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WATERMELON EPICUTICLE CHANGES RELATED TO FRICTION TEST PARAMETERS

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Abstract. A surface friction method was used to apply a mechanical load to the watermelon fruit's epicuticle. By varying the degree of abrasion intensity, four increasingly larger degrees of epicuticle were identified. These altered stages were related to unique features on the friction force vs. displacement curve, marks on the watermelon, and marks on the abrasive surface. Failure threshold distance and epicuticle layer removal distance were good indicators of resistance to abrasion and were affected by roughness of the abrasive surface, sliding speed, normal force and measurement location on the sample. The magnitude of changes in the fruit's epicuticle structure varied with harvest date and between the two watermelon cultivars.

Keywords: abrasion, friction, watermelon, wax, resistance

INTRODUCTION

The outer layers, epicuticle, of plants constitute a natural protective barrier between them and their environment. For many fruits and vegetables like watermelon the outer-most portion of the epicuticle consists of a wax layer which reduces water loss and gaseous exchange [4]. It also is responsible for reducing the visible and infra-red radiation penetrating the sample surface due to its ability to reflect light. The composition of wax shows great qualitative variations within the same plant as well as between different organs [5]. The structure and arrangement of the wax platelets change during growth and fruit development. Corey *et al.* [3], using a scanning electron microscope, observed that structural changes in watermelon wax from the unripe to overripe stages were accompanied by a 71 % increase in the quantity of epicuticular waxes. The quantitative and qualitative changes of the watermelon surface during abrasion were presented in the paper [12]. After harvest, additional wax is commercially added to a lot of fruit to increase their moisture retention characteristics and improve visual appearance for better market sales [2]. A method has been proposed to assess watermelon surface abrasion using a friction apparatus and Instron testing machine [9]. Watermelon abrasion resistance was correlated with parameters derived from the test abrasive surface and the force vs displacement curve [11]. The objective of this study was to quantify the observed changes in the watermelon fruit's epicuticle and correlate them with the parameters derived from the force vs. displacement curve of a friction test.

MATERIALS AND METHODS

Fruits from two cultivars of watermelon, Black Diamond and Allsweet, were obtained from the Oklahoma Vegetable Research Station at Bixby, Oklahoma. Watermelons from each cultivar were harvested on six different dates at commercial maturity. The watermelons were similar in mass Black Diamond were more round and not as long as Allsweet. Black Diamond were tested on July 27, 29, August 4, 9, 17 and 23. Allsweet were tested on July 28, 29, August 8, 12, 24, and Sept. 7. Immediately after harvest, the watermelons were transported 110 km to the laboratory in Stillwater for testing. Following arrival, the watermelons were covered with plastic and stored at room temperature (about 24 ^{o}C and 50-60 % RH) for at least 15 h to allow sufficient time to equilibrate. For each watermelon; mass, length, and width (largest diameter) were measured to get a uniform material.

Mechanical properties of the watermelon's surface were determined using the abrasion method developed by Puchalski and Brusewitz [9]. Measurements were made at 50, 100, and 150 N normal force and 0.83, 3.33 and 8.33 mm s^{-1} sliding speed over a travelling distance of 0.8 m of a rough masonite abrasive surface (with 1057 kg m^{-1} density and 91 hardness by Durometer PTC). Each abrasion test was repeated three times at two different locations on each watermelon. During movement of the abrasive surface over the watermelon, observations were made of the sample in the area of contact and related to changes in the recorded force - displacement curve. More detailed observations with a microscope of the distorted and removed cuticle material were made after conclusion of the friction test. The following measurements were made: 1) friction force versus time (displacement) was recorded by the Instron universal testing machine and 2) a tracing of an outline of the abrasion area on the watermelon was made on paper and digitised for computer computation of dimensions. From these data, various parameters were derived and subjected to analysis of variance; those which were significant were further analysed using Duncan's multiple range test. After abrasion test and qualitative assessment of abrasion, the watermelons were cut open and visually checked for ripeness on the basis of flesh colour and flavour to ensure that they were as mature as judged nondestructively at the time of harvest.

RESULTS

Stages of altering epicuticle

The force - displacement curves (Fig. 1) for over 120 tests were compared to observations and measurements taken on the abrasive surface (Fig. 2). Due to varying degrees of abrasion four unique stages of altering and/or removing the outer layer of the watermelon were identified as:

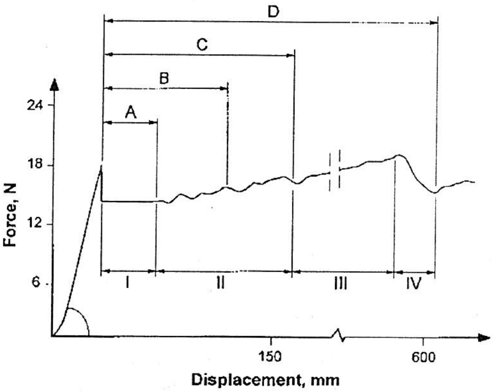

Fig. 1. Stages altering and removing outer layers of the watermelon fruit as indicated on the force vs. displacement chart are: I - relocating loose wax platelets, II - removing the layer of loose wax platelets, III - removing deeper layer of wax platelets, IV - removing entire epicuticle layer. Resistance parameters are: A - wax platelet relocation distance, B - wax platelet removal distance, C - failure threshold di-

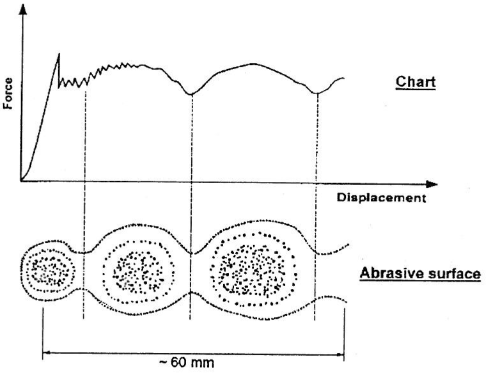

Fig. 2. Comparison force - displacement curve with marks on the abrasive surface.

I) relocating loose wax platelets,
II) removing the entire layer of loose wax platelets,
III) removing deeper layers of wax platelets,
IV) removing the entire epicuticle layer.

The first stage, relocating loose scattered wax platelets, began just after the abrasive surface started to move against the sample. After pulling the abrasive surface across the watermelon, large pieces of loose material were found on the abrasive surface that had come from the watermelon (Fig. 2). This material could have come from relocating the loose wax platelets that were scattered over the watermelon's surface. This stage usually occurred without the typical round wax peaks shown on the force - displacement chart presented in the previous study [9].

The next stage, II, was characterised by a larger friction force with fewer, usually large rounded force - displacement peaks on the chart (Fig. 1) that were associated with continuously pushing a layer of loose wax platelets into a growing mass until it yielded and the process of forming another mass started again. This stage is the removal of the outer layer of epicuticle with less dense array of wax platelets (more porous and with more asperities). Removed wax on the abrasive surface was concentrated with large visible pieces, arranged in the form of circles (Fig. 2).

The next stage, III, lacked large rounded force - displacement peaks on the chart (Fig. 1). As abrasion penetrated into the layer of continuous wax platelets, a smoother watermelon abrasion surface was produced. Appearance of this smooth surface was associated with a reduced friction force. This point marking the beginning of the decrease in friction force was called the failure threshold [9] - and constituted an important abrasion parameter. Removed wax from watermelon and left on the abrasive surface was more scattered and less visible.

Removing the entire epicuticle layer, stage IV, was associated with a decrease in the friction force (Fig. 1). As the epicuticle layers were gradually removed, the surface changed, and the friction force became smaller as also noted by Sherwood [14]. After the wax layer was removed, the sample surface was pitted.

Proposed structural mechanical parameters during changes in epicuticle

Parameters developed from the force - displacement curve were associated with marks on the abrasive surface. The following parameters were defined:

1) displacement index (indicating roughness) as measured by the length, mm, of rounded peak on the force-displacement chart of the removed wax spot from sample;

2) force index (indicating porosity) as measured by the force, N, of rounded peaks on the force-displacement chart, required to remove the wax spot from the sample;

3) total energy index (indicating total porosity), mJ, as measured by the area of all rounded peaks on the force-displacement chart of the removed wax spot from sample until failure-threshold;

4) average energy index, mJ, as the ratio of total energy to the number of rounded peaks on the force-displacement chart.

The average values for these four parameters for six harvest dates and two cultivars, at 100 N normal force and 8.33 mm s^{-1} sliding speed are given in Table 1. The displacement index declined by 39% over the six harvest dates, indicating that the watermelon' s surface became more smooth.

The epicuticle evidently changed, as one would expect, with harvest date, for both cultivars. The force index decreased by 50 %, on the average (Table 1). Total energy index decreased to 1/3 for Black Diamond and decreased to 1/7 for Allsweet from the first harvest date to the fifth harvest date (Table 1). This tendency for smoothing of the epicuticle was further supported by the observation that the average energy index decreased by 36 % for Black Diamond and 74% for Allsweet. There was a difference between the two cultivars in the appearance of the mark on the abrasive

Table 1. Structural mechanical paramters for Black Diamond (B) and Allsweet (A) on six harvest dates at 100 N normal force and 8.33 mm s^{-1} sliding speed

Harvest date number	Displacement index (mm)		Force index (N)		Total energy index (mJ)		Average energy index (mJ)	
	B	A	B	A	B	A	B	A
1	16a	17b	0.65a	0.65a	18.6a	15.2a	4.7a	5.1a
2	17a	24a	0.49b	0.49b	15.2b	13.5a	3.8b	4.5a
3	12b	17b	0.42bc	0.39c	11.0c	14.3b	3.7b	4.8a
4	12b	8c	0.39c	0.39c	5.1d	2.0c	1.7d	1.0b
5	11b	8c	0.39c	0.25d	6.1d	2.0c	2.0d	1.0b
6	10b	10c	0.39c	0.25d	9.1cd	4.0c	3.0c	1.3b

Means in columns followed by the same letter are not significantly different at p=0.05 from Duncan's multiple range test.

surface. Allsweet had a less porose epicuticle as indicated by a lower force index and lower total energy than Black Diamond. This agrees with the reported smaller coefficient of friction for Allsweet than for Black Diamond [10].

Factors influencing epicuticle abrasion resistance

Four parameters were identified on the force - displacement chart (Fig. 1) which were associated with the watermelon epicuticle's resistance to abrasion: A - wax platelet relocation distance (mm), B - wax platelet removal distance(distance to the largest rounded force-displacement peak on the chart in mm), C - failure threshold distance (mm), D - epicuticle layer removal distance (mm).

Abrasive surface

The re-use of the same abrasive surface affected two of the four epicuticle resistance parameters for Allsweet as shown in Table 2. The re-use of the same surface was expressed as the same roughness as an unused, new surface as determined by an equation presented in the earlier work [9]. There was no significant effect of the surface re-use on the loose wax platelet relocation distance and wax platelet removal distance due to the large scatter of data. The effect on failure threshold distance and epicuticle layer removal distance of the surface re-use was significant. As the abrasive surface became more smooth, there was an increase in the failure threshold distance and epicuticle layer removal distance. Black Diamond showed similar trends but they were less dramatic.

Sliding speed

Sliding speed, at a specific normal force and harvest date, had a significant effect on the failure threshold distance and the area of wax removed from Black Diamond (Table 3). These parameters were larger at the higher sliding speed. This implies that the epicuticle provides more resistance to abrasion at higher sliding

Table 2. Influence of re-use of abrasive surface on force - displacement curve derived parameters for Allsweet tested on September 7 with 150 N normal force and 8.33 mm s^{-1} sliding speed

Parameter (mm)	Number of times abrasive surface re-used					
	4	7	9	10	14	17
Wax platelet relocation distance	50a[z]	50a	137a	70a	140a	180a
Wax platelet removal distance	142a	62a	150a	520a	550a	350a
Failure threshold distance	285a	350b	757c	1122d	1987e	2017e
Epicuticle layer removal distance	542a	555a	1412b	1472b	2862c	2877c

[z] Means in rows followed by the same letter are not significantly different at the p = 0.05 level according to Duncan's multiple range test.

speeds. This confirms the lower amount of epicuticle removed from the sample with an increasing sliding speed (Table 3). The increases in the failure threshold distance for Black Diamond were 36, 62, and 72 %, at normal forces of 50, 100 and 150 N, respectively. The effect of normal force was twice as high for 150 N as for 50 N normal force. The significant influence of the sliding speed on failure threshold failure distance and epicuticle layer removal distance for Allsweet is shown in Table 4. Generally, these parameters increase with higher sliding speed.

Normal force

Normal force had a significant effect on the watermelon's epicuticle resistance parameters at all the sliding speeds (Table 5). Generally, larger normal force produced lower values of

Table 3. Influence of the sliding speed on the force vs. displacement curve derived parameters for Black Diamond

Parameter	Tested 8/9 at 50 N normal force			Tested 8/17 at 100 N normal force			Tested 8/23 at 150 N normal force		
	Sliding speed (mm s^{-1})								
	0.83	3.33	8.33	0.83	3.33	8.33	0.83	3.33	8.33
Platelet relocation distance (mm)	84a[z]	106a	110a	54a	50a	75a	41a	70a	-
Platelet removal distance (mm)	162a	187a	250a	112a	92a	117a	93a	114a	-
Failure threshold distance (mm)	210a	260ab	287b	154a	184a	250b	190a	274b	327c
Epicuticle layer removal distance (mm)	526a	642b	742c	357a	340a	445b	346a	436b	625c
Epicuticle removed area (mm^2)	245a	186b	161c	514a	410b	258c	897a	666b	533c

[z] Means in rows at each normal force followed by the same letter are not significantly different at the p = 0.05 level according to Duncan's multiple range test.

Table 4. Influence of sliding speed on force vs. displacement curve derived parameters for Allsweet

Parameter (mm)	Tested 8/9 at 50 N normal force		Tested 8/17 at 100 N normal force			Tested 8/23 at 150 N normal force	
	Sliding speed (mm s^{-1})						
	0.83	8.33	0.83	3.33	8.33	3.83	8.33
Platelet relocation distance	11a[z]	17a	8a	17a	17a	44a	50a
Platelet removal distance	19a	25a	20a	28a	37a	90a	57a
Failure threshold distance	127a	250b	165a	234b	277c	174a	220b
Epicuticle layer removal distance	207a	562b	284a	504b	795c	374a	555b

[z] Means in rows followed by the same letter are not significantly different at the p = 0.05 level according to Duncan's multiple range test.

Table 5. Influence of normal force on force vs. displacement curve derived parameters for Black Diamond tested on August 17

Parameter (mm)	Sliding speed (mm s^{-1})						
	0.83		8.33			3.33	
	Normal force						
	50	100	50	100	150	50	100
Platelet relocation distance	84a[z]	54a	110a	12a	12a	-	-
Platelet removal distance	162a	112a	250a	85a	57a	-	-
Failure threshold distance	210a	154b	287a	170b	130b	260a	160b
Epicuticle layer removal distance	526a	357b	742a	370b	377b	642a	466b

[z] Means in rows followed by the same letter are not significantly different at the p = 0.05 level according to Duncan's multiple range test.

the failure threshold distance. At 50 and 100 N normal force, the highest decrease in the parameters was 41% at the highest sliding speed and the lowest decrease was 27 % at the lowest speed.

Measurement location

The test location on the watermelon affected the wax layer failure distance and the area of the epicuticle removed (Table 6). The top of the watermelon (opposite the ground spot) had the largest failure threshold distance; it appeared to be more resistant to abrasion than the side of the watermelon. The area of epicuticle removed from the top was significantly smaller than the area removed from the side of the watermelon, confirming the hypothesis that the top is more resistant to abrasion.

Relationship between wax removal area and failure threshold distance

Failure threshold distance, a parameter indicating wax resistance to abrasion, was inversely related to the removed wax area for all three normal forces as shown in Table 7 by a negative coefficient on the X term. The slope values were greater, more negative, for larger normal forces.

Table 6. Influence of measurement location on the fruit's epicuticle removal parameters for Black Diamond (with 0.83 mm s^{-1} sliding speed and 50 N normal force)

Location on water-melon	Epicuticle area (mm^2)		Failure distance (mm)		Epicuticle layer removal distance (mm)	
	Average	St. dev.	Average	St. dev.	Average	St. dev.
Side	334	9.8	165	1.2	523	1.7
Top	218	3.9	174	1.2	528	5.5

Table 7. Regression equation for epicuticle removed area (Y in mm^2) as a function of failure threshold distance (X in mm) at three normal forces for Black Diamond

Normal force (N)	Equation	r^2
50	$Y = 475 - 1.1 X$	0.996
100	$Y = 905 - 2.6 X$	0.989
150	$Y = 1401 - 2.7 X$	0.999

DISCUSSION

This study considered the watermelon fruit's epicuticle from a mechanical viewpoint. The epicuticle plays an important role as a protective barrier between plants and their environment [6]. One of the protection is against injuries due to physical abrasion. The abrasion of watermelon epicuticle in this study was considered in four stages from relocating loose wax platelets to removing entire epicuticle layer. Each of these stages, uniquely marked on the force-displacement chart, corresponded to a different force behaviour and various degrees of shearing and deforming [1,14]. Stages of wax relocation on the watermelon epicuticle were then correlated to marks on the watermelon. Then, the following abrasion resistance parameters were identified: wax platelet relocation distance, wax platelet removal distance, failure threshold distance, and epicuticle layer removal distance. Failure threshold distance and epicuticle layer removal distance appeared to be good indicators of resistance to abrasion. Failure threshold distance, as the beginning of the abrasion process is similar to the bioyield point [8], as an indication of initial cell rupture. After passing that point, there was some evidence of discolouration in the wax, indicating possible breakdown of cells. This suggests that wax platelets may act as a protection against mechanical damage caused by external forces. Failure threshold distance indicates initiation of the epicuticle layer removal followed by the removal of the entire epicuticle and correlates very closely to the beginning of skin removal.

The changes in displacement index, force index , total energy index, and average energy index with harvest date are probably related to Corey's *et al.* [3] observation that the amount of wax changes with ripening of the fruit getting more smooth. According to Gulz [5], Richmond and Martin [13] composition of wax varies during growth, development of the fruit and between plants. The results from this study revealed also differences in the structure of epicuticle between two cultivars. Generally, Black Diamond had a less dense surface wax than did Allsweet, as indicated by higher force index, total energy index and larger left wax spots observed on the abrasion surface. It could be explained according to Bowden and Tabor's [1] concept of asperity, irregularities in the abrasive surface "plow out" the loose wax platelets. If the wax is softer or platelets looser than the abrasive surface irregularities could plow deeper into the watermelon with a larger friction force. The ir- regularities of an abrasive surface act as a plow to shear, deform, and move wax platelets. The magnitude of this effect depends not only on the dimensions of the irregularities but also on the load producing the pressure (normal force) which in turn reduces the failure threshold dis- tance (resistance). A smoother abrasive surface produced a greater failure threshold distance, indicating that the watermelon's surface wax became more resistant to abrasion.

The results showed that the abrasion resistance of the fruit's epicuticle is affected by sliding speed, normal force, roughness of abrasive surface, and location on the sample. This study of the watermelon's epicuticle provides a further interpretation of the causes and factors influencing abrasion of watermelon. Increasing the resistance to abrasion reduces risk during handling and insures the delivery of high quality watermelon to consumers.

CONCLUSIONS

1. Abrasion of watermelon's epicuticle can be considered in increasing intensity as one of the following; relocating loose wax platelets, removing the layer of loose wax platelets, removing deeper layers of wax platelets and removing entire epicuticle layer.

2. Failure threshold distance and epicuticle layer removal distance were good indicators of the resistance to abrasion.

3. Epicuticle abrasion resistance was affected by; roughness of abrasive surface, sliding speed, normal force, and location on the sample. Smoother abrasive surfaces, smaller normal forces, higher sliding speeds, and locations on the top of a watermelon produced greater failure threshold distance, indicating that the watermelon's surface became more resistant to abrasion.

4. Marks on the abrasive surface, when correlated with the force - displacement chart led to identification of the following parameters; displacement index, force index, total energy index, and average energy index.

5. The measured and derived parameters indicated that the fruit's epicuticle became smoother with later harvest dates and Allsweet was smoother than Black Diamond.

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