Accumulation of Sucrose in Irradiated Agricultural Products

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Irradiation of agricultural products with ionizing radiation causes various physiological changes[5,13] and one of the interesting phenomena is the increase of sucrose in irradiated potatoes.[1~4,14,15] The relationship, however, between sucrose content and irradiation dose was not clarified. The author[7,8] has made the relationship clear and found out that the sucrose content once enhanced by a high dose of irradiation does not lower during storage for a long period. It has been found that the sucrose accumulation caused by irradiation occurred in sweet potatoes[7,8] and chestnuts[10] as well as potatoes. In this article the effect of gamma-irradiation on the sucrose content of potato tubers, sweet potato roots and chestnuts will be reviewed and the mechanism of this sucrose accumulation will be discussed.

Sucrose content of irradiated potatoes

The sucrose content of irradiated potato tubers during storage at 20°C is shown in Fig. 1. The sucrose content of the potato tubers irradiated at 2 kGy increased for 2 weeks after irradiation from 0.13 to 2% and then remained at that level, while that of the tubers irradiated at 0.15 kGy increased for 1 week after irradiation and then decreased to the level of unirradiated tubers. The sucrose content of the irradiated tubers increased rapidly for the first 3 days after irradiation. The sucrose content of the unirradiated potato tubers was almost the same during the whole storage period.

Unirradiated potatoes were stored for 2 weeks at 5 or 20°C followed by irradiation at 2 kGy and storage at 20°C. The sucrose content of unirradiated potatoes increased by

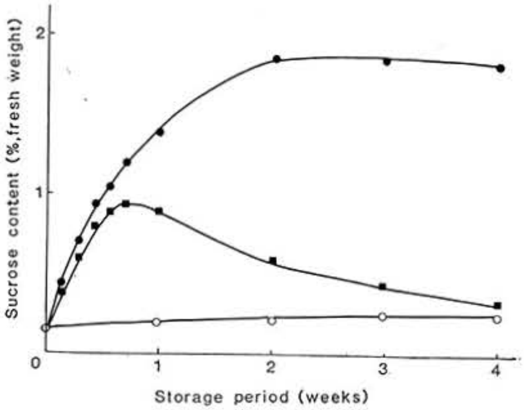

Fig. 1. Sucrose content of irradiated potato tubers during storage at 20°C
○; 0 kGy, ■; 0.15 kGy,
●; 2 kGy

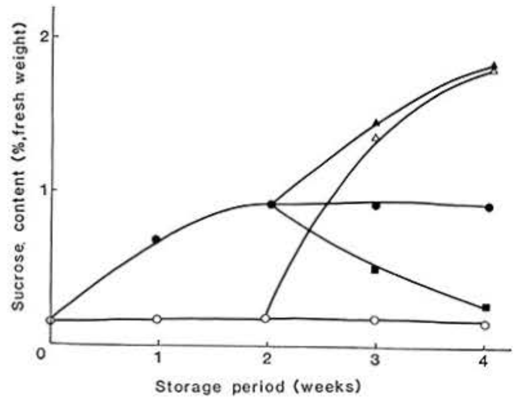

Fig. 2. Sucrose content of potato tubers stored under different conditions
○; unirradiated, stored at 20°C
●; unirradiated, stored at 5°C
△; stored at 20°C for 2 weeks, then irradiated
▲; stored at 5°C for 2 weeks, then irradiated
■; unirradiated, stored at 5°C for 2 weeks, then at 20°C
The irradiated potato tubers were stored at 20°C.

7 times during storage for 2 weeks at 5°C, and the content increased further 2 times upon storage at 20°C after irradiation (Fig. 2). The sucrose level decreased when the unirradiated potatoes were transferred from a 5°C storage room to a 20°C room. The sucrose content of unirradiated potatoes did not significantly change during storage at 20°C, while that of the irradiated potatoes increased by 15 times during storage for 4 weeks at 20°C, up to ca. 2% which is almost the same level as that of the pre-cooled and irradiated samples. These results indicate that the sucrose content of irradiated potatoes is not influenced by storage temperature before irradiation treatment.

Sucrose content of irradiated sweet potatoes

The sucrose content of sweet potato roots which were irradiated at 1 kGy and stored in a temperature range of 25 to 35°C continued to increase for 3 weeks after irradiation (Fig. 3). At 40°C the sucrose content continued to increase over the whole storage period tested. The effect of storage temperature on the sucrose content was distinct when the roots were stored for 3 weeks or longer, and higher storage temperatures resulted in higher sucrose contents. The sucrose content reached 10.4, 12.0, 12.6 and 15.3% when the roots were stored for 4 weeks at 25, 30, 35 and 40°C, respectively. In the calculation of the increase in the total amount of sucrose in the roots, both the increase in the sucrose content and the loss in weight of the roots should be taken into consideration. The weight of the irradiated sweet potatoes decreased to a greater extent at a higher irradiation dose and a higher storage temperature.[8] The total amount of sucrose in the roots irradiated at 1 kGy and stored for 4 weeks at 25°C increased 5.8 times, while the increase was 6.5 times, 6.4 times and 6.2 times in the roots irradiated at 1 kGy and stored for 4 weeks at 30, 35 and 40°C, respectively.[8] Higher irradiation dose and higher storage temperature resulted in a higher degree of spoilage of sweet potato roots.[8]

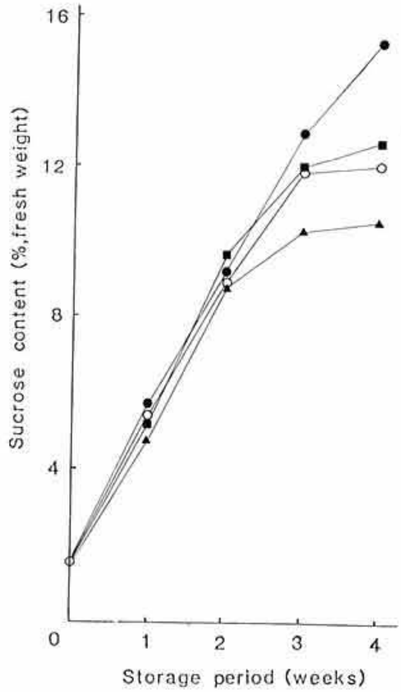

Fig. 3. Sucrose content of sweet potato roots irradiated at 1 kGy and stored at various temperatures (Beni-kokei)
▲; 25°C, ○; 30°C, ■; 35°C, ●; 40°C

The effect of irradiation on the sucrose content of sweet potato roots pre-treated at 15 or 25°C was investigated. Sweet potato roots were stored at 15°C (pre-cooling) or 25°C (not pre-cooling) for 2 weeks, then irradiated at a dose of 0 to 5 kGy followed by storage for 2 weeks at 20°C. The pre-cooling treatment (15°C, 2 weeks) made the sucrose content almost 2 times higher—from ca. 2 to ca. 4% (Fig. 4). The sucrose content was at the highest level, when the roots were irradiated at 0.8 to 2 kGy, irrespective of the pre-cooling treatment. The level of sucrose in the roots irradiated at a dose of 0.8 to 2 kGy was not influenced by the pre-cooling. The sucrose content decreased at a dose higher than 2 kGy. Consideration of sucrose content, weight loss and spoilage led to the conclusion

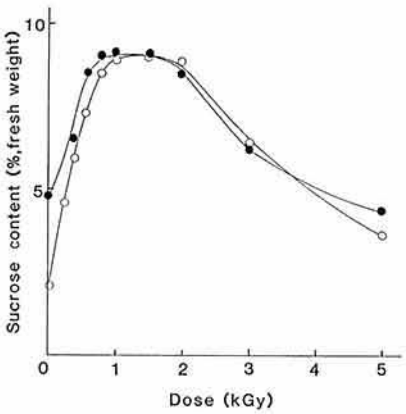

Fig. 4. Relationship between irradiation dose and sucrose content of sweet poato roots
Following storage for 2 weeks at 15 or 25°C the roots were irradiated at various doses, then stored for 2 weeks at 20°C.
●; pre-cooling (15°C, 2 weeks)
○; not pre-cooling (25°C, 2 weeks)

that the optimum condition for sucrose accumulation in sweet potato roots was irradiation at 1 kGy and storage at 30°C.[8]

The sucrose content of various varieties of sweet potato roots increased to 5.2 to 12.5% after irradiation at 1 kGy and storage at 30°C (Table 1). The sucrose content of the irradiated roots was 2 to 6 times higher than that observed in the unirradiated roots. It was not possible to predict the final sucrose content after irradiation from the original sucrose content of the unirradiated roots, because no direct relationship could be found between these values. For example, the sucrose contents of both Hayatoimo and L-4-89 were 4.9%, but in the irradiated roots they were 12.5 and 10.6%, respectively. Benikokei also gave a high sucrose content of 12.0% after irradiation, although the initial content was 1.6% (Fig. 3). In the sweet potato roots of Beniaka and Kintoki the sucrose content of the roots exceeded 10% after the irradiation and storage.

Table 1. Effect of irradiation* on the sucrose content of various varieties of sweet potato roots

Variety	Sucrose content(%, fresh basis)		
	No treat	1 kGy 2 weeks	1 kGy 3 weeks
L-4-89	4.9	9.8	10.6
Hayatoimo	4.9	10.3	12.5
Benikomachi	1.6	8.9	9.2
Beniaka	2.3	8.9	11.0
L-4-5	2.7	6.3	5.2
Minamiyutaka	3.2	7.6	8.7
Okinawa No. 100	2.0	9.1	9.5
Koganesengan	2.2	7.5	7.7
Kintoki	1.6	9.9	10.1
Norin No. 1	1.9	6.0	7.5
NQ 46	2.2	6.4	8.9
NQ 50	2.4	6.3	7.7

* The roots were irradiated at 1 kGy, then stored at 30°C for 2 or 3 weeks.

Sucrose content of irradiated chestnuts

The sucrose content of irradiated chestnuts was always at higher levels than unirradiated ones irrespective of storage temperature. Storage temperture significantly affected the sucrose content: the sucrose content of both the unirradiated and irradiated chestnuts increased with the decrease in storage temperature. The sucrose contents of the unirradiated chestnuts stored for 9 weeks at 1, 5 and 10°C were 11.0, 8.7 and 6.0%, respectively, while those of the chestnuts which were irradiated at 0.75 kGy followed by storage for 9 weeks at 1, 5 and 10°C were 14.5, 11.6 and 8.7% respectively (Figs. 5, 6 and 7).

The chestnuts stored for 2 weeks at 5°C, of which the sucrose content was 6.5%, were irradiated at a dose of 0 to 3 kGy and then stored at 5°C. The sucrose content of the chestnuts irradiated at a dose of 0.25 to 1 kGy increased during storage at 5°C, while that of the chestnuts irradiated at 3 kGy increased for a short period after irradiation and then decreased (Fig. 8). The sucrose content of the pre-cooled chestnuts reached almost the same level during storage after irradiation as those which were irradiated without pre-storage at

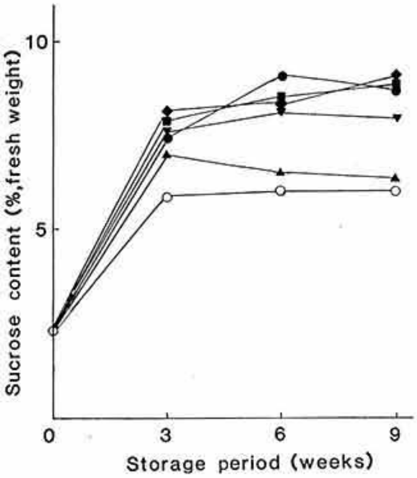

Fig. 5. Sucrose content of irradiated chestnuts during storage at 10°C
○; 0 kGy, ▲; 0.25 kGy, ▼; 0.5 kGy, ●; 0.75 kGy, ■; 1 kGy, ◆; 1.5 kGy

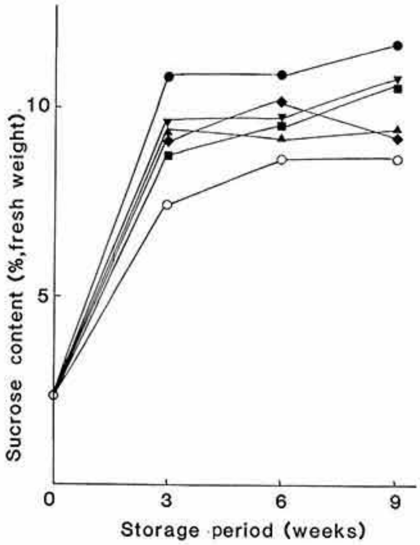

Fig. 6. Sucrose content of irradiated chestnuts during storage at 5°C
○; 0 kGy, ▲; 0.25 kGy, ▼; 0.5 kGy, ●; 0.75 kGy, ■; 1 kGy, ◆; 1.5 kGy

a low temperature (Fig. 6). These results showed a good agreement with those of potatoes (Fig. 2) and sweet potatoes (Fig. 4).

Mechanism of sucrose accumulation in irradiated potato tubers

Very little was known about the mechanism of sucrose accumulation in irradiated potato tubers and sweet potato roots and only the enhancement of the activities of phosphorylase[2,15,16] and sucrose synthase[1,12] in potatoes by gamma-irradiation was reported.

The sucrose content increased accompanied by the decrease in the content and size of starch in irradiated sweet potato roots during storage, which indicated that starch was converted into sucrose in irradiated sweet potato roots.[7] Generally, phosphorylase, UDP-glucose pyrophosphorylase, phosphoglucose isomerase, phosphoglucomutase, sucrose synthase and sucrose phosphate synthase are thought to be responsible for the starch-sucrose conversion in plants. The activities of phosphorylase, UDP-glucose pyrophosphorylase, sucrose

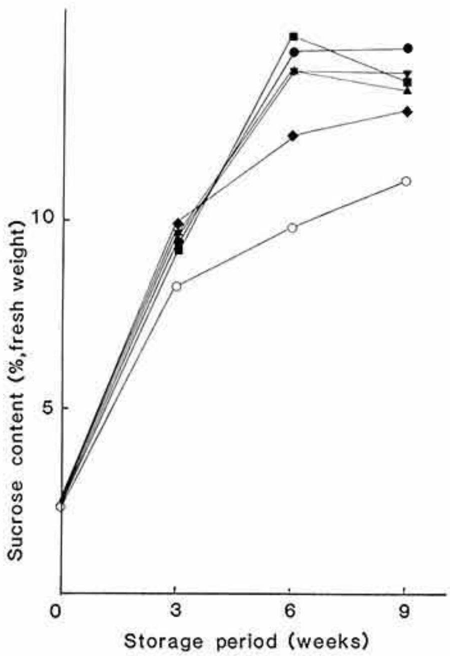

Fig. 7. Sucrose content of irradiated chestnuts during storage at 1°C
○; 0 kGy, ▲; 0.25 kGy, ▼; 0.5 kGy, ●; 0.75 kGy, ■; 1 kGy, ◆; 1.5 kGy

synthase (Fig. 9) and sucrose phosphate synthase (Fig. 10) in patato tubers increased for 2 to 3 days after irradiation and then decreased, while those of phosphoglucose isomerase, phosphoglucomutase and invertase were not significantly influenced by irradiation.[9]

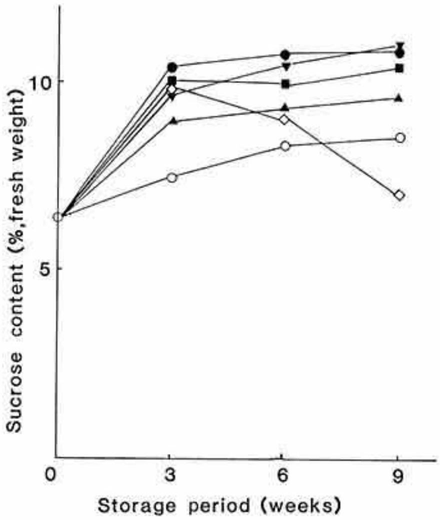

Fig. 8. Sucrose content of the chestnuts which were pre-stored at 5°C followed by irradiation and storage at 5°C
○; 0 kGy, ▲; 0.25 kGy,
▼; 0.5 kGy, ●; 0.75 kGy,
■; 1 kGy, ◇; 3 kGy

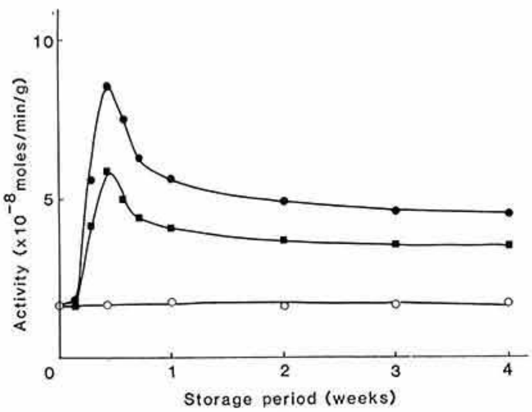

Fig. 9. Activity of sucrose synthase in irradiated potato tubers during storage at 20°C
○; 0 kGy, ■; 0.15 kGy
●; 2 kGy

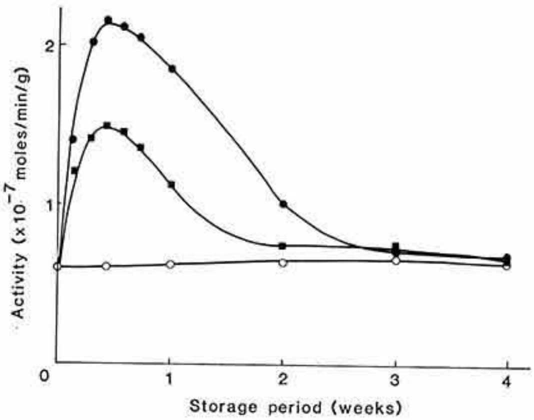

Fig. 10. Activity of sucrose phosphate synthase in irradiated potato tubers during storage at 20°C
○; 0 kGy, ■; 0.15 kGy,
●; 2 kGy

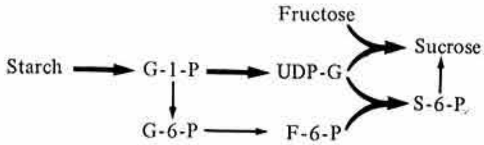

Fig. 11. Pathway of sugar metabolism in potato tubers enhanced by irradiation

The enzymes of which the activities were enhanced by irradiation are shown in Fig. 11 with thick allows. These results suggest that phosphorylase, UDP-glucose pyrophosphorylase, sucrose synthase and sucrose phosphate synthase play an important role in the sucrose accumulation in irradiated potato tubers, because the enzyme activities were at high levels when the sucrose content increased at a high rate (2–4 days after irradiation). Sucrose synthase, however, would not play a role in the sucrose accumulation in irradiated potato tubers at least for 1 day after irradiation, because its activity did not change for 1 day after irradiation, when the sucrose accumulation had already started. The enhancement of the activities of sucrose synthase and sucrose phosphate synthase by gamma-irradiation was also observed in sweet potato roots.[11]

Table 2. Carbohydrate metabolism of irradiated potato tissues

(a) Distribution of ^{14}C after metabolism of ^{14}C-UDP-glucose by potato tissues for 10 hr at 20°C (percent)

Fraction	Unirradiated	Irradiated
CO_2	6.2	12.3
Water-insoluble substances	21.0	3.1
Phosphate esters	29.9	21.5
Sucrose	7.9	33.0
Hexoses	3.1	1.1
UDP-glucose, ADP-glucose	17.5	9.0
Others	14.4	20.0
Total count, dpm	1.02×10^6	9.18×10^5

(b) Distribution of ^{14}C after metabolism of ^{14}C-fructose by potato tissues for 10 hr at 20°C (percent)

Fraction	Unirradiated	Irradiated
CO_2	3.6	6.1
Water-insoluble substances	26.8	12.3
Phosphate esters	22.4	38.9
Sucrose	10.4	15.0
Hexoses	21.6	20.6
UDP-glucose, ADP-glucose	1.9	1.4
Others	13.3	5.7
Total count, dpm	1.36×10^6	9.18×10^5

(c) Distribution of ^{14}C after metabolism of ^{14}C-fructose-6-phosphate by potato tissues for 10 hr at 20°C (percent)

Fraction	Unirradiated	Irradiated
CO_2	10.8	19.3
Water-insoluble substances	23.8	5.3
Phosphate esters	24.1	13.0
Sucrose	18.1	45.1
Hexoses	4.4	10.6
UDP-glucose, ADP-glucose	1.5	1.4
Others	7.3	5.3
Total count, dpm	1.05×10^6	1.29×10^5

The effect of gamma-irradiation on the carbohydrate metabolism of potato disks was investigated by using radio-labelled compounds. The measurement of the rate of sucrose degradation in potato tissues with ^{14}C-sucrose proved that the breakdown of sucrose was inhibited by irradiation in potatoes.[6] When ^{14}C-UDP-glucose, ^{14}C-fructose or ^{14}C-fructose-6-phosphate was metabolized in potato tissues, sucrose in the irradiated potato tissues had more radioactivity than that in the unirradiated ones (Table 2). The degree of incorporation of ^{14}C into sucrose in the irradiated tissues was much higher when ^{14}C-fructose-6-phosphate was administered as compared with when ^{14}C-fructose was administered. The incorporation of ^{14}C into water-insolube substances (starch) was reduced by irradiating tissues, when any radio-labelled compound was metabolized, which together with the enhancement of phosphorylase activity in irradiated potatoes suggested that starch synthesis was inhibited and starch degradation was accelerated by irradiation. The incorporation of ^{14}C into sucrose was inhibited by the treatment of the irradiated tissues with cycloheximide, protein synthesis inhibitor, which suggested that the enzymes responsible for sucrose synthesis in potatoes were synthesized by irradiation.[6]

Conclusion

The sucrose content was increased by irradiation in some agricultural products, and the content reached 2, 12 and 15% in irradiated potatoes, sweet potatoes and chestnuts, respectively, when they were irradiated and stored under appropriate conditions. Although cold-storage of agricultural products enhanced their sucrose content, the sucrose content of the irradiated agricultural products was not influenced by cold-storage before irradiation. It was indicated that the conversion of starch into sucrose was accelerated in these irradiated agricultural products. The activities of enzymes such as phosphorylase, UDP-glucose pyrophosphorylase, sucrose synthase and sucrose phosphate synthase were enhanced by irradiation. The results obtained by determining enzyme activities and by examining carbohydrate metabolism with radio-labelled compounds suggest that sucrose phosphate synthase play a more important role in the sucrose accumulation in irradiated potatoes as compared with sucrose synthase. The accelerated synthesis of sucrose phosphate synthase is one of the important physiological changes responsible for the accumulation of sucrose in irradiated potatoes. The reduced breakdown of sucrose and the increased degradation of starch also play a role in the sucrose accumulation. It is concluded that gamma-irradiation brings about various physiological changes that together contribute to the accumulation of sucrose in irradiated potato tubers.

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