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High Viscosity of Cell Wall Suspensions Prepared from Tomato Juice[a]

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PROGRESS TOWARD IDENTIFYING the factors that control the viscosity of tomato products has been made by many investigators *(1, 7, 8, 9, 10, 11, 13, 14, 15, 16, 19, 20, 22, 23,* and others). Two factors, the quantity and quality of pectic materials, and the quantity, configuration, and character of the insoluble solids have been shown to be of major importance.

While we were studying the role of insoluble solids in the viscosity of tomato juice, and were attempting to isolate the insoluble solids, we obtained a result that was totally unexpected and we believe previously undescribed. We observed that when tomato juice was centrifuged and the sediment was washed repeatedly with distilled water by centrifugation, viscosity at first dropped, then rose to a value far exceeding that of the original juice. In some cases, the washed product thickened to a semi-gel.

The present paper proposes to describe in detail the thickening effect just mentioned, to disclose the properties and behavior of the thickened product and of various juice fractions, and to provide new fundamental information on the factors determining tomato juice viscosity.

PROCEDURE AND RESULTS

Effect of washing. Changes in viscosity of a pectin-rich unhomogenized, commercial tomato juice brought about by centrifuge washing are shown in Table 1. The juice was centrifuged 9 times under identical conditions (2000 r.p.m., 10 min., 25° C.) in an International[c] size 1 centrifuge. After each centrifuge run, the supernatant layer was decanted and replaced with distilled water, which then was mixed with the settled layer or insoluble solids prior to re-centrifugation.

Viscosity, as measured at 25° C. with a Brookfield viscometer,[c] rotor No. 2 at 60 r.p.m., decreased initially as distilled water was substituted for the original serum (soluble solids fraction). As the washing procedure continued, however, viscosity gradually increased, reaching a value more than double that of the original juice at the ninth wash.

Associated with the increase in viscosity was an increase in the volume of the centrifuged insoluble solids. These swelled, and packed less tightly in the centrifuge tube as washing progressed. At the same time the soluble solids content and the conductivity of the sample decreased (Table 1).

The microscopic structure of the insoluble solids *(23)* is shown in Figure 1. Only two principal structures were visible.

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[c] Mention of specific products does not imply endorsement of them by the Department to the possible detriment of others not mentioned.

TABLE 1
Increase in viscosity attendant on the washing of soluble solids from tomato juice by centrifugation

No. of centrifuge washings of original juice[1]	Viscosity, apparent centipoises	Soluble solids, % (Abbe)	Volume of insoluble solids after centrifugation, cc.	Electrical resistance, ohms[2]
0	240	5.8	148	6
1	200	2.5	153	14
3	240	0.7	168	30
5	290	0.3	181	175
7	380	0.1	200	650
9	500	0	223	1500

[1] After each centrifugation, the supernatant liquid was decanted and replaced witth distilled water. Volume of original juice was 400 cc.
[2] With the conductivity cell used, the resistance of N/10 KCl was 7 ohms.

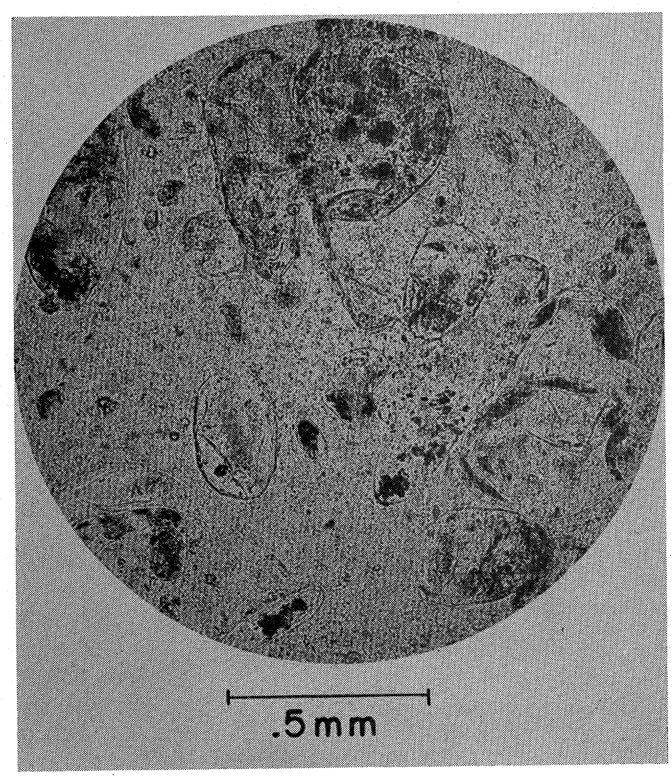

Figure 1. Insoluble solids of tomato juice, showing numerous granules separated from cells, single and clustered granules within cells, and walls of the cells.

These were tomato cell walls, visible as lines outlining the predominantly spherical cells, and numerous small granules, occurring singly outside the cells and commonly in clusters within the cells. The relative importance of these structures in determining total viscosity will be shown later.

It became apparent that tomato juice could be washed simply and quickly by sieving. Accordingly, a specified volume of juice was poured onto a 200-mesh sieve and washed gently with the distilled water for 15 minutes. Soluble materials, as well as the bulk of the small insoluble granules, passed through the sieve. Cell walls, mostly in the form of near-spheres ranging in diameter from 100 to 500 microns, were retained on the sieve. During the sieve-washing the cell walls swelled, just as they did during the centrifuge washing. Walls were removed from the sieve and made to the original juice volume with distilled water. Figure 2 shows the washed cell walls and the portion of granules entrapped within the walls.

Several juices were washed in this manner; all gave products of increased viscosity (Table 2). The increases were large, ranging from 1½- to 4-fold. Whereas the original juices were relatively thin liquids, some of the washed products resembled plastic solids more closely than liquids. Sample No. 3 (850 apparent centipoises), for instance, would not flow from a horizontal test tube (Figure 3B), and when lifted with a spatula, formed a mounded mass on the blade. There was a tendency for the products from hot-break (pectin-rich) juices to thicken somewhat more than those from cold-break (pectin-deficient) juices.

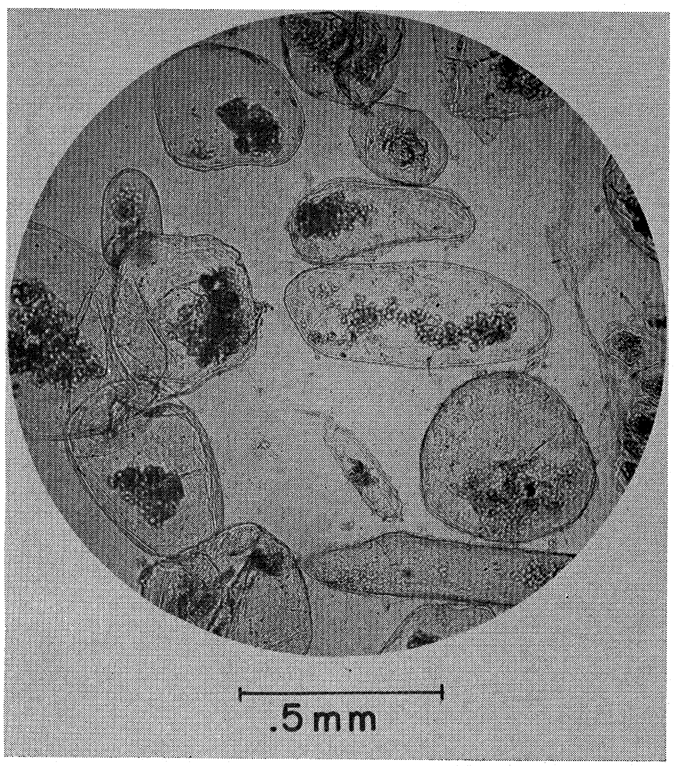

Figure 2. Sieved, washed, and diluted tomato juice cells. Walls outlining the cells and entrapped granules within the cells are seen.

TABLE 2

Increase in viscosity associated with the washing of soluble solids and small insoluble particles from tomato juice by sieving

Sample	Viscosity, apparent cp.		Total solids, %	
	Original	Washed[1]	Original	Washed[1]
1. Commercial juice, hot break	235	480	....	......
2. Commercial juice, hot break	230	520[2]	6.1	0.48
3. Commercial juice, hot break	185	850[2]	6.7	0.74
4. Commercial juice, cold break	220	430	6.3	0.50
5. Commercial juice, cold break	160	255	....	......
6. Commercial juice, cold break	145	210	6.0	0.38
7. Laboratory juice, unsalted	130	300	4.9	0.57
8. Laboratory juice, unsalted	60	215	....	0.39
9. Laboratory juice, raw, unheated	95	115	....	0.35

[1] Juices were poured onto a 200 mesh sieve, washed with distilled water for 15 minutes, and made to their original volumes with distilled water.

[2] Viscosities above 500 apparent cp. were determined with Brookfield rotor No. 3 at 60 r.p.m.

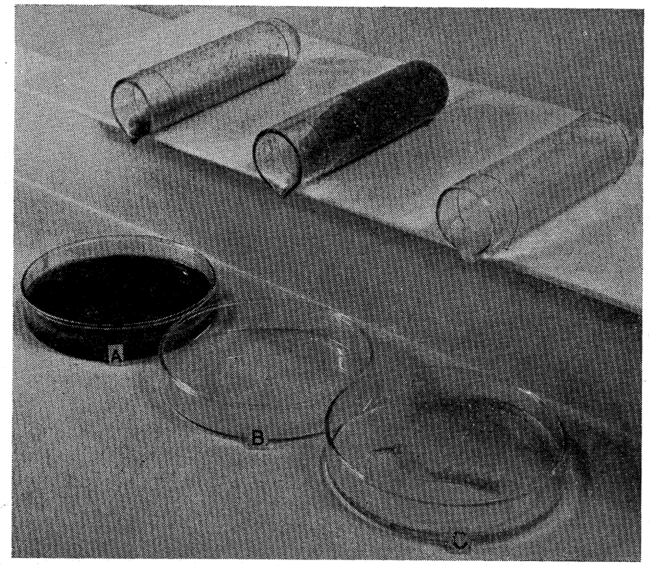

Figure 3. Demonstration of the differences in viscosity between: A, whole tomato juice; B, sieve-washed juice product; and C, homogenized pure cellulose walls from the juice. Viscosity of samples A, B, and C was 185, 850, and 700 apparent centipoises, respectively.

Tomato juice fractions. In order to picture the distribution of solids of a tomato juice as affected by the centrifuge- and sieve-washing procedures, Figure 4 is provided. As previous workers have found *(3, 11)* about 87% of the total solids were soluble (serum). This fraction, as is well known *(3, 11, 24)* was composed chiefly of sugars, organic acids, proteins, mineral salts, and pectins and other polysaccharides. The remaining 13% of the solids, the insolubles, consisted principally of small carotenoid and proteinaceous granules and cellulosic cell walls *(12)*. Sieve-washing the insolubles separated more than half of the granules from the cell walls.

The most interesting feature of the fractionation was the demonstration that viscosity of the whole juice was almost entirely dependent on one relatively small fraction. The washed

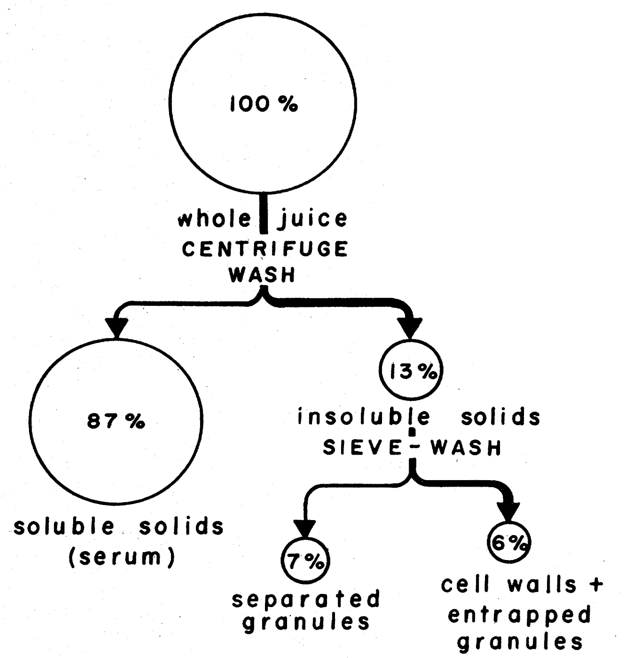

Figure 4. Diagram of fractionation of tomato juice by centrifugation and sieving. The per cent of the total solids comprised by each fraction is shown.

cell walls, comprising only 6% of the total solids, formed a suspension whose viscosity was twice that of the original whole juice (Table 3). In the absence of cell walls the other juice fractions possessed no significant viscosity. The serum, for instance, although containing 87% of the total solids and the bulk of the pectic materials, had a viscosity of only 2 cp. Viscosity of the granules suspension alone was only 5 cp. It was clear, therefore, that the cell wall fraction constituted the backbone of whole juice viscosity, and that the serum contained substances which inhibited the development of maximum viscosity in whole juice.

Properties of the washed product. Various substances were added to the washed juiced products (i.e., washed insolubles) in order to determine their properties and to investigate the causes for the high viscosity. The addition of serum caused a sharp drop in viscosity (Table 4). Subsequent removal of the serum caused viscosity to return again to its high value; thus the change in viscosity was reversible.

Addition of sucrose, a natural component of serum, to the washed products had little effect on viscosity. Viscosity also was maintained at a high level in the presence of glycerin, urea, and ethyl alcohol. However, the addition of soluble pectin, citric acid, sodium chloride, or calcium chloride caused a marked lowering in viscosity. In general, viscosity was stable in the presence of nonelectrolytes, but was decreased by electrolytes. Relatively small amounts of electrolyte produced the effect. We have found that even the quantity of electrolytes occurring naturally in fresh tomatoes is sufficient to keep viscosity at a low level.

Confirmatory evidence that the electrolytes in tomato juice depress viscosity was obtained by treatment of a juice with synthetic ion-exchange resins. Both cations and anions were removed from the serum fraction, which was recombined with the insoluble-solids fraction, then separated again and deionized. Nine repetitions of this treatment were needed to complete ion removal; the deionized juice had increased viscosity. Further work on the use of deionizing resins is planned, since their use would produce minimal changes in total juice composition.

TABLE 3

Viscosity of tomato juice fractions

Juice or juice fraction	Viscosity, apparent cp.	Solids content[1]	Electrical resistance
		%	*ohms*
Original whole juice	240	6.3	7
Soluble solids only (serum)	2	5.5	7
Insoluble solids, washed	500	0.8	1500
Separated granules, washed	5	0.45	....
Cell walls plus entrapped granules, washed	500	0.35	1650

[1] For the fractions, same concentration as in original juice.

TABLE 4

Effect of various substances on viscosity of the washed product from tomato juice

Substance added	Concentration, of substance	Viscosity, apparent cp. Washed product A[1]	Washed product B[2]	Standard error[3] B
	%			
1. None	....	345	890	12
2. Juice serum	3	180	330	6
3. Soluble pectin	0.2	210	200	7
4. Citric acid	0.2	120	205	21
5. Sucrose	3	390	980	12
6. Glycerin	3	375	920	24
7. NaCl	0.2	155	315	31
8. $CaCl_2$	0.2	150	200	15
9. Ethanol	50	500	895	42

[1] Prepared from cold break juice; solids content, 0.50%.
[2] Prepared from hot break juice; solids content, 0.74%.
[3] Standard error of measuring viscosity was relatively high in some samples, owing to clumping in the samples. Samples of product A showed the same relative errors.

Effect of homogenization. Apart from its direct effect on viscosity, the washing of tomato juice had an important indirect effect. In most cases the washed products were considerably more susceptible to mechanical break-up than were the original juices, and homogenization produced a degree of thickening not achieved with the whole juices (Table 5). This was true particularly of the products from cold-break juices.

With the hot-break juice product that thickened most during the original washing (sample 2, Table 5), the standard homogenizing treatment (2 min. treatment in an electric blender) gave no further increase in thickness. Microscopic examination showed that most of the cell walls remained whole and unbroken during the treatment. Only slight thickening was produced by prolonged homogenization. Apparently in this case, the relatively large quantities of pectic substances in the walls acted as plasticizers and rendered the walls less brittle and more resistant to mechanical stresses. Following enzymatic removal of the pectins *(23)*, homogenization was effective in disrupting the cells and in increasing viscosity.

Cellulose wall suspensions. The question arose as to what substance was primarily responsible for the high viscosities described in previous sections of this paper. Although tomato cell walls were identified as the indispensable structures, they were not isolated in pure form or as a single chemical substance. It is widely known that most fleshy plant cell walls contain a number of substances, including cellulose, hemicellulose, protein, and pectin compounds (*4*, *5*, *6*, and others).

The effect on viscosity of removing all substances except cellulose from the cell walls of tomato juice is shown in Table 6. The walls were boiled in 2% sulfuric acid and in 2% sodium hydroxide, and then extracted with ethyl alcohol and ether, just as in a crude fiber determination *(2)*. They finally were made to their original juice volume with distilled water, without being dried previously. The viscosity of all juices decreased with the treatments, indicating that the non-cellulosic components of the walls made an important contribution to viscosity (Table 6). Yet the pure cellulose walls alone, in the form (Figure 5) and concentration at which they occurred in the whole juice, yielded suspensions of appreciable viscosity. The suspensions were colorless, translucent, and heat-stable.

The cellulose wall suspensions responded quickly and strikingly to homogenization. Viscosity of sample 1 (Table 6),

TABLE 5

Effect of homogenization on the viscosity of tomato juice before and after the removal of soluble materials

Sample	Original juice, Viscosity, apparent cp. Not homogenized	Original juice, Viscosity, apparent cp. Homogenized[2]	Washed juice product[1], Viscosity, apparent cp. Not homogenized	Washed juice product[1], Viscosity, apparent cp. Homogenized[2]
1. Hot-drink juice	235	300	480	830
2. Hot-break juice	220	375	890	810
3. Hot-break juice	210	295	485	885
4. Cold-break juice	200	240	310	760
5. Cold-break juice	190	240	370	940
6. Cold-break juice	160	260	255	620

[1] Juices were washed on a 200 mesh sieve with distilled water for 15 minutes.
[2] Samples were treated for 2 minutes in an electric blender.

TABLE 6

Viscosity of cellulose cell wall suspensions prepared from tomato juices

Sample	Original juice Viscosity, apparent cp.	Cellulose wall suspension, Viscosity, apparent cp. Original	Cellulose wall suspension, Viscosity, apparent cp. Homogenized	Cellulose wall suspension, Solids[1] content
				%
1	375	100	500	0.21
2	220	140	880	0.24
3	210	100	285	0.22

[1] Cellulose concentration was the same as that of the original juice.

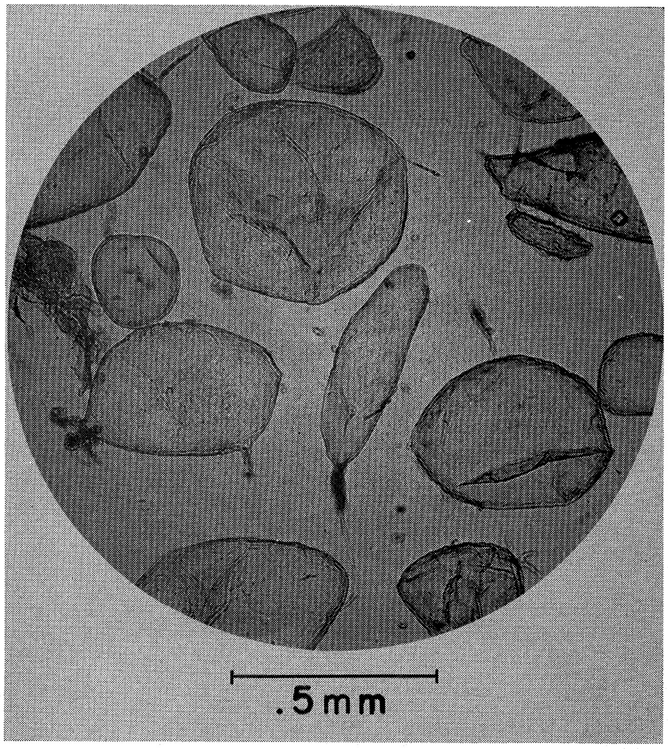

Figure 5. Tomato cell walls following the removal of all substances except cellulose. Compare with Figures 1 and 2.

for instance, increased from 100 to 500 apparent cp. during the standard homogenizing treatment. The latter value far exceeded that of the original whole juice, despite the fact that the whole juice contained about 30 times as much solids. In fact, the homogenized cellulose wall suspensions were thicker, per unit concentration, than any of the commonly used thickening agents such as starch, pectin, gelatin, methyl cellulose, or

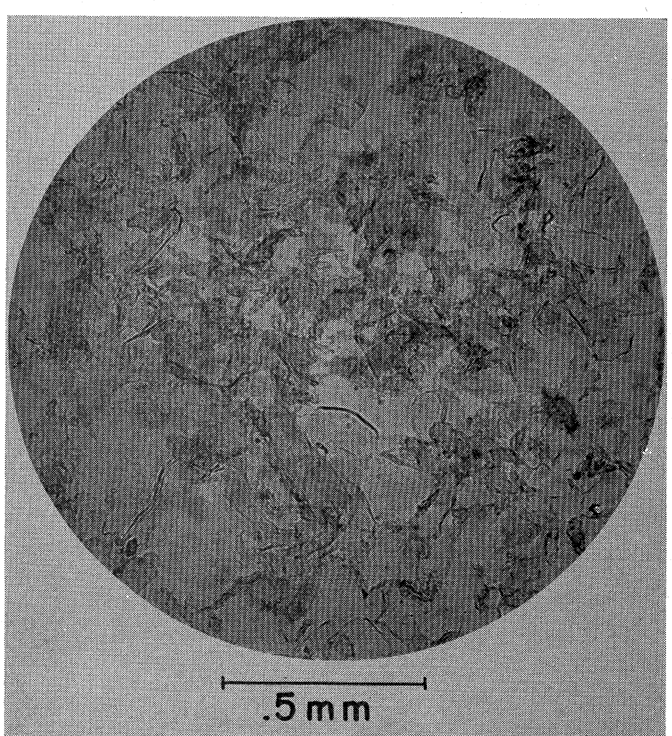

Figure 6. Tomato cellulose walls following homogenization.

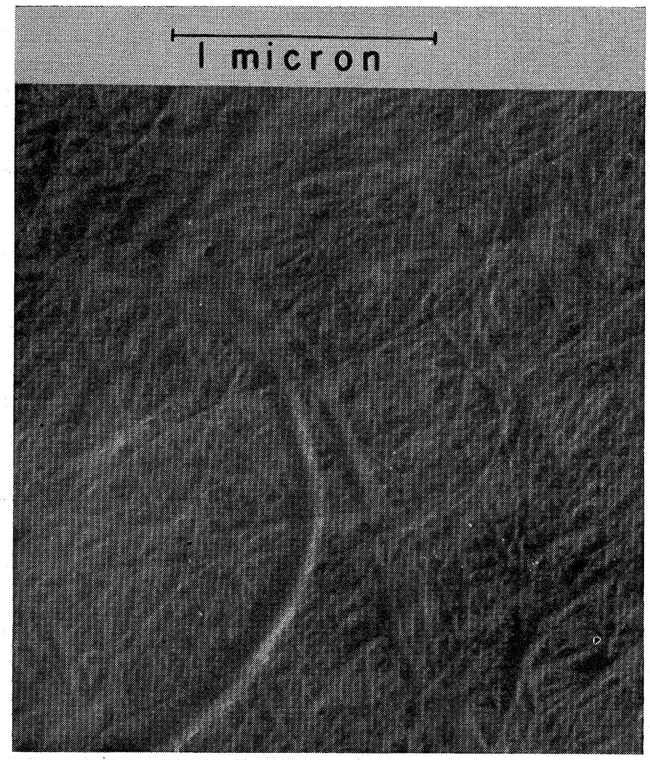

Figure 7. Electron micrograph of tomato cellulose wall, showing network of cellulose microfibrils.

sodium alginate *(21)*. Figure 3C gives a visual impression of the thickness of a sample containing only 0.24% of cellulose.

Microscopic studies showed that the homogenizing treatment destroyed the near-sphericity of the cellulose shells and shredded the walls into twisted ribbons and irregular sheets (Figure 6). This change in structure probably was basic to the increased viscosity. The fine structure of the cellulose walls is shown in the electron micrograph (Figure 7).

DISCUSSION

From an interpretative or fundamental viewpoint, the present findings are significant. They reveal tomato juice as having a potential for thickening not heretofore recognized. They cause a re-evaluation of the factors known to effect consistency and indicate that a new factor, electrolyte content, should be given a position of importance. They de-emphasize the role of soluble pectins *(11)* but reaffirm and strengthen the role of insoluble solids *(7, 11, 20, 23)*. They show consistency to be dependent primarily on the structure and composition of the tomato cell wall.

The exact manner in which electrolytes affect juice consistency is the subject of our present research. Only the cell wall fraction of the juice is involved. Apparently the surfaces of the walls bear electric charges which help maintain the walls in suspension, thereby contributing to viscosity. Insoluble pectin, intimately associated with the cellulose fibrils in the walls, doubtless contributes to the electric charges. In the absence of soluble electrolytes, the charges exhibit their maximum effect. The walls swell, bind quantities of water, and promote high viscosity, just as potato starch granules in suspension swell during gelatinization and give rise to increased paste viscosity *(17, 18a)*. Homogenization, by fragmenting the walls and increasing the surface area, may augment these effects. In the presence of electrolytes, however, the charges on the walls become neutralized, the walls shrink, and a drop in viscosity ensues.

Tomato cellulose suspensions exhibit at least two properties which are not commonly associated with cellulose suspensions. In the first place, tomato cellulose forms relatively thick suspensions at dilute concentration, and secondly, the suspensions are thickened further by a very brief homogenizing treatment. In these respects the suspensions differ quantitatively from those of wood or cotton natural cellulose *(18b)*. One reason for these differences in behavior is revealed by microscopical, x-ray, and infrared studies of the structure of the walls. The cellulose of tomato walls, although fibrillar in appearance, is essentially amorphous; that of wood and cotton is largely crystalline. Further research on the structure and composition of tomato cellulose walls is being pursued.

Since the cell walls of apples, apricots, and peaches are generally similar in structure and composition to those of tomatoes, it might be expected that nectars of these fruits would show the same general response to the removal of electrolytes as does tomato juice. Our preliminary experiments indicate that this indeed is the case, and that the phenomenon, therefore, is widespread.

SUMMARY

Experiments have shown that the viscosity of tomato juice is kept at a relatively low level by the presence of naturally-occurring and added electrolytes. Removal of electrolytes, including soluble pectins, organic acids, and mineral salts, may cause the remaining fraction of juice to thicken to a semigel. Electrolyte content thus is established as a newly-discovered factor in determining tomato juice viscosity.

Only a small fraction of the juice solids is directly involved in the thickening process. Tomato cell walls, comprising less than 6% of the total solids and less than half of the insoluble solids, have been shown to be the juice component essential for high viscosity. As electrolytes are removed, the walls swell, become increasingly hydrophilic, and give rise to increased viscosity. Viscosity remains high in the presence of non-electrolytes such as sucrose, glycerin, and ethyl alcohol, but decreases as the electrolytes are returned to the juice.

In most cases the removal of electrolytes from juice accentuates the thickening effect of homogenization.

Of the substances comprising the tomato cell wall, cellulose has been found to be the single substance most closely related to viscosity. Tomato cellulose alone has formed suspensions that are thicker, at equivalent concentration, than most of the common thickening agents.

The significance of the new information is discussed.

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