POTATO QUALITY XXVII: INVESTIGATIONS ON THE ROLE OF PHOSPHORUS IN POTATO CHIP BROWNING[1]

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In an earlier publication, Hart and Smith (2) first reported a correlation between radiophosphorus location in fresh potato tuber slices and the browning patterns of potato chips processed from adjacent slices of the same potatoes. This paper deals with a series of further investigations on this subject.

MATERIALS AND METHODS

Plant Growing

Experiment 1: Whole "B" size Katahdin potato seed were green-sprouted and rooted in moist vermiculite. After abundant rooting was obtained, 24 vigorous young plants were detached from mother tubers and thoroughly rinsed in tap water to remove all vermiculite from root systems. One plant was transplanted and grown in each of 24 twelve-inch diameter clay pots. Pots were painted with horticultural grade asphalt internally to prevent transport of salts through capillaries and precipitation of salts on the outer walls of the pots. The growing medium was glass sand mixed mechanically at a ratio of 1 part coarse to 1 part fine. Each plant received 2½ liters of distilled water every other day and 2½ liters of appropriate nutrient solution on alternate days throughout the growing period. Excess water or nutrient solution was allowed to drain from the pots into a ground bed on the greenhouse floor.

Plants were grown from March 5 to June 28, 1963. On May 28 and 30, the 1 meq P treatments received 20 uc of P-32 in 1 liter of nutrient solution. The five meq P treatments received 100 uc of P-32 on the same days. For three consecutive days following the last application of radiophosphorus, each plant was watered with 2½ liters of distilled water, then allowed to senesce for 26 days before the tubers were harvested. Tubers were stored for two weeks at 50 F prior to chipping. (Table 1).

TABLE 1.—*Experiment 1. Composition of nutrient solutions.*

	milliequivalents per liter of nutrient solution							
Treatment	NH_4	NO_3	H_2PO_4	K	Ca	Mg	SO_4	Cl
KCl x P	9	8	1	8	5	5	5	13
K_2SO_4 x P	9	8	1	8	5	5	13	5
KCl x 5P	11	6	5	8	5	5	5	13
K_2SO_4 x 5P	11	6	5	8	5	5	13	5

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Experiment 2. The plant growing technique was similar to that of Experiment 1, except 12 inch diameter plastic pots were used; only 12 plants were grown and the growing medium was horticultural grade vermiculite, and the composition of nutrient solutions was different. (Table 2).

TABLE 2.—*Experiment 2. Composition of nutrient solutions.*

	milliequivalents per liter of nutrient solution							
Treatment	NH_4	NO_3	H_2PO_4	K	Ca	Mg	SO_4	Cl
K_2SO_4 x P	8	10	1	8	5	5	13	2*
K_2SO_4 x 3P	8	10	3	8	5	5	13	0

*2 meq Cl from 2 ml of M NH_4 Cl.

Plants were grown from October 7, 1963, to February 23, 1964. Radiophosphorus applications to each plant were made according to the sequence given in Table 3.

TABLE 3.—*Radiophosphorus applications to potato plants.*

Date	uc P-32	Solvent	Volume of Solvent
February 7	100	nutrient solution	2 liters
February 8	0	distilled water	2 liters
February 9	100	nutrient solution	2 liters
February 10	0	distilled water	2 liters
February 11	100	nutrient solution	2 liters
February 12	0	distilled water	2 liters

Tubers were stored for 58 days at 50 F prior to chipping.

All plants in both experiments received adequate amounts of the micro nutrient elements Fe, B, Mn, Zn, Cu, Mo throughout the growing periods in the greenhouse.

Preparation of Tubers for Chips, Autoradiograms and Counting

These methods have been previously given in detail by Hart and Smith (2). All radioactive samples from the experiments reported in this paper were counted in a Versamatic II Scaler.

Determinations for Sugar

Reducing sugars were determined colorimetrically by the 3, 5-dinitrosalicylic acid method of Sumner (8). The procedures involved in sampling, preparing, extracting and clarifying sugar samples from potatoes for reducing sugars, sucrose and total sugar are given in detail by Hart (1).

Determinations for Phosphorus

Total phosphorus was determined colorimetrically by the molybdivanado yellow method described by Kitson and Mellon (3).

Inorganic phosphorus was determined by a slight modification of Wright's isobutanol extraction and stannous chloride reduction method (9). Organic phosphorus was determined by difference, i.e., total phosphorus minus inorganic phosphorus. The procedures for all phosphorus methods and determinations on potatoes are outlined in detail by Hart (1).

Determination of Potato Chip Color

Experiment 1: Chips were designated subjectively as either light or dark.

Experiment 2: Chip color was determined objectively using an Agtron Model F Reflectance meter with standard disc numbers 5005 and 5052.5.

Results

Experiment 1

Appearance and Spectrographic Analysis of Potato Leaves

The appearance of the plants varied tremendously, according to nutritional treatment, throughout the growing period. The appearance of leaves is shown in Fig. 1.

The most abnormal plants were those of the KCl x 5P treatment. Leaves from these plants were very light green compared with other plants; considerable anthocyanin was prevalent on the underside of leaflets and the leaflets always exhibited a high degree of upward marginal curvature.

Spectrographic analyses of these leaves, presented in Table 4, show that the concentration of P, K and Fe was considerably higher than in leaves of other treatments.

TABLE 4.—*Spectrographic analysis of potato leaves 42 days after planting.*

Nutritional Treatment	per cent P	Ca	K	Mg	Fe (ppm)
KCl x P	.78	.88	5.76	.54	214
K_2SO_4 x P	.90	,76	6.20	.46	214
KCl x 5P	1.34	.88	7.60	.48	386
K_2SO_4 x 5P	1.12	.56	5.44	.36	214

Paired Autoradiogram Density and Potato Chip Color Comparisons

When the density and location of radiophosphorus in a potato slice was traced by an autoradiogram, then compared with the browning pattern of a chip processed from an adjacent slice of the same potato, a definite correlation was observed. Potato slices having a relatively high radiophosphorus concentration produced light color chips, while slices having a relatively low concentration of radiophosphorus produced dark color chips. Chips showing rather distinct dark and light areas were found to possess rather low radiophosphorus density and high radiophosphorus density, respectively. This is in agreement with results reported by Hart and Smith (2). These correlations are shown in Figs. 2, 3 and 4.

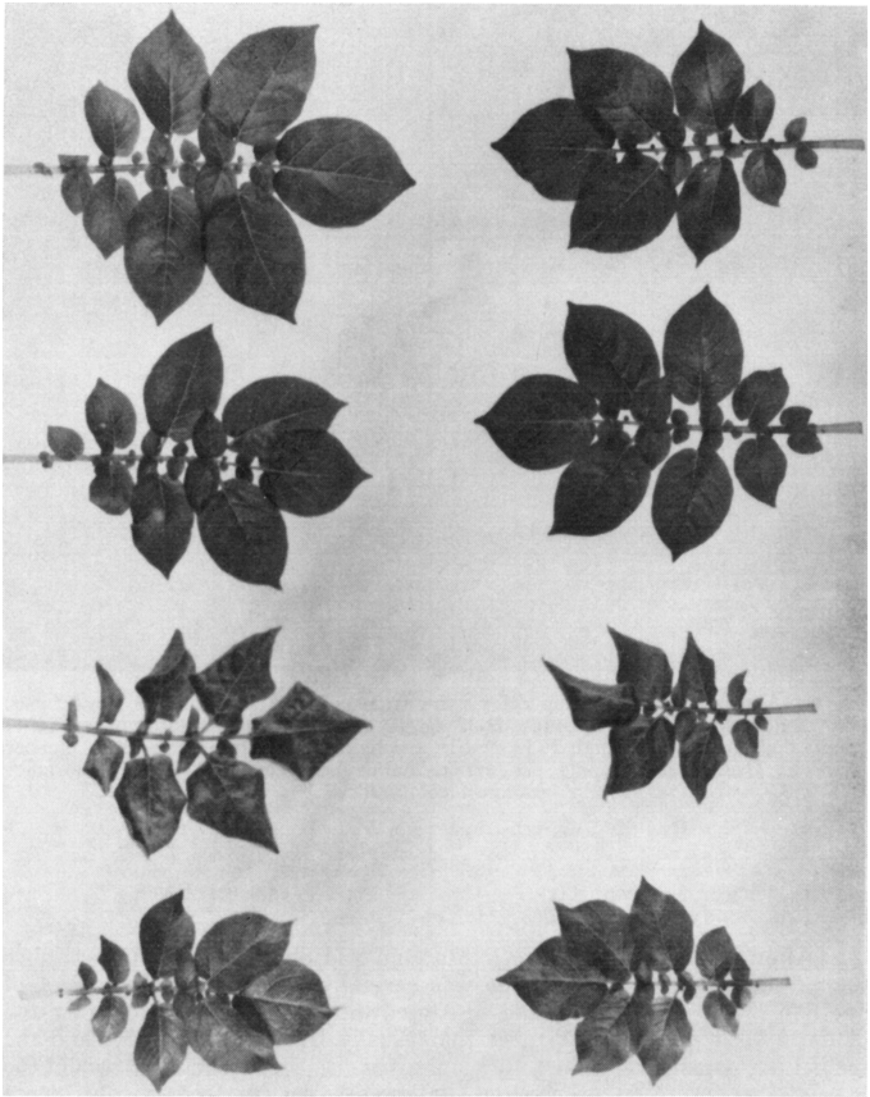

FIG. 1.—Potato leaves fourth node below apex from plants 42 days after planting. Nutritional treatment of leaves from top to bottom are: KCl x P, K_2SO_4 x P, KCl x 5P, K_2SO_4 x 5P.

Experiment 2

Paired Autoradiogram Density and Potato Chip Color Comparisons

Correlations of P-32 density and chip color patterns for 11 different potatoes are shown in Fig. 5.

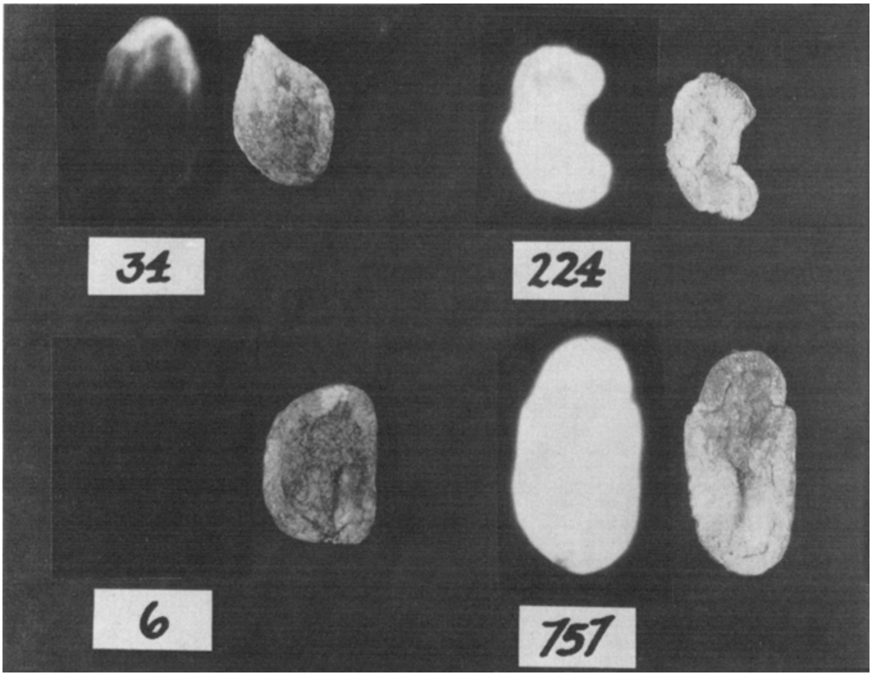

FIG. 2.—Autoradiogram — Chip color pairs from adjacent slices of the same tuber. Left: Autoradiograms showing low P-32 density and dark color potato chips. Right: Autoradiograms showing high P-32 density and light color potato chips. Each number refers to (cpm - bg) counts per minute minus background of entire autoradiogrammed potato slices.

Chemical Analyses of Potatoes

After frying a potato slice into a chip and obtaining an adjacent slice for autoradiography, raw tissue was carefully cut from stacked slices of one half of the same potato and separated into two lots. One lot consisted of tissue from areas in the tuber that usually fry to a light color and the second lot consisted of tissue from areas in the tuber that would be expected to fry to a dark color. The areas to be cut from a tuber were determined by examining the browning pattern of the potato chip processed from that tuber. The remaining potato-half was sliced and fried into chips. The light colored areas of the chips from each tuber were separated from dark colored areas and placed into two lots. Chip color values, sugar determinations and phosphorus determinations were performed on both halves of each potato sampled. A total of 10 large potatoes were analyzed and the data are presented in Table 5.

The raw data which constituted the average values given in Table 5 were subjected to multiple regression analysis. The results are summarized in Tables 6, 7 and 8.

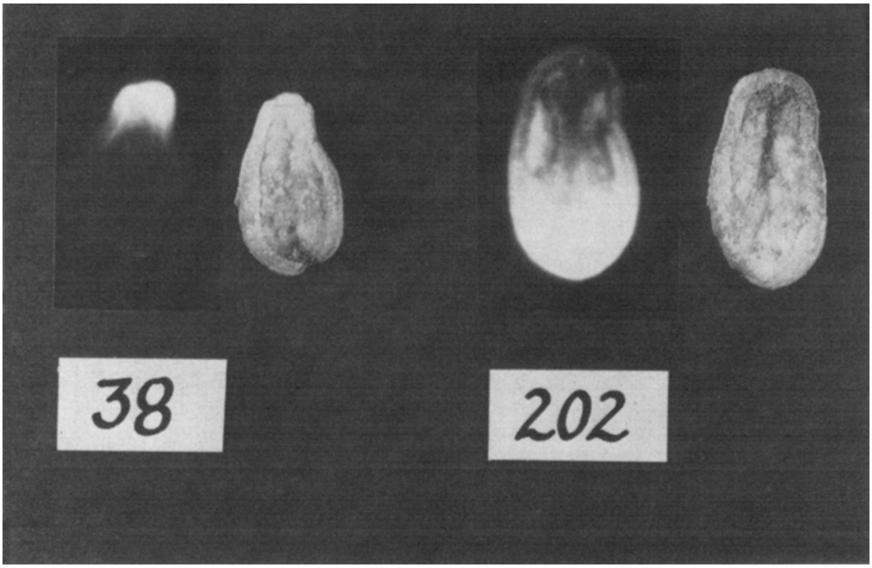

FIG. 3.—Autoradiogram — Chip color pairs from adjacent slices of the same tuber. Autoradiograms and potato chips revealing that the distribution of radiophosphorus in potato slices is well-correlated with the browning pattern in potato chips. Each number refers to cpm - bg of entire autoradiogramed potato slice.

TABLE 5.—*Mean values for various analyses performed on potatoes.*

	Chip color Agtron reflectance (5005-5052.5)	Micrograms per gram fresh weight						picocuries per gram fresh weight P-32
		Reducing sugars	Total sugar	Sucrose[a]	Total P	Inorganic P	Organic P	
Light	70.8	683	992	154	662	368	283	142
Dark	45.5	1848	1873	13	629	331	301	120

[a]All samples designated as *light* contained at least 100 ug of sucrose per gram fresh weight. However, 9 of 10 samples designated as *dark* contained no detectable sucrose.

Model System Studies with Sugar Phosphates

Model system experiments were conducted to find what effect certain phosphorylated monosaccharides had on the development of browning. Fried filter paper discs and fresh and frozen slices from a well-conditioned Merrimack potato were used in these tests. The results of model system studies are shown in Figs. 6 and 7.

The authors felt that the correlation between chip color and radiophosphorus concentration, as shown in Figs. 2, 3 and 5, might be linked in part, at least, to sugar phosphate concentrations of potatoes. However, Mori et al. (4) and Schwimmer et al. (6) have presented

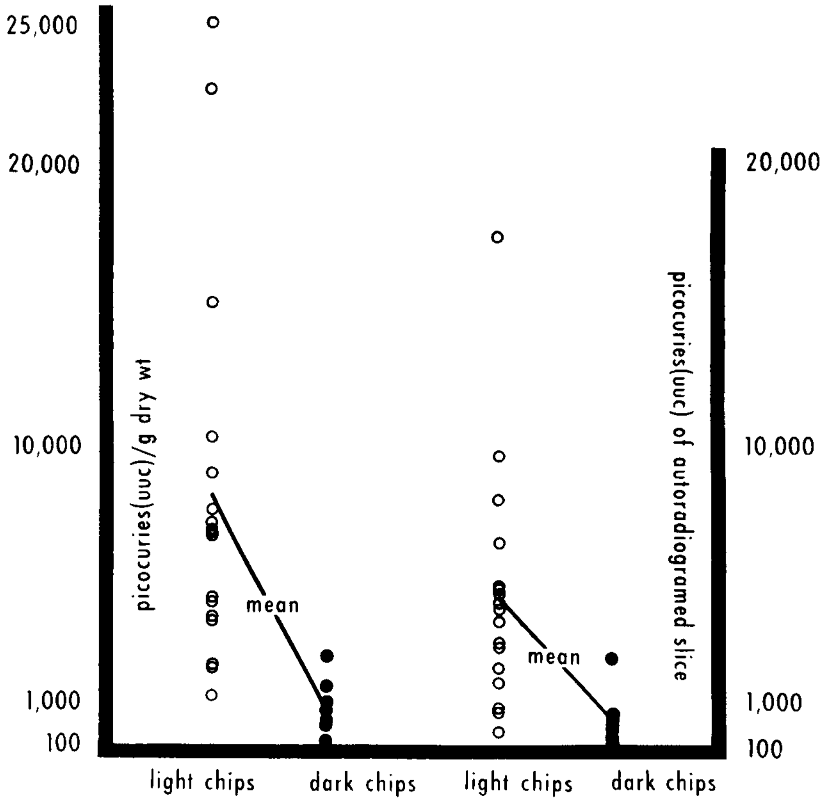

FIG. 4.—Experimental observations showing correlation between P-32 concentration in individual potato tubers and chip color.

data which show that the quantity of sugar phosphates in potatoes is too small to have any direct effect on the potato chip browning reaction. Earlier, Schwimmer and Olcott (5) reported that phosphorus increased the extent of browning in prepared test tube solutions of certain sugar phosphates.

DISCUSSION

Variation in appearance of plants, Experiment 1, may be explained by results of spectrographic analysis of the leaves. The leaves from KCL x 3P plants were quite abnormal as described earlier. The data presented in Table 4 show that the per cent phosphorus and potassium are highest in these leaves compared with leaves from other treatments 42 days after planting. Furthermore, the iron concentration is almost twice as high in these leaves compared with others. The poor appearance of these plants may be attributable to one or more of the following reasons:

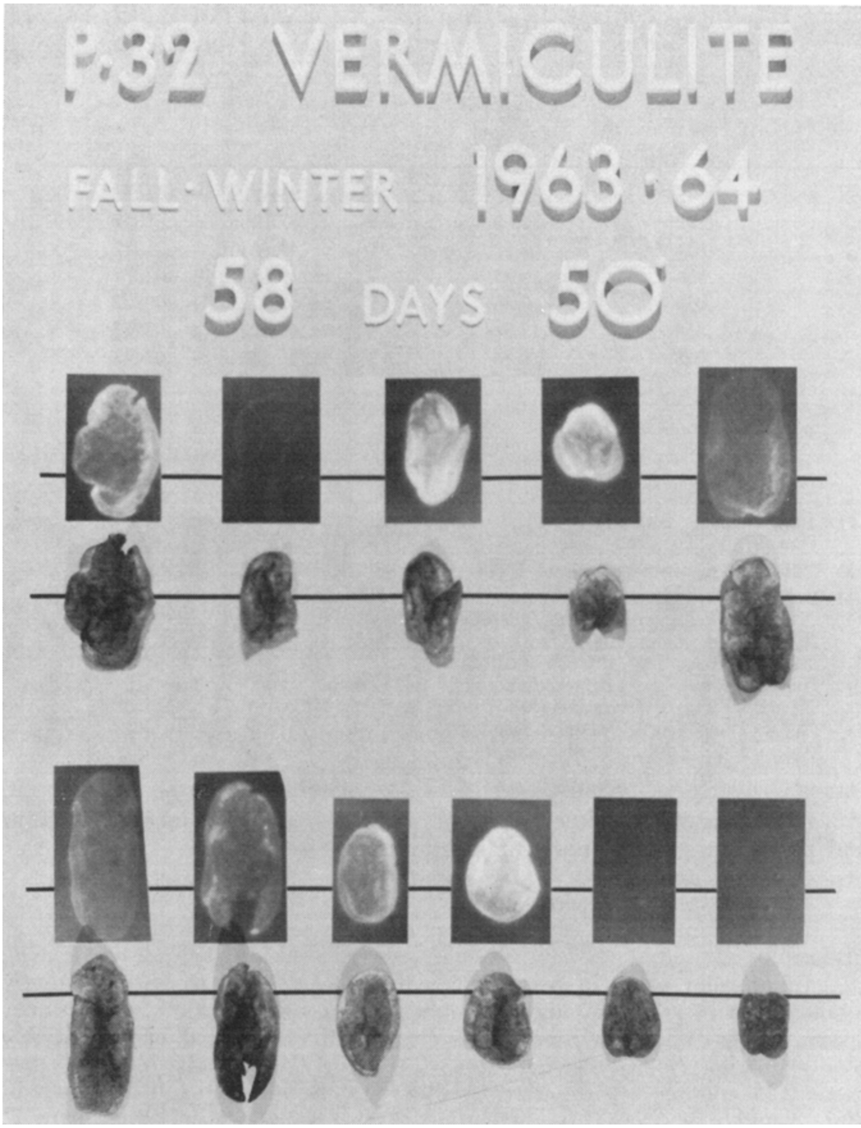

FIG. 5.—Autoradiogram — Chip color pairs from adjacent slices of the same tuber representing eleven different potatoes.

Upper Row: samples 1-5. Left to right.

Lower Row: samples 6-11. Left to right.

Note that radiophosphorus concentration and chip color patterns (light versus dark areas) correspond extremely well in samples 1, 3, 4, 8 and 9.

TABLE 6.—*Simple Correlation Coefficients, Association Coefficients (in per cent) and Regression Equations Between Y and* X_i.

Y	r	per cent $(r^2)(100)$	Y_{ij}		a_i	+	b_i	X_{ij}
X_1	.945**	89.27	Y_{1j}	=	81.62193	—	.01652	X_{1j}
X_2	.892**	79.60	Y_{2j}	=	87.19669	—	.01868	X_{2j}
X_3	.834**	69.58	Y_{3j}	=	49.18361	+	.01217	X_{3j}
X_4	.556	30.93	Y_{4j}	=	9.83720	+	.07272	X_{4j}
X_5	.059	0.35	Y_{5j}	=	53.82230	+	.00872	X_{5j}
X_6	.354	12.54	Y_{6j}	=	46.82230	+	.03251	X_{6j}
X_7	.038	0.14	Y_{7j}	=	56.38668	+	.00413	X_{7j}

(1) r for 8 degrees of freedom
.01 .05
.765 .632

(2) i = 1 7
j = 1 10

(3) **denotes significance at the 1 per cent level

(4) Y = potato chip color (Agtron Model F 5005-5052.5)
X_1 = reducing sugars (ug/g fresh weight)
X_2 = total sugar (ug/g fresh weight)
X_3 = sucrose (ug/g fresh weight)
X_4 = Pt (ug/g fresh weight)
X_5 = Pi (ug/g fresh weight)
X_6 = Porg (ug/g fresh weight)
X_7 = P-32 (uuc/g fresh weight)

(1) Calcium deficiency brought about by an imbalance of calcium and phosphorus in the nutrient solution.

(2) Iron toxicity.

(3) Phosphorus toxicity

(4) An imbalance of potassium with respect to calcium and magnesium.

Light color areas in potato chips have been found to be consistently associated with relatively high radiophosphorus concentration in raw tuber tissue, while dark color areas were consistently associated with relatively low radiophosphorus concentration. This correlation was reported previously in another investigation by Hart and Smith (2) and is shown in Fig. 2 and 3 above. This correlation is also apparent in Experiment 2, Fig. 5 but the results are not as striking. This could be due to the fact that potatoes from this experiment were stored at 50 F considerably longer than any of the potatoes of previous experiments. The prolonged exposure at 50 F of these potatoes (58 days compared with 14 days for potatoes from other experiments) resulted in a greater accumulation of reducing sugars in these potatoes which made the possibility of obtaining light color chips less likely.

Data in Table 5 show that the concentration of radiophosphorus was higher in areas of tubers that produced light chip color than in tissue

TABLE 7.—*Analysis of Variance for Regression.*

		Mean Square						
Source of Variation	Degrees of Freedom	X_1	X_2	X_3	X_4	X_5	X_6	X_7
Due to Regression	1	1379.7854**	1230.2488**	1075.4948**	478.0344	5.3440	193.7952	2.2056
Deviations from Regression (error)	8	20.7268	39.4189	58.7594	133.4457	192.5320	168.9756	192.9243
Total	9							

F.05 (1, 8) = 5.32 = *
F.01 (1. 8) = 11.26 = **

TABLE 8.—*Multiple Correlation Coefficient, Association Coefficient (in per cent) and Regression Equation Between Y and* $X_1 + X_2 + X_3 + X_4 + X_5 + X_6$

$X_1 + X_2 + X_3$ $X_4 + X_5 + X_6$	r	per cent (r^2) (100)	Y =	a	$+ b_1X_1$	$+ b_2X_2$	$+ b_3X_3$	$+ b_4X_4$	$+ b_5X_5$	$+ b_6X_6$
Y	.988*	97.57	Y =	106.30284	+2.14033X	—2.15585X	+4.35646X	—.03506X	—.01807X	—.00615X

(1) r for 3 degrees of freedom with 6 independent variables

.01	.05
.990	.968

(2) *Denotes significance at the 5 per cent level
(3) Y — Potato chip color (Agtron Model F 5005-5052.5)
X_1 — Reducing sugars (ug/g fresh weight)
X_2 — Total sugar (ug/g fresh weight)
X_3 — Sucrose (ug/g fresh weight)
X_4 — Pt (ug/g fresh wweight)
X_5 — P_i (ug/g fresh weight)
X_6 — P-32 (ug/g fresh weight)

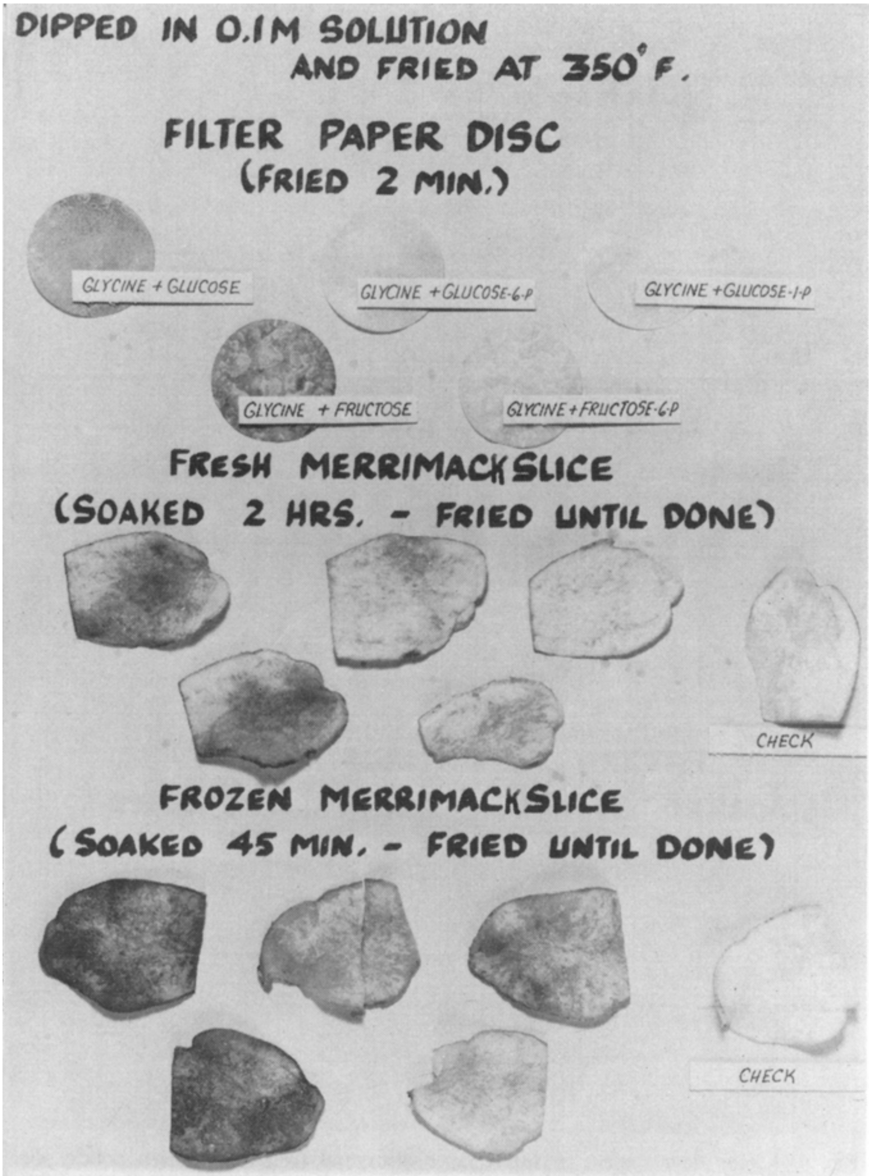

FIG. 7.—Color development in filter paper discs and fresh and frozen potato slices with combined reagents.
Two Top Rows: In the presence of glycine, all sugars produced some browning in filter paper discs.
Two Middle Rows: When fresh potato slices were subjected to these solutions the sugar phosphates increased browning only slightly over the check.
Two Bottom Rows: When frozen slices were subjected to these solutions the browning became more intensified.

which fried to a dark chip color. Total phosphorus, inorganic phosphorus and sucrose concentrations were also higher in areas of tubers that produced light chip color, but the concentrations of reducing sugars and total sugar were much lower.

Data in Table 6 show that reducing sugars, total sugar and sucrose content of potatoes are significantly correlated with potato chip color at the 1% level. Although not statistically significant, the simple correlation coefficient for total phosphorus and chip color comes close to being significant at the 5% level. The regression equation indicates that chip color will be somewhat lighter as total phosphorus content increases.

Data in Table 8 show that the multiple correlation coefficient for chip color versus reducing sugars plus total sugar plus sucrose plus total phosphorus plus inorganic phosphorus plus radiophosphorus is $r = .988$ and is significant at the 5% level.

The results of model system experiments substantiate the conjecture that the quantity of phosphorylated sugars in potatoes would be too small to have any effect on browning; for even at concentrations of 0.1 molar, these sugars have little influence on potato chip browning.

Any tendency for sugar phosphates to lighten the color of potato chips, if such a phenomenon occurs, would probably be nullified in the presence of the much greater quantities of reducing sugars in potatoes.

Summary

Radiophosphorus concentration in localized areas of potato tuber slices is well correlated with the color of chips in those areas. High radiophosphorus concentration is associated with light color chips while low radiophosphorus concentration is associated with dark color chips. However, the simple correlation coefficient between radiophosphorus and chip color is very low and not significant. Total phosphorus content was higher in areas of tubers that produced light chip color than in areas which fried dark. The simple correlation coefficient between total phosphorus and chip color comes close to being significant at the 5% level.

The amount of P-32 found in given portions of potatoes is consistently, inversely proportional to the amount of reducing sugars found in those portions of potatoes.

The multiple correlation coefficient for chip color versus reducing sugars plus total sugar plus sucrose plus total phosphorus plus inorganic phosphorus plus radiophosphorus for potatoes obtained from Experiment 2, was found to be $r = .988$ and significant at the 5% level.

Simple correlation coefficients between reducing sugars, total sugar and sucrose versus chip color, were all significant at the 1% level.

It is highly probable that phosphorylated monosaccharides per se, have no effect on the browning reaction in potato chips owing to their intrinsically low concentration in fresh potatoes. Compared with reducing sugars in model systems, certain hexose phosphates gave much lighter colors to fried filter papers and fresh or frozen slices of a well-conditioned Merrimack potato when the concentration of each solute in various dipping solutions was 0.1 molar.

Resumen

La concentración de radiofósforo en las areas localizadas de las rebanadas de tubérculo de papa, se correlaciona bien con el color de las hojuelas en aquellas areas. La alta concentración de radiofósforo, está asociada con el color claro de las hojuelas, mientras que la baja concentración de radiofósforo, está asociada con el color oscuro de las hojuelas. Sin embargo, el coeficiente de correlación simple entre radiofósforo y color de hojuelas, es muy bajo y no es significativo. El contenido total de fósforo fue más alto en las areas de los tubérculos que produjeron hojuelas de color claro, que en las areas e las cuales fueron fritas hasta tomar un color oscuro. Aunque sin ser significativo, el coeficiente de correlación simple entre ei total de fósforo y color de las hojuelas, se asproxima a ser significativo al 5%.

La cantidad de P-32 encontrada en porciones dadas de las papas, es consistente, inversamente proporcional a la cantidad de azúcares reducidas, encontradas en aquellas porciones de papa.

El coeficiente de correlación múltiple, para el color de hojuelas contra azúcares reducidas, más total de azucar, más sucrosa, más total de fósforo, más fósforo inorgánico, más radiofósforo para la papa obtenida del Experimento 2, se encontró que $r = .988$ y significativo al nivel de 5%.

Los coeficientes de correlación simple entre los azúcares reducidos, azucar total y sucrosa, contra el color de las hojuelas, fueron todos significativos al nivel de 1%.

Es altamente probable que los monosacáridos fosforilados, no tienen efecto en la reacción de oscurecimiento en las hojuelas de papa, debido a la baja concentración, intrinsicamente, en papa fresca. En la comparación con las azúcares reducidas en el sistema modelo, ciertos fosfatos de hexosa dieron colores más claros a los filtros de papel de freido y las rebanadas frescas o congeladas, de papa Merrimack bien condicionada, cuando la concentración de cada soluto en varias soluciones de inmersión fue de 0.1 molar.

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