Enzyme Treatment of Popcorn Ears to Facilitate Shelling

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ABSTRACT

An apparatus that measures shelling torque and energy during shelling of popcorn ears was used to determine the degree of kernel-to-cob attachment. The shelling energy was strongly affected by the cob moisture content, increasing exponentially as moisture content increased. To reduce the force and energy required for shelling, a commercial pectolytic enzyme was used to depolymerize the pectin substance in the abscission zone of the kernel-to-cob attachment. The enzyme absorption and equilibrium moisture content of enzyme-treated samples increased with increasing enzyme concentration. The factors and associated levels studied were: 1) enzyme concentration (0, 5, 15, 50%); 2) dipping time (1 min, 3 min); 3) holding time (1 hr, 24 hr); and 4) holding temperature (5°C, 20°C). The optimal conditions for enzyme treatment of popcorn ears in this study were 50% enzyme concentration with 1 min of dipping, held at 20°C for 1 hr after treatment. When samples were treated with 50% enzyme solution, a large variation in shelling energy and expansion volume was observed. The pectolytic enzyme reduced the maximum shelling torque and shelling energy per kernel, but no conclusions could be made about the effect of long-term storage on expansion volume and unpopped kernels.

Mechanical damage to popcorn significantly reduces its expansion volume and increases the number of unpopped kernels (UPK). Mechanical harvesting can reduce the expansion volume by as much as 28% (Walton 1968). Two kinds of mechanical damage occur during shelling: internal stress cracks and pericarp damage. The degree of mechanical damage during shelling is significantly dependent upon the kernel detachment force, kernel moisture content, kernel deformation, cob moisture content, cob strength, ear orientation, and impact velocity (Waeti 1967, Walton 1968, McGhee 1971). The actual mechanism involved in shelling is a combination of compression and rotation (twisting) of the ears, which involves friction and produces forces in tangential, longitudinal, and radial directions on the kernel itself. This mechanism should be considered in the design of a shelling-force measurement device.

The force required to shell the kernels off the cob is related to the nature of the attachment of the kernel to the cob. The strength of the kernel-to-cob attachment is a function of corn variety and maturity (Baker 1977, Robertson and Farkas 1982). Bittner et al (1987) found that the pericarp is less vulnerable to damage at lower moisture contents because of the reduced force required to remove kernels from the cob. Low-moisture corn is more susceptible to internal cracks, but the pericarp is softer at higher moisture contents and becomes more susceptible to damage.

Baker (1977) developed a test procedure to determine the ease of popcorn shelling by measuring the force required to shell individual and groups of kernels from the ear. The shelling force is significantly dependent upon the popcorn variety, the type of load, the number of kernels shelled, and the location of kernels on the ear. Also, the torque required to shell a band of kernels around an ear could be used as a predictor of the ease of shelling, which is significantly dependent upon the variety and cob diameter.

The corn kernels are physically subtended by the cupulate rachis segments, indicating that the compactness and arrangement of kernels on the cob may affect the shelling force and energy. A specific characteristic of the mature maize kernel is the presence of a closing layer, the so-called hilar or black layer between the basal endosperm and the vascular region of the pedicel or tip cap, that serves as the attachment point of the kernel to the cob (Johann 1935, Kiesselbach and Walker 1952). At the time of ripening, the kernel often breaks off from the ear, exposing this hilar layer. This layer forms a plane of cleavage that extends entirely across the hilar orifice (Kiesselbach and Walker 1952). Once the closing layer develops in the maturing kernel, it prevents the passage of chemical compounds and serves as a good indicator of physiological maturity in maize.

Kiesselbach and Walker (1952) found suberization of the cellulose walls in the upper part of the closing layer; the lower portion held pectic substances. Hydrolyzing enzymes (i.e., pectinase and cellulase) readily increase in the abscission zone just before abscission (Morre 1968). Application of these enzymes to the region of kernel-to-cob attachment could contribute to the ease of the detachment. If the force and energy required to shell the kernels off the cob could be reduced, mechanical damage could be minimized during shelling.

The objectives of this study were to develop a testing device to measure the force and energy required for shelling, to evaluate the influence of pectinase enzymes on the attachment of the popcorn kernel to the cob, and to evaluate the quality of corn resulting from pectinase treatment.

MATERIALS AND METHODS

Popcorn ears (Orville Redenbacher's Popcorn Co., Brookston, IN) were harvested and stored at 4°C in plastic bags for six months before the tests. The initial kernel and cob moisture contents were 17.5 ± 1.9% and 18.5 ± 1.9%, respectively. The moisture content of kernel and cob samples was determined by drying a 15-g sample at 103 ± 1°C for 72 hr (AACC 1983).

Measurement of Shelling Force (Torque) and Shelling Energy

Figure 1 shows the apparatus developed for measuring shelling force (torque). The twisting motion is provided by a 0.25-hp motor rotating at 2.5 rpm. The shelling ring is tapered inside at a 3° angle; it has a 38 mm inside diameter and seven rubber teeth (4 mm high). A compression spring applies a constant downward force to the popcorn ear, forcing it into the shelling ring. Strain gauges with a four-wire full-bridge connection measure the shelling torque. These strain gauges were connected to an inverting amplifier (gain = 75) and a data acquisition system (DAS-8, MetraByte Corp., Taunton, MA) in an IBM PC/XT computer. The data acquisition and control software (Labtech Notebook, Laboratory Technologies Corp., Cambridge, MA) was used for data collection and processing. The apparatus was calibrated using a torque wrench in the range of 0–61.0 N·m with ±2% accuracy.

Popcorn ears were hand shelled to remove approximately 1 in. of corn from the butt end of the ear. This section of the cob was clamped tightly with the cob-holding device and forced into the shelling ring until the compression spring had a 1-in. deflection. When the motor was turned on, the shelling ring began to rotate, shelling the kernels off the ear. During shelling, the data acquisition system recorded the data from the load cell at a 25-Hz sampling rate for 15 sec. When shelling was completed, the compression spring was released, and the number of kernels that had dropped off the ear were counted.

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Effect of Moisture Content on Shelling

To investigate the effect of moisture content on shelling, 80 popcorn ears were randomly separated into eight groups (10 replicates each). One group was rehydrated to a moisture content of 19.8% (wb) by spraying water directly on the popcorn ears with a spray bottle and storing in a sealed plastic bag at 5°C for one week. One group was air-dried at 50°C for 36 hr. The other six groups were equilibrated at various relative humidities at 25°C for four weeks using saturated salt solutions (Table I). The maximum shelling torque and shelling energy of popcorn ears with various moisture contents were determined by the torque-measurement device.

Enzyme Treatment of Popcorn Ears

To determine the optimal conditions for the enzyme treatment of popcorn ears, a four-factor full-factorial design was used. The factors and associated levels were: 1) enzyme concentration (0, 5, 15, 50%); 2) dipping time (1 min, 3 min); 3) holding time (1 hr, 24 hr); and 4) holding temperature (5°C, 20°C). A commercial pectolytic enzyme, Pectinol RS (Gennecor, Int., Cedar Rapids, IA), was used to depolymerize pectic substances in the abscission zone of kernel-to-cob attachment. The enzyme activity of the pectolytic enzyme is 1,320 apple pomace pectin viscosity units per milliliter. It is derived from a selected strain of *Aspergillus niger* and contains the pectinases, pectin lyase, polygalacturonase, and a low level of hemicelluloase. Popcorn ears with a minimum of kernels missing from the center section of the ear were chosen randomly but were selected to be of similar size and shape. A total of 15 ears were tested for each condition; the replicates were blocked in three groups of five ears. Popcorn ears were immersed in the enzyme solutions at 20°C for a predetermined dipping time and drained over a screen for 1 min to remove excess enzyme solution. Samples were weighed before and after immersion to determine the amount of solution absorbed during treatment. Enzyme absorption of popcorn ears after dipping (EAB) was defined as:

$$\text{EAB} = \frac{(W_f - W_i)}{W_i} \times 100\% \quad (1)$$

where W_i and W_f are the sample weights before and after dipping, respectively.

Before drying, the treated samples were sealed in plastic bags and held for various times at the designated holding temperature. After the holding period, the samples were dried to approximately 13.5% (wb) moisture content using air at 39°C. Samples were then equilibrated in air at 20°C with 75% rh for approximately two weeks before shelling. A control sample (without any treatment) was dried to 13.5% (wb) moisture content using air at 39°C to evaluate the effects of enzyme treatment and rehydration.

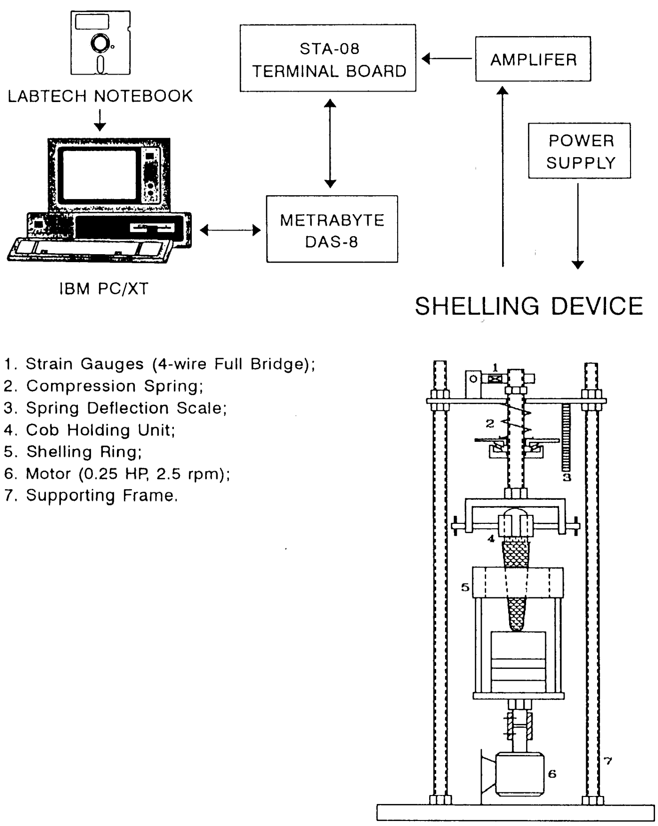

Fig. 1. Diagram of the apparatus and data acquisition system used for measuring the shelling force.

TABLE I
Equilibrium Moisture Contents of Popcorn Kernels and Cobs at Various Relative Humidities[a]

Salt	Relative Humidity (%)	Equilibrium Moisture Content, %, wb Kernel	Cob
CH_3CO_2K	22.5	8.6 ± 0.2	7.8 ± 0.1
$MgCl_2$	32.8	9.1 ± 0.0	8.3 ± 0.1
KCO_3	43.2	10.4 ± 0.1	9.5 ± 0.1
NaCl	75.3	13.8 ± 0.2	13.4 ± 0.5
KCl	84.3	14.9 ± 0.1	13.3 ± 1.8
KNO_3	93.6	17.3 ± 0.1	17.6 ± 0.4

[a]Relative humidities were controlled using the specified salt solutions maintained at 25°C.

Expansion Volume and UPK

After measuring the shelling torque, the remainder of the ear was shelled using a Black Beauty hand sheller (Seedburo Equipment, Chicago, IL). The shelled corn from all five replicate ears was mixed together. Small kernels were removed over a 4.37-mm round-hole screen, and the sample was stored in an incubator at 20°C and 75% rh. The expansion volume and number of UPKs of each sample were determined using a metric weight volume tester (C. Cretors and Co., Chicago, IL). Mazola corn oil (110 ± 5 g) was used for popping.

RESULTS AND DISCUSSION

The output signal of the shelling device increased linearly with shelling torque. A typical curve of shelling torque versus time during shelling is shown in Figure 2. Based on the results, the maximum peak torque and shelling energy per kernel can be determined. Maximum torque represents the instantaneous impact during shelling, which can be affected by the shape of

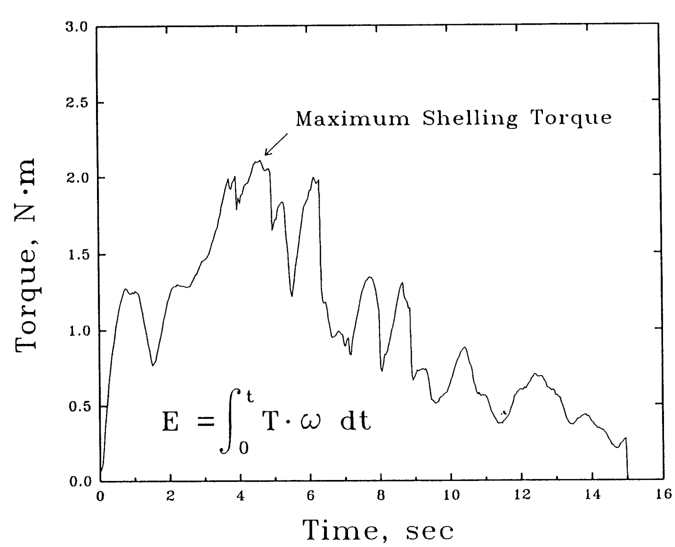

Fig. 2. Torque measured by shelling apparatus shown in Fig. 1. Shelling energy (E) is the area under the torque versus time curve.

the popcorn ears and the compactness of the kernel arrangement on the cob. The shelling energy (E) was calculated from the area under the torque-time curve (A):

$$E = \int_0^\theta T \times d\theta = \int_0^t T \times \omega \times dt = \omega \times \text{A Joule} \quad (2)$$

where T is the shelling torque (N·m); θ is the rotating angle (radian); and ω is the twisting speed ($\pi/12$ radian/sec, 2.5 rpm). The maximum shelling torque and energy per kernel have physical meaning to characterize the shelling mechanism and provide better resolution to distinguish the differences between the popcorn ears with various degrees of attachment.

Effect of Moisture Content on Shelling

The final and equilibrium moisture contents of popcorn ears are listed in Table I. The shelling energy per kernel is significantly correlated to the kernel and cob moisture contents. The cob moisture content increased linearly as kernel moisture content increased ($r = 0.9906$). Figure 3 shows the shelling energy per kernel plotted on a log scale for the control sample. The straight line indicates that shelling energy per kernel increases exponentially as average moisture content of popcorn kernels and cobs (MC) increases. The relationship between shelling energy per kernel (EPK) and MC at 6–20% (wb) can be expressed as:

$$\ln(\text{EPK}) = -4.31 + 0.19 \times \text{MC} \quad (3)$$

Since moisture content of popcorn ears significantly affects EPK, equation 3 can be used to adjust the shelling energy for enzyme-treated samples with moisture content other than reference moisture content. To isolate the influence of enzyme treatment, the EPK of all samples was adjusted by the relative EPK using the following equation:

$$\begin{aligned} \text{EPK}_{adj} &= \text{EPK}_{exp} + \Delta\text{EPK}_{MC} \\ &= \text{EPK}_{exp} + (\text{EPK}_{MC} - \text{EPK}_{ref}) \end{aligned} \quad (4)$$

where EPK_{adj} is the adjusted shelling energy, EPK_{exp} is the measured shelling energy, ΔEPK_{MC} is the relative EPK due to effect of moisture content, and EPK_{MC} and EPK_{ref} are the shelling energy calculated from equation 3 at measured moisture content and reference moisture content (21.0%, wb), respectively. Figure 4 shows the maximum shelling torque at various moisture contents. Apparently, moisture content of popcorn ears did not affect the maximum shelling torque.

Effect of Enzyme Treatment

The amount of enzyme absorbed during dipping increases as enzyme concentration and dipping time increase. Enzyme absorption was around 12.4% (11.6–13.7%) and 13.9% (13.4–14.7%) of initial sample weight for the 1-min and 3-min dipping times, respectively. Enzyme solutions of higher concentration have higher viscosities, and this may allow more solution

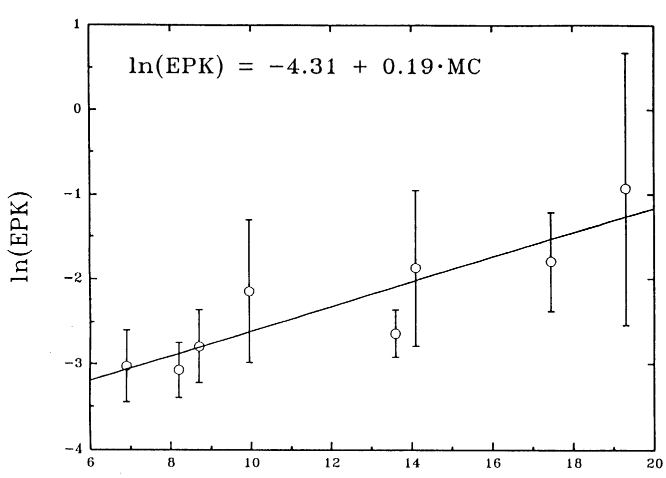

Fig. 3. Effect of moisture content on shelling energy per kernel (EPK) and linear regression line ($r = 0.8418$) for the logarithm of EPK versus cob moisture content (MC). Average of 10 replicates. Bars represent one standard deviation.

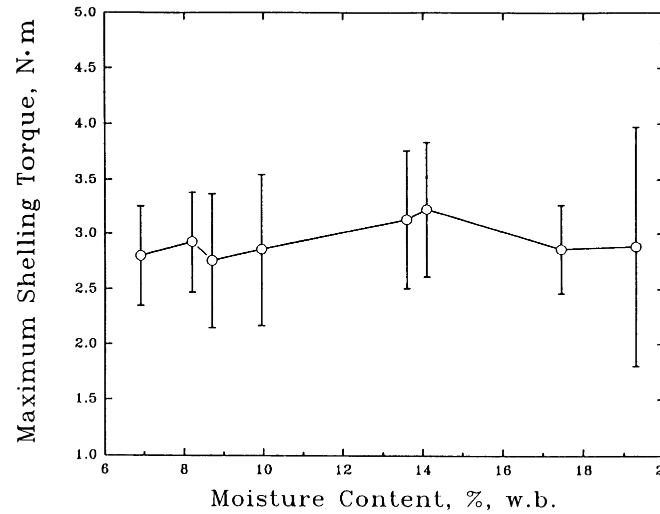

Fig. 4. Maximum shelling torque at various moisture contents (average of 10 replicates). Bars represent one standard deviation.

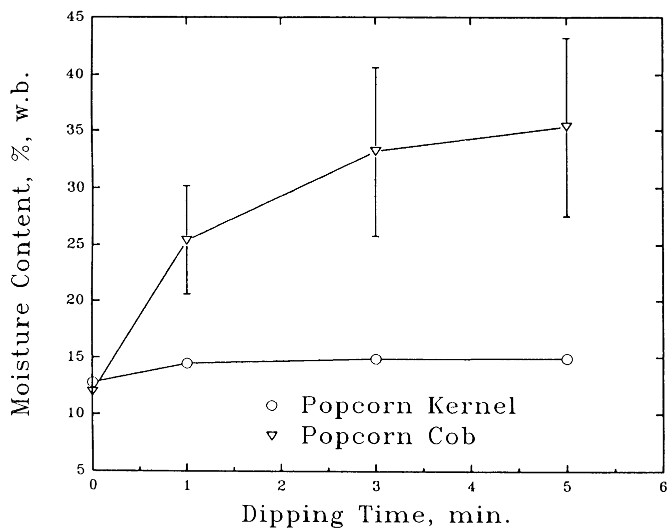

Fig. 5. Final moisture contents of popcorn kernels and cobs with various dipping times in 21°C pure water.

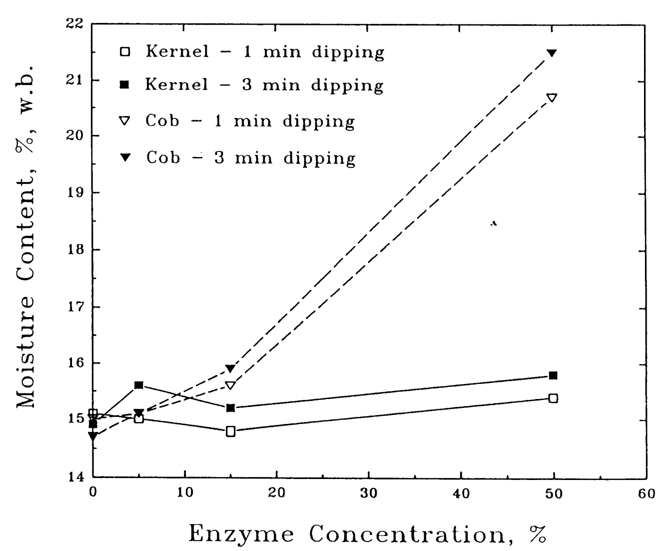

Fig. 6. The equilibrium moisture contents of popcorn kernels and cobs at 20°C and 75% rh, as a function of enzyme concentration.

TABLE II
Correlation Matrix of 11 Variables[a] for Enzyme Treatment of Popcorn Ears

Variable	1 ECO	2 DTI	3 HTE	4 HTI	5 IMC	6 EAB	7 FKM	8 FCM	9 MTO	10 EPK	11 AEPK
ECO	1.0000	0.0000	0.0000	0.0000	0.0191	0.3936*[b]	0.1646	0.8189*	0.0871	0.4098*	0.1785
DTI		1.0000	0.0000	0.0000	−0.0551	0.4488*	0.1136	0.0302	−0.2637*	0.1208	0.0972
HTE			1.0000	0.0000	−0.0814	−0.0681	0.1238	−0.0128	0.0266	−0.0810	0.0897
HTI				1.0000	0.0349	0.0821	0.0170	−0.1008	−0.2377*	0.1357	0.1751
IMC					1.0000	−0.1618	0.3898*	0.1608	−0.1172	0.0120	−0.0667
EAB						1.0000	0.0817	0.4151*	−0.1276	0.2329*	0.1142
FKM							1.0000	0.4651*	−0.1998*	0.1208	−0.1074
FCM								1.0000	0.0277	0.2740*	−0.0474
MTO									1.0000	0.0499	0.0567
EPK										1.0000	0.9403*
AEPK											1.0000

[a]ECO = enzyme concentration; DTI = dipping time; HTE = hold temperature; HTI = hold time; IMC = initial moisture content; EAB = enzyme absorption; FKM = final kernel moisture content; FCM = final cob moisture content; MTO = maximum shelling torque; EPK = energy per kernel; AEPK = adjusted energy per kernel.
[b]Significant at $\alpha = 0.05$.

TABLE III
Means and Standard Deviations of Maximum Shelling Torque and Adjusted Shelling Energy per Kernel (EPK) for Enzyme Treatment with a 1-Min Dipping Time and 1-Hr Holding Time

Enzyme Concentration (%)	Maximum Shelling Torque (N·m)	Adjusted EPK (joule per kernel)
0	3.17 ± 0.18	0.472 ± 0.085
5	2.94 ± 0.32	0.529 ± 0.169
15	3.43 ± 0.74	0.543 ± 0.321
50	2.97 ± 0.30	0.227 ± 0.163

to cling to the popcorn ears. Some preliminary tests showed that 63 and 70% of the enzyme absorption was by the cob for 1- and 3-min dipping times, respectively. Figure 5 shows the final moisture contents of popcorn kernels and cobs with various dipping times in 21°C pure water. For the 3-min dipping time, the kernel moisture content increased from 13 to 15%, but the cob moisture content increased to as much as 33%. At 20°C and 75% rh, the equilibrium moisture contents of enzyme-treated samples increased with increasing enzyme concentration. The effect was particularly apparent for the cob (Fig. 6). When cobs were treated with a 50% enzyme-concentration solution, they became fragile and broke easily during shelling. The corn cob contains 41.2% cellulose, 36.0% hemicellulose, 6.1% lignin, and 3.1% pectin (Foley 1978). The hemicellulase activity of the Pectinol RS apparently softened the corn cob.

The 11 experimental variables examined in enzyme treatment of popcorn ears included: enzyme concentration, dipping time, holding temperature, holding time, initial moisture content, enzyme absorption, final kernel moisture content, final cob moisture content, maximum shelling torque, shelling energy per kernel, and adjusted shelling energy per kernel. Table II shows the correlation matrix of these 11 variables. The significant relationships can be summarized as: 1) enzyme absorption, final cob moisture content, and energy per kernel increase with increasing enzyme concentration; 2) longer dipping time (3 min) increases the enzyme absorption, but reduces the maximum shelling torque; 3) hold temperature was not significantly correlated with any other variable; 4) a longer hold time (24 hr) reduces the maximum shelling torque; 5) maximum shelling torque decreases with increasing final kernel moisture content; 6) shelling energy per kernel increases with increasing final cob moisture content.

The maximum shelling torque and adjusted shelling energy of the control samples were 2.82 N·m and 0.5538 J per kernel, respectively. The treatment with pure water (0%) slightly reduced the maximum shelling torque compared to that of the control samples. Otherwise, the enzyme treatment did not significantly affect the maximum shelling torque. The optimal conditions were 50% enzyme concentration with a 1-min dipping time and a hold time of 1 hr at 20°C. This gave a 36% reduction in shelling energy.

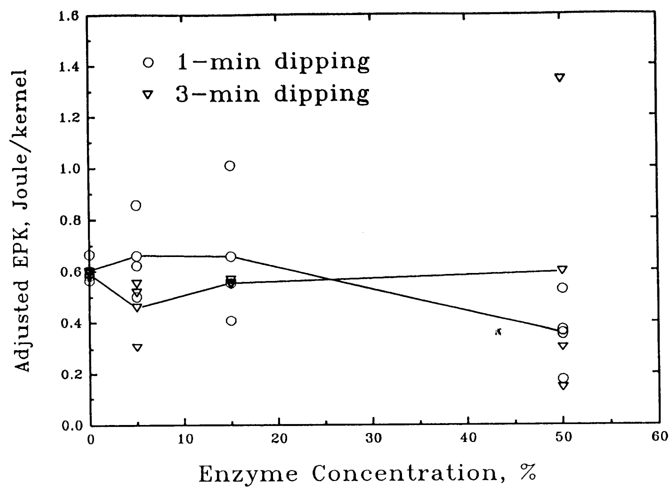

Fig. 7. Effect of dipping time on adjusted shelling energy per kernel (EPK) when samples were held at 20°C for 1 hr (each data point represents average of five replicates).

Table III shows the means and standard deviations of the maximum shelling torque and the adjusted shelling energy per kernel for enzyme treatment with a 1-min dipping time and a 1-hr holding time. The effects of dipping time, hold temperature, and hold time on adjusted shelling energy per kernel at various enzyme concentrations are plotted in Figures 7–9, respectively. The enzyme treatment with enzyme concentration lower than 15% did not significantly reduce the adjusted shelling energy.

The enzyme activity is a function of temperature and increases with increasing temperature at 30–60°C. This means a higher holding temperature should favor the detachment of kernels. However, the experimental results show that, at lower enzyme concentration, holding time and temperature did not significantly affect the shelling energy.

As storage time increased, the enzyme treatment appeared to decrease the expansion volume. The expansion volume and UPK of control samples were 40.5 ml/g and 8 kernels per 250 g, respectively, and these values changed very little during storage. For samples stored for one week, as compared to those stored for one month, there was a 2% reduction in expansion volume. For samples stored for two months, the same comparison revealed a 12% reduction in expansion volume and an increase in UPKs. The effect of storage was particularly evident in samples treated with 15 and 50% enzyme solutions.

Most of the commercial pectolytic enzymes, which are frequently used for depectinization of fruit juice and wine, contain a low level of cellulase, hemicellulase, and protease after enzyme purification. These enzymes may hydrolyze the cellulose and hemicellulose components in the pericarp and affect the popcorn expansion volume and number of UPKs. The low water activity

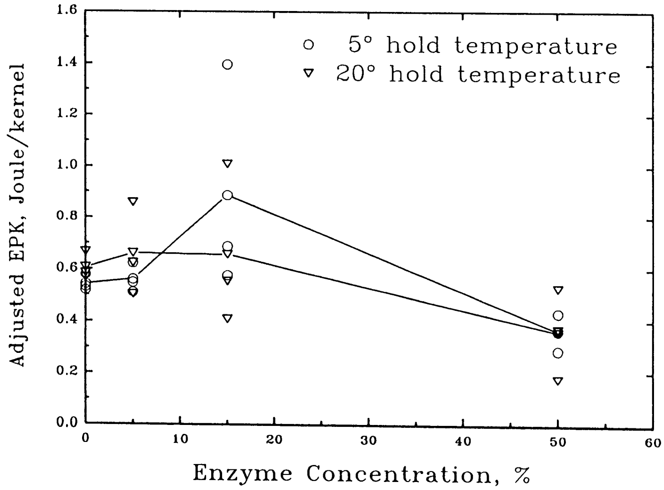

Fig. 8. Effects of hold temperature and enzyme concentration on adjusted shelling energy per kernel (EPK) when samples with 1-min dipping time were held at specific temperature for 1 hr (each data point represents average of five replicates).

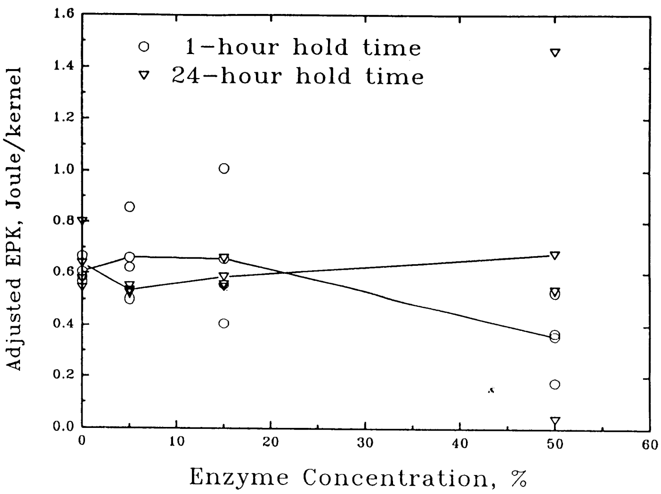

Fig. 9. Effect of hold time on adjusted shelling energy per kernel (EPK) when samples with 1-min dipping time were held at 20°C (each data point represents average of five replicates).

after drying the corn should inactivate the enzymes. Therefore, the observed loss of expansion volume and increase in UPKs with storage can not be adequately explained.

The effect of moisture content may overcome the effect of enzyme treatment on the shelling energy. For instance, a 42% reduction in shelling energy can be accomplished by reducing cob moisture content from 15 to 12% (wb). However, lower moisture content may induce stress cracks and reduce the expansion volume. The optimal kernel moisture content for maximum expansion volume is 13.5% for most of the popcorn varieties.

CONCLUSIONS

The apparatus developed for measuring the shelling torque was capable of distinguishing differences in degree of kernel-to-cob attachment. Moisture content strongly affected the shelling energy, which increased exponentially as cob moisture content increased. A large variation in shelling energy was observed, probably because the area of contact between popcorn ear and shelling ring may have changed due to the ear shape and the compactness of kernel arrangement on the popcorn ears.

The enzyme absorption and equilibrium moisture content of enzyme-treated samples increased with increasing enzyme concentration. The corncob became fragile and broke easily during shelling when samples were treated at the 50% enzyme concentration. The optimal conditions for enzyme treatment were a 50% enzyme concentration with a 1-min dipping time and a holding time of 1 hr. The pectolytic enzyme reduced the maximum shelling torque and shelling energy per kernel, but the effect of long-term storage was uncertain.

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