at 4 ℃, compared with that of the raw potatoes.

3) VI-cooked unpeeled and peeled potatoes had 63-94 times and 47-75 times higher zinc contents than that of raw-cooked unpeeled and peeled potatoes, respectively. In the world, daily potato intake per capita, in 2005, was 86 g. Thus, daily worldwide potato consumption of the VI-cooked unpeeled and peeled potatoes can provide adult men with 130-148 and 100-135% of the RDA of zinc, respectively. Also, the daily worldwide potato consumption of the unpeeled and peeled potatoes can supply adult women with 178-203% and 137-185% of the RDA levels, respectively. The high zinc content of VI whole potatoes was kept during 4 ℃-storage for 30 days.

4) Microstructure analysis showed that VI occurred without disrupturing internal cells of whole potato tubers.

5) The bud end of VI-uncooked and VI-cooked potatoes had higher ($p<0.05$) iron and zinc contents compared with that of the middle and stem sections of VI-uncooked and VI-cooked potatoes. Moreover, the outer section within VI-uncooked and VI-cooked potatoes had higher ($p<0.05$) iron, zinc and ascorbic acid contents than that of the middle and center sections of VI-uncooked and VI-cooked potatoes. This information will be useful for school lunches and hospital foods where cut pieces are supplied

instead of whole potatoes.

6) The iron, zinc and ascorbic acid contents of VI-uncooked and VI-cooked potatoes decreased during storage. The optimal VI treatment time for potatoes stored at 4 ºC was within one month of storage. This result will give useful information for potato processors to determine the optimal VI treatment time of stored potatoes.

Finally, this study indicated that VI treatment of whole potatoes with iron, zinc and ascorbic acid solutions was useful for enriching the iron, zinc and ascorbic acid contents of peeled or unpeeled cooked potatoes.

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要旨

　近年，食品製造の分野では，消費者の要求が大幅に変化してきている。食品が直接，健康に貢献すると，消費者は考えている。食品は空腹を満たし，人間に必要な栄養素を供給するだけでなく，栄養に関連する疾患を予防し，消費者の物理および精神的幸せを改善するものとして今日，とらえられている。機能性食品の開発は，現在，世界中で最も重点的に行われている食品開発分野の一つである。機能性食品市場は世界で 476 億米ドルと推定され，米国が最も大きく，次いで欧州と日本がそれに続いている。さらに，機能性食品産業は，現在，急速に成長している市場に対応し，新しい機能性食品開発にしのぎを削っている。

　機能性成分の内，鉄はヘモグロビン生産に必要であり，鉄の赤血球前駆体に対する不十分な供給は赤血球生成障害や鉄欠乏性貧血をもたらす。鉄欠乏は，世界で最も広範にみられ，20 億の人々に影響を及ぼし，人々の鉄依存性酵素やタンパク質機能の損傷をもたらしている。20 歳以上の女性の 62%が鉄欠乏であると，アメリカ農務省は報告している。また，亜鉛は生命を支える多くの生化学的プロセスに関与しているが，世界人口の 25%以上が亜鉛欠乏の危険にさらされている。アスコルビン酸（AA）は，ほとんどの生体組織の必須成分であり，酸化ストレスに対する防御として重要な役割を担っている。英国低所得者層の食事と栄養調査（2003〜2005 年）では，男性の 25%，女性の 16%がビタミン C 欠乏状態にあり，さらに，それらの人々の 20%がビタミン C 枯渇レベルにあった。

　ジャガイモは，世界中で生産される基幹食用作物であり，人類にとって最初の非穀物食料である。ジャガイモは世界の主要作物の内，消費量で第 5 位，生産量で 4 位にランクされている。

　食品産業における新製品開発のための 1 つの選択肢は，真空含浸（VI）の適用である。VI は先ず固液系への低圧力の負荷，その後の大気圧への復帰操作であるが，VI 工程で，より効率的な含浸を達成するには，適切な VI 条件を知ることが求められる。VI 効率は，真空圧力，真空時間や復帰時間を含む VI 工程パラメータに依存することが報告されている。

　この研究では，栄養価の高いジャガイモ塊茎そのものを消費者に供給するために，ジャガイモ塊茎の鉄，亜鉛及び AA 含量を VI によって増強することを試みた。ジャガイモの VI について，鉄と亜鉛についての研究はなされていない。また，VI ジャガイモのアスコルビン酸含量の塊茎内分布及び貯蔵期間の影響に関する研究はみられない。

この研究は，VI ジャガイモの鉄及び亜鉛含量に及ぼす真空圧力，真空時間と復帰時間の影響を評価するために行った。さらに，ジャガイモ塊茎の鉄と亜鉛含量に及ぼす蒸気調理や貯蔵の影響を評価した。また，ジャガイモ塊茎の細胞構造に及ぼす VI 処理の影響を調べた。さらに，VI ジャガイモ塊茎の鉄，亜鉛及び AA 含量の長軸または横断面方向の塊茎内分布を調べた。VI ジャガイモの鉄，亜鉛や AA 含量に及ぼす貯蔵期間の影響も，同様に研究した。

　上記の研究から，以下の結論が得られた。

1）VI ジャガイモの鉄含量は，真空レベル（圧力）の上昇と共に増加した。また，VI ジャガイモの鉄と亜鉛含量は，真空時間や復帰時間と共に増加した。

2）VI 皮付き調理，または皮なしジャガイモは，VI 未処理のものよりも 6 倍高い鉄含量を有した。さらに，これらのジャガイモのヨーロッパ人 1 日当たりのジャガイモ消費量（260 グラム）は，VI 皮付き調理ジャガイモで，1 日推奨摂取鉄量の 93〜104％，皮なしで 67〜90％の鉄分を成人男性に供給する。同様に，成人女性に皮付きで，一日推奨量の 43〜48％，皮なしで 31〜41％の鉄分供給となる。加えて，VI ジャガイモは未処理のものよりも，4℃で 30 日の貯蔵期間を通して，6 倍高い鉄含量（> 4 mg/100g fr.wt.）を有した。

3）亜鉛も同様に，VI 皮付き調理，または皮なしジャガイモは，VI 未処理のものよりも 63〜94％または 47〜75％高い亜鉛含量を有した。全世界の 1 日当たりの平均ジャガイモ消費量（86 グラム）は，VI 皮付き調理ジャガイモで，1 日推奨摂取亜鉛量の 130〜148％，皮なしで 100〜135％の亜鉛を成人男性に供給する。同様に，成人女性に皮付きで，一日推奨量の 178〜203％，皮なしで 137〜185％の亜鉛供給となる。また，VI ジャガイモは 4℃で 30 日の貯蔵期間を通して，高含量を維持した。

4）電子顕微鏡による微細構造解析は，VI がジャガイモ塊茎の内部の細胞を破壊することなしに，起きていることを示した。

5）VI 未調理または調理ジャガイモの頂芽部の鉄及び亜鉛含量は，中央部や基部と比べて高かった。さらに，それらのジャガイモの周皮部の鉄，亜鉛及び AA 含量は，他の中間や中心部よりも高かった。ジャガイモが塊茎全体でなく，カットして供給される学校給食や病院食に，この情報は有用である。

6）VI 未調理または調理ジャガイモの鉄，亜鉛及び AA 含量は貯蔵中に減少した。4 ℃貯蔵ジャガイモの最適 VI 処理時期は貯蔵 1 ヶ月以内であった。この結果は，ジャガイモ加工業者が貯蔵ジャガイモの最適 VI 処理時期を決めるのに，有用な情報である。

　上記のように，本研有用な情報を与えるものである。本研究は，鉄，亜鉛及び AA 溶液を用いた VI 処理は，皮つき，または皮なし調理ジャガイモの鉄，亜鉛及び AA 含量を増強するのに有用であることを示した。