Sugar Development in Potatoes

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Excess sugar development—in storage or as a result of field conditions—makes potatoes unfit for processing. Sugars will cause a dark color when potatoes are processed into chips, fries, or other products.

Research at Washington State University shows how to keep sugars from developing:

**IN THE FIELD**

1. Initiate harvest at the optimum time for maximum starch and minimum sugar content. In the Columbia Basin of Washington this generally occurs about the middle of September.

2. Do not allow stress upon the plant to interrupt normal growth of the tubers. Fertilize adequately so plants will not die prematurely. Maintain adequate moisture supply.

3. Initiate maturation process by killing vines a week to ten days prior to harvest and limiting nitrogen fertilization toward end of season.

**IN STORAGE**

1. Cool potatoes as rapidly as possible to wound healing temperatures of approximately 50° F (10° C).

2. Maintain wound healing and suberization temperatures of 50° F for at least a month.

3. Gradually lower to holding temperatures of 42° F (5.6° C) to 48° F (8.9° C) depending upon the type of processed product for which the potatoes will be used.

4. Tubers which have been subjected to stress conditions during growth or which have died prematurely because of disease or lack of fertilizer should be placed in short-term storage or processed immediately.

5. If for uncontrollable reasons excessive sugars develop in storage, reconditioning to lower the sugar levels should be initiated after a period of wound healing or more preferably in the spring when sugars are more easily reconverted back to starch.
SUGAR DEVELOPMENT IN POTATOES
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INTRODUCTION
Potato processing has been a major factor in the tremendous expansion of the convenience food industry in the United States. In 1975 approximately 57% of the total potato crop in the United States was processed. During this same period in Washington, Idaho, and Oregon, 80 to 85% of the crop was processed primarily of the Russet Burbank variety.

The major sugars found in potatoes are sucrose, glucose, and fructose. The latter two are reducing sugars and are responsible for the undesirable dark color which may develop in processed potato products. Heat applied during processing causes reducing sugars to react with amino acids, ascorbic acid, and other organic compounds in a non-enzymatic process called the Maillard reaction. The result is darkening. This is the major reason excess sugars in stored potatoes are undesirable. High sugars can also cause undesirable flavor after cooking and can have a detrimental influence on texture.

The presence of sugars in raw potatoes is a major problem for processors. The amount of reducing sugar the processing industry can tolerate depends upon the type of processed product. Potatoes used for making chips must have a minimum of reducing sugars while frozen fries and dehydrated mash can withstand slightly larger amounts.

FACTORS INFLUENCING SUGAR DEVELOPMENT
Both the storage environment and the conditions of the growing environment determine ultimate sugar content. Factors affecting sugar accumulation include stress during growth, relative maturity at harvest, specific gravity, storage temperatures, temperature management, and stress conditions in storage. All can act alone or in combination with other factors to determine ultimate sugar content. For minimum sugar development, attention should be paid to all of these factors.

Stress during growth. Many different types of stress can occur during growth of the potato plant. These include lack of moisture, high temperatures, low temperatures, fertilizer imbalance, and early vine death due to diseases or insects. Stress early in the growth cycle generally has the most effect on the tubers. Moisture or heat stress during early tuber development results in formation of translucent or “jelly-end” tubers. Stress interrupts normal tuber enlargement, causing mal-
TUBER SHAPES AND WHAT THEY MEAN

EARLY STRESS

MIDSEASON STRESS

LATE STRESS

Figure 1—The influence of stress during different stages of tuber development on tuber shape.
formed tubers (Fig. 1) as well as increased sugar development. Fertilizer imbalance, such as insufficient nitrogen, can cause premature dying of foliage. Tubers under vines which have died prematurely age physiologically while in the soil. When placed in storage, they develop increased amounts of reducing sugars (Fig. 2). These tubers should be dug early or processed as soon as possible after harvest.

**Specific gravity of tubers.** Specific gravity is an indirect method of determining dry matter or starch content in a tuber. In processing, high starch content is desirable for several reasons—greater yield of processed product per unit of raw product, less fat absorpton during processing, and better cooked texture and mealiness. As a rule, high specific gravity potatoes generally accumulate less reducing sugars during low-temperature storage (Fig. 2). This relationship generally holds only when comparisons are made within the same lot of potatoes. When different lots are compared, different

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**Figure 2**—The effect of fertility and specific gravity on reducing sugar accumulation in low temperature storage.
Figure 3—The influence of relative maturity of tubers on reducing sugar formation when stored at 42 F.

amounts of sugar accumulation can result at the same specific gravity because of other contributing factors. At the high fertility level the difference in sugar accumulation due to specific gravity was enhanced (Fig. 2).

Maturity of tubers. Maturity is a very elusive term when used in reference to potatoes. Generally it means degree of skin set plus condition of vines at harvest time. Immature potatoes, which skin rather easily, are tubers harvested from relatively green vines. Immature potatoes accumulate greater amounts of reducing sugars in storage (Fig. 3) than potatoes which were properly matured by killing the vines a week to ten days before harvest. The maturation process can take place in storage if the potatoes are kept at 50° F (10° C), a non-sugar forming temperature, for at least a month under high
relative humidity. However, it is better to initiate the maturation process in the field. From the standpoint of sugar development, tubers can also be overmature. Overmature tubers are from vines which have died prematurely, regardless of cause. If these tubers are not dug, physiological aging is speeded up, causing greater sugar accumulation when tubers are exposed to low temperatures (Figs. 2, 3). in storage.

A stage known as "physiological maturity" occurs when a peak of dry matter is attained (Fig. 4). Sugar content is also usually minimal at this stage. In the Columbia Basin of Washington, physiological maturity occurs in most years at about the middle of September. Harvesting of processing potatoes for storage should be initiated at this time. Sucrose content gives some indication of relative maturity.
Figure 5—Reducing sugar level of tubers held at curing or pre-holding temperatures of 42, 48, 56, and 70 F for two weeks prior to holding temperatures of 42 F for two months.

Figure 6—The effect of constant storage temperatures of 42, 45, and 48 F on reducing sugar formation.
Immature tubers contain large amounts of sucrose, with the apical (bud) portion having greater amounts than the basal (stem) portion. The amount of sucrose decreases rapidly as tubers grow and mature. Toward the end of the season (October) there is an increase in reducing sugars, due to lower overall temperatures. Starch or percent dry matter content peaks about the middle of September, after which it decreases slightly. This is due to cooler temperatures, which result in greater availability of moisture, causing more rapid tuber enlargement than translocation of starch into the tubers.

**Wound healing and curing temperatures.** Wound healing and maturation (thickening and setting of the skin) are necessary when potatoes are first brought into storage. Curing (wound healing and maturation) reduces decay and keeps moisture loss to a minimum. From the standpoint of minimum sugar development, the best temperature for wound healing and maturation appears to be about 50°F (10°C) (Fig. 5). Curing potatoes at higher temperatures speeds wound periderm formation, but increases chances for rot development and also causes physiological aging of the tubers, resulting in increased amounts of sugars. Curing at lower temperatures increases sugar accumulation, and also results in inadequate wound healing.
Storage temperature. Sugar accumulation is generally higher at lower storage temperatures (Fig. 6). The sugars accumulated at a given temperature vary considerably, depending upon many factors. Generally potatoes are most susceptible to sugar accumulation during the first month or two in storage (Fig. 7). Tubers held at low temperatures (42° F) during the first two months accumulate higher levels of sugars than if low temperatures occur later (Fig. 7). Therefore it is important not to expose potatoes to low temperatures during the early storage period.

Carbon dioxide in the storage atmosphere. Under normal conditions in a modern potato storage, excessive levels of carbon dioxide (CO₂) do not occur. However, if proper ventilation is not provided, especially early in the storage season when respiration rates are high, CO₂ can accumulate. A high CO₂ atmosphere actually slows
TABLE 1—SUGARS IN SEEDLINGS AND VARIETIES GROWN AND STORED UNDER THE SAME CONDITIONS.

<table>
<thead>
<tr>
<th>Sugar</th>
<th>% Total Sugar</th>
<th>% Reducing Sugar</th>
<th>% Sucrose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A 6135-4</td>
<td>7.2</td>
<td>6.3</td>
<td>0.9</td>
</tr>
<tr>
<td>2. W280-11</td>
<td>4.7</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td>3. WC 304-4</td>
<td>9.4</td>
<td>8.5</td>
<td>0.9</td>
</tr>
<tr>
<td>4. WC 314-2</td>
<td>5.4</td>
<td>4.6</td>
<td>1.3</td>
</tr>
<tr>
<td>5. A503-42</td>
<td>6.9</td>
<td>5.0</td>
<td>1.9</td>
</tr>
<tr>
<td>6. Russet Burbank</td>
<td>5.9</td>
<td>3.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

the conversion to reducing sugars (Fig. 8). However, sucrose content is very high and once the potatoes have been returned to a normal atmosphere, the levels of reducing sugars will increase. High CO₂ concentrations (anaerobic conditions) are conducive to rot and also hinder proper wound healing. Therefore it is important to maintain normal ventilation during the early storage period.

**Variety.** Varieties differ in their capacity to form reducing sugars in storage. Why they do so is not clearly understood. Membrane permeability, enzyme activity, starch content, and relative maturity all probably play a part. Varieties differ not only in total sugars (Table 1), but also in type of sugars accumulated under a given set of conditions, i.e., some varieties tend to form more sucrose while others produce more reducing sugars. Table 1 shows the extreme differences in reducing sugar content which can exist with the same harvest and storage conditions. Seedling WC-304-4 accumulated over twice as much reducing sugar as Russet Burbank. Some varieties, such as Monona, can be processed into chips directly out of low-temperature storage due to resistance to starch-sugar conversion. This is the ultimate solution for control of sugars in processing potatoes.

**Sugar end development.** The term “sugar end” refers to potatoes which fry dark on one end and light colored on the other. This type of potato is undesirable for processing into frozen french fries. There are at least three distinct causes of sugar end development (Fig. 9). By far the most troublesome is early growth stress in the field, which produces translucent end potatoes. Many of these tubers eventually develop jelly end rot. They have low starch content with high sugar development in the basal (stem) end relative to the apical (bud) end.

The second type of sugar end is produced by late-season stress in the field. If tubers stop growing in late summer because of moisture or fertility stress, growth starts again when favorable conditions
Figure 9—The causes of sugar end potatoes: early stress in field, late stress, and early death of the plant.

return. The result is a tuber somewhat pointed on the apical end (Fig. 1). The pointed apical portion is very immature, has high sugar content, and produces dark fries when processed directly out of the field. This type of tuber has relatively low starch and high sugar content in the apical end compared to the basal end.

The third type of sugar end potato is produced by premature death of the vine. In most cases vine death is due to disease or insufficient fertilizer. Vines which die prematurely produce tubers which are over-mature. These tubers have high starch and high sugar content in the basal end in comparison to the apical end. The difference in starch and sugar content between the two ends is much greater than with normal tubers. This type of potato does not store well. It accumulates greater total amounts of sugars and therefore should be processed shortly after harvest.

RELATIONSHIP BETWEEN SUCROSE AND REDUCING SUGARS

Although glucose and fructose are the chief sugars which cause darkening of processed products, the amount of sucrose present is also important because sucrose level can indicate the physiological condition of a tuber. High sucrose may result from immaturity and
physiological stress of tubers during growth or after they have been put into storage.

Sucrose is the intermediate product in the formation of reducing sugars from starch. It is the primary form in which carbohydrates formed in the leaves are translocated into the tubers. Immature potatoes contain very high levels of sucrose (Fig. 4) which decrease rapidly with maturity. Potatoes from vines which die prematurely do not attain minimum sucrose content (less than 1% on a dry weight basis).

Research shows that tubers placed in storage with high sucrose content generally accumulate more reducing sugars, lose a greater amount of weight, and are more susceptible to rot than tubers stored with a low sucrose content. Stress conditions in storage, such as low temperature or high carbon dioxide (Fig. 8) can cause high accumulations of sucrose. Varieties differ in the ratio of sucrose to reducing sugars formed under a given set of conditions. For example, at low temperatures seedling WC-304-4 accumulated greater amounts of reducing sugars than Russet Burbank, but Russet Burbank had a greater amount of sucrose (Table 1).

**BIOCHEMICAL ASPECTS OF SUGAR DEVELOPMENT**

The conversion of potato starch to sugars during low-temperature storage is well known, but the biochemical mechanism is not well understood.

The steps in this transformation of starch to sugars which takes place during low-temperature storage are presented in Fig. 10. Many, but not all, of the enzyme reactions are reversible. Invertase catalyzes the reaction of sucrose to reducing sugars. This reaction is irreversible and seems to be controlled by an invertase inhibitor which prevents formation of invert sugars (glucose, fructose). This inhibitor is present at high temperatures and disappears at low temperatures. It was thought at one time that invertase controlled starch-sugar conversion. However, recent work in Israel and the United States strongly indicates that the controlling factor is membrane permeability. Starch granules are surrounded by a membrane called amyloplast which prevents enzymes from attacking the starch. Low temperatures cause disintegration of this membrane and increase permeability, allowing enzymes access to the starch. The lipid (fat) component of the membrane apparently undergoes a phase change at low temperatures.
Figure 10—Flow diagram of starch-sugar transformation in potatoes during low temperature storage.

FACTORS INFLUENCING RECONDITIONING

Reconditioning is the process by which high reducing sugar concentrations are lowered to levels more acceptable for processing. This is done by storage at elevated temperatures of from 60° F (15.5° C) to 70° F (21.1° C) for varying lengths of time. Varieties differ considerably in their ability to recondition. The growing environment and storage conditions can also influence reconditioning ability (Table 2). Potatoes from plants which die prematurely due to lack of fertilizer or disease are over-mature and tend to be more difficult to
recondition. Low specific gravity tubers tend to accumulate more sugars at a given temperature in storage and are also more difficult to recondition, regardless of initial sugar content. In Russet Burbank, the stem or basal portion accumulates significantly more sugars in storage and it is harder to get rid of the sugars in this portion than in the apical or bud end.

Tubers which have been stressed in the field, particularly under conditions which produce translucent or jelly end potatoes, are very difficult to recondition. The reason for this is not clearly understood. Part of the reason could be because of extremely high levels of sugar accumulation.

If excessive sugars accumulate in storage in the fall, it is much easier to recondition the potatoes in the spring than earlier in the storage season (Table 2). The more rapid loss of sugars in the spring is likely due to greater respiration rate and greater use of sugar because of increased sprout activity. Tubers must be properly healed before they are subjected to high temperatures in the reconditioning process.

**TABLE 2—THE INFLUENCE OF FERTILITY LEVEL, SPECIFIC GRAVITY, TUBER PORTION, AND STORAGE PERIOD ON LOSS OF SUGARS BY RECONDITIONING.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% Reducing Sugars (Av. 2 yrs. Data)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Recond.</td>
<td>After Recond.</td>
</tr>
<tr>
<td><strong>Fertility</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>5.37¹</td>
<td>1.72</td>
</tr>
<tr>
<td>Low</td>
<td>5.59</td>
<td>2.08</td>
</tr>
<tr>
<td>*LSD @ 5% = 4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Specific Gravity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High (1.085)</td>
<td>5.70</td>
<td>1.74</td>
</tr>
<tr>
<td>Low (1.075)</td>
<td>5.27</td>
<td>2.07</td>
</tr>
<tr>
<td>**LSD @ 1% = 5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tuber Portion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem</td>
<td>7.82</td>
<td>3.54</td>
</tr>
<tr>
<td>Center</td>
<td>4.91</td>
<td>1.57</td>
</tr>
<tr>
<td>Bud</td>
<td>3.72</td>
<td>0.59</td>
</tr>
<tr>
<td>**LSD @ 1% = 7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Storage Period</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early</td>
<td>6.40</td>
<td>3.14</td>
</tr>
<tr>
<td>Mid</td>
<td>4.50</td>
<td>1.54</td>
</tr>
<tr>
<td>Late</td>
<td>5.54</td>
<td>1.04</td>
</tr>
<tr>
<td>**LSD @ 1% = 7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Average of 8 analyses.
FOR MORE INFORMATION

For further details on starch-sugar conversion in potatoes refer to the following publications.


