EVALUATION OF FIVE GREEN CHILE CULTIVARS UTILIZING FIVE DIFFERENT HARVEST MECHANISMS

P. A. Funk, S. J. Walker

ABSTRACT. High cost and unavailability of labor for hand harvest has resulted in domestic green chile production declining even as consumption grows. Mechanization is clearly necessary, but has resisted four decades of research and development. In these trials five picking mechanisms were tested in five cultivars in two fields in New Mexico in 2008. Harvest efficiency was 41% to 88%, with 11% to 48% mechanical damage, for a net collection of marketable fruit that ranged from 26% to 78% of total yield. An inclined counter-rotating double open-helix design with a low relative tip speed and a clear product path had both the highest harvest efficiency and lowest fruit damage.

Keywords. Capsicum annuum, Chilis, Harvest efficiency, Specialty crop mechanization.

Even with domestic consumption rising, domestic production of chile (Capsicum annuum var. annuum) (alt.: chili) has plummeted as U.S. growers reduce planted area or switch to other crops. The limited availability and high cost of hand labor is the main reason local chile cannot compete with imports. The three major types of chile peppers grown in the southwest, each including numerous cultivars, are New Mexican pod-type green chile, cayenne peppers, and New Mexican pod-type red chile and paprika. The green chile crop is harvested when the fruit have reached full size, but are physiologically immature. Green chile is either processed into a canned or frozen product, or marketed directly to consumers. Cayenne peppers are harvested when succulent, but physiologically mature. The majority of the cayenne crop is processed into hot sauces. Red chile peppers and paprika are preferentially harvested when physiologically mature, but also partially dried on the plant. Most of the red chile crop is dried and ground into powders. Some of the paprika crop, which includes cultivars that are highly pigmented and low in heat, are used in the production of oleoresin paprika, a natural red food dye (Bosland and Walker, 2004). Of these chile types, green chile poses the greatest challenge for mechanization because product damage is unacceptable.

More than an agricultural commodity, the chile pepper has significance that intertwines history, heritage, cuisine, and cultural identity. Pueblo, Colorado elites chose chile in an attempt to change the identity of their community from a gritty steel town to something of a destination (Haverluk, 2002). Transforming cultural landscape through chile-centered heritage tourism illustrates the symbolic strength of chile. Yet for New Mexico, chile production and its association with cultural identity is neither recent nor contrived. The chile has been cultivated in the Rio Grande basin for more than four centuries; a chile ristra hanging by an entryway remains the New Mexico icon of prosperity. Chile is the state legacy. To lose this particular crop to foreign competition would have significant cultural consequences.

To loose this crop would have significant economic consequences, as well. Considered the state’s signature crop, chile is the foundation for a healthy and complex industry that includes commodity and value-added products. The crop ranks fifth in the state for cash receipts from agricultural commodities (USDA-NASS 2007a). The chile pepper industry contributes significantly to New Mexico’s economy and employs many workers engaged in production, processing, marketing, and related areas. All types of domestic chile production are being replaced by imports, which have grown rapidly since the North America Free Trade Agreement (NAFTA) became law in January of 1994 (fig. 1) (Lucier and Dettmann, 2008). Change in New Mexico production is also documented by harvested area, which declined from 13,962 ha (34,500 acres) in 1992 (Hall and Skaggs, 2003) to 4,324 ha (10,684 acres) in 2007 (USDA-NASS, 2007b).

While extensive harvest mechanization research has been conducted and commercial harvesters have been produced and used to varying extents in an assortment of chile types, the New Mexico Chile Pepper Task Force and later the New Mexico Chile Association felt the loss of domestic production could only be addressed by fully mechanizing the industry. They petitioned for a systems approach to research that integrated plant breeding, production practices, harvest mechanization, post-harvest processing and agricultural economics. In response, Senate Bill 60 appropriated $1 million from the general fund to the Board of Regents of New Mexico State University for the College of Agriculture and Home Economics to conduct research in the genetics,
mechanization, and production of chile (New Mexico State Legislature, 2008).

Accordingly, an interdisciplinary team of research and extension scientists, processing industry representatives, regulators, vendors and growers, led by the New Mexico Chile Association, cooperated to address various aspects of mechanization. The general research objective was to accelerate chile harvest mechanization so domestic production could compete with foreign sources. This paper focuses on evaluation of different harvester head types specifically for green chile, though the larger project integrates all of the aforementioned aspects in red chile and cayenne as well.

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The first mechanical harvester was tested in New Mexico in 1965 (Marshall, 1979). In Georgia, Fullilove and Futral (1972) reported on an inclined counter-rotating double open-helix picking mechanism with a 4-cm (1.6-in.) gap between elements (cited in Wolf and Alper, 1984). Shaw and Ozaki (1976) reported on shaking and combing mechanisms intended to harvest all or selectively only marketable sizes of fruit, respectively. Gentry et al. (1978) presented a spring-tine mechanism developed to harvest green chile (New Mexico 6-4). They attained 80% harvest efficiencies in Arizona. Lenker and Nascimento (1982) described a harvest mechanism having two belts inclined 45° with rows of 7.6-cm (3-in.) rubber fingers spaced 4.4 cm (1.7 in.) on center. As it combed peppers upwards it attained a harvest efficiency of 78% to 86%.

Marshall (1979) asserted that every type of pepper grown in the United States can be mechanically harvested with the inclined counter-rotating double open-helix design. He added that 80% to 90% (harvest efficiency) was possible with as little as 1% to 10% fruit damage. Dillon (1981) reported success harvesting jalapeños. Marshall (1981) measured recovery of banana, bell, and cherry peppers as a function of ground and helix speed. Harvest efficiency increased with helix rotational speed (from 152 to 758 rpm) and decreased with harvester ground speed. Damage was independent of helix rpm but increased with ground speed.

Wolf and Alper (1984) chronicled the development of a mechanical harvest system in Israel, starting in 1968. They credit Fullilove and Futral (1972) with the inclined counter-rotating double open-helix concept that proved to be successful in harvesting paprika. They tested three inclined (30°) counter-rotating double open-helices with a 4-cm (1.6-in.) gap between elements. It was operated 90° out of phase to increase fruit removal by shaking. Operating with a linear velocity of 4 to 5 m/s (790 to 980 fpm) they obtained the same result with 20-, 10-, and 6.5-cm (7.9-, 3.9-, and 2.6-in.) diameter helixes. Harvest efficiencies between 70% and 90% were obtained at 3-km/h (1.9-mph) field speed (0.1 to 0.3 ha/h or 0.25 to 0.75 acre/h) using a 10-cm (3.9-in.) helix made of 1.2-cm (0.47-in.) pipe with a 30° wind. Several factors contributed to mechanical harvest development and acceptance in Israel (Wolf and Alper, 1984): the limited availability and high cost of labor (amounting to 100 workdays per hectare or 40 workdays per acre); the dry growing season which facilitated once-over harvest; and close cooperation with horticulturists and plant breeders, which resulted in varieties and production practices that suit mechanization such as low fruit attachment force [0-3 kg (0-6.6 lb)] and slender, well-rooted plants having few branches producing fruit well above the ground.

Palevitch and Levy (1984) also describe cultural practices and cultivars supporting mechanical chile harvest in Israel, where once-over mechanical harvesting began about 1980. Planting date contributed to mechanization-friendly plant architecture and higher yields. Ethephon (Ethrel, Bayer Crop Science, Research Triangle Park, N.C.) has long been used with hand harvest as a defoliant and to facilitate picking by reducing fruit attachment force. The use of ethephon with mechanical harvesting was found to be counter-productive due to resultant pre-harvest fruit drop from the plants (also observed by Wall et al., 2003). Palevitch and Levy suggested increasing plant population to favor mechanical harvest, recommending as many as 10 plants/m (3/ft). This reduced side shoots and increased stem length from soil surface to main branch.

Marshall (1984a) listed horticultural requirements for mechanical harvest. He generalized ideal plant types as having an upright, flexible main stem 0.6 m (2 ft) high with minimal basal branching and a well-developed root structure to anchor it firmly in the ground. Mechanical harvest is also aided by pendant fruit with minimum fruit attachment force distributed at least 10 cm (4 in.) above ground. These objectives can partly be achieved through reduced in-row spacing (increased plant population) to obtain more upright, taller plants with higher fruit. Yields increase as in-row plant spacing approaches 15 cm (5.9 in.).

Though commercial machines from four manufacturers, all using the open-helix mechanism, were available as early as 1978, sales were limited due to an abundance of hand labor and difficult market conditions at that time (Marshall, 1984b). Marshall reaffirmed his belief that a 15-cm (5.9-in.) diameter counter-rotating double open-helix with a pitch twice the diameter can effectively harvest 80% to 90% of commercially-grown pepper types. He also cautioned that field cleaning apparatuses need to be customized to pepper size and shape. He mentioned the 1980 import of an Israeli chile harvester to New Mexico.

Marshall (1984b) summarized two decades of chile harvester research claiming over 130 harvesters have been built by 59 research groups employing a dozen principles. Ten years later he identified 195 pepper pickers by 75 different groups (Marshall, 1994). The count was revised.
upwards a third time to 230 machines world-wide employing 30 concepts covered by 14 patents in an attempt to harvest 20 pepper types (Marshall and Boese, 1998). Whitney et al. (1997) reported on research using a John Deere 482 cotton stripper (East Moline, Ill) modified to harvest paprika peppers for food dye in Oklahoma. An important innovation was the device feeding plants into the harvest mechanism. They had the most success with three pairs of powered disk brushes. Five experimental harvest mechanisms (helical brush, closed helix, short rubber bats, long split rubber bats and combined bats, and brushes) were tested. They attained harvest efficiencies of between 94% and 98% with cotton stripper rolls (short and long bats) turning from 200 to 560 rpm. They harvested less trash at 200 rpm. Additionally, they learned that using a forage fan for conveyance can damage fruits.

Shooter and Buffinton (1999) described a design process involving engineering students to assist a manufacturer in modifying a forced-balance shaker (tomato harvester) mechanism to pick chile peppers. Quantitative data was not provided, but the lack of market penetration with mechanical harvesters in New Mexico was noted. It was attributed to the poor reliability and low harvest efficiency of existing harvesters. They report that three Pik Rite mechanical chile harvesters were sold in 1998. Pik Rite currently markets both this modified tomato harvester (their pepper harvester cuts plants at ground level, conveys them to a tine-lined drum where succulent fruit is removed by a forced-balance shaker) and a specialized chile harvester (vertically rakes dry fruit from plants with a pair of rubber finger-covered belts). Wall et al. (2002, 2003) examined counter-rotating double open-helices, rubber-finger rake, and forced-balance shaker harvest mechanisms all found in New Mexico. All worked fairly well; recovery rates (harvest efficiencies) were from 70% to 90% of full yield potential. Field cleaning (removing leaves, stems, and trash) was the greatest obstacle, along with destemming, to complete mechanization. Desirable plant growth habit includes tall, well-rooted plants, narrow branch angles, and a dispersed fruit set well above ground. Wall et al. (2003) advise direct seeding high plant densities, hilling soil around plants during cultivation, and selecting varieties such as ‘B-18’ and ‘B-58’ having fewer basal branches and a less concentrated fruit set. However, the harvest efficiency of an open helix four-row harvester operating at 1.6 km/h (1.0 mph) was 73% to 74% with ‘B-18’ and ‘B-58’ but it was 83% with ‘NM 6-4’ and ‘Sonora.’ The two varieties had a more concentrated fruit set, possibly because they had a low number of basal branches, certainly because less fruit dropped in response to ethephon treatments.

To maximize harvest efficiency, Salton and Wilson (2003) suggest synchronizing open helix rotation with forward ground speed and improving the mechanism that lifts low-lying branches. They also propose, rather vaguely, adding intelligence in the form of sensors and adaptive control schemes. They observe the challenges to mechanization, including the fact that ripeness ranges from dense and succulent to withered and light weight, with a range of sizes, shapes, and surface texture characteristics through the long harvest season.

Paroissien and Flynn (2004) recommend doubling plant populations to aid in machine harvesting of paprika chile, to a minimum uniform density of from 100,000 to 200,000/ha (40,000 to 80,000/acre). This production practice increases plant and fruit height and reduces branching angle and stem diameter. The resulting advantage to mechanical harvest was expected to make up for reductions in yield and color.

Abernathy and Hughes (2006) summarize observations of 13 harvesters at 12 farms from Wilcox, Arizona to Hobbs, New Mexico, from mid-October to mid-November. Harvesters operated at 1 to 4 km/h (0.6 to 2.5 mph) depending on crop condition. The difference in field capacity between two- and four-row harvesters was smaller than expected [0.59 to 0.71 ha/h (1.5 to 1.8 acre/h)] while the labor required to operate mechanical harvesters greatly favored two-row machines [1.1 v. 2.0 h/ha (2.8 v. 5.1 man-hours per acre)].

Abernathy et al. (2006) tested machine adjustments of open-helix and rubber-finger picking mechanisms on dry red chile. Higher open-helix rotational speed (500 rpm) minimized ground fall and fruit remaining on plants; helix spacing did not impact ground loss, but wide spacing [3.8 cm (1.5 in.)] caused more plant loss; forward speeds of 1.6 and 2.5 km/h (1.0 and 1.5 mph) were not significantly different. Higher rubber-finger rotation speed caused more fruit damage but damage was still acceptably low (7% to 11%); plant losses were less than half of 1%; ground losses were high primarily because fruit was thrown from the front of the picker head.

This is but a sample of over four decades of mechanization research documenting harvest efficiencies that were often 90% or better. Abernathy et al. (2006) and Marshall (1979) also document low levels of fruit damage. The jalapeño crop has been almost entirely mechanized in the United States (though approximately 95% of domestic consumption, the portion that requires de-stemmed fruit, is imported), and red chile and paprika presently enjoy a level of harvest mechanization that is approximately 80% (Bosland and Walker, 2004). Furthermore, there are several manufacturers offering mechanical harvesters, including: Boese (Saginaw, Mich.); McClendon (Tulia, Tex.); Pik Rite (Lewisburg, Pa.); and Yung-ETgar (Bet-Lehem-Hgililit, Israel). It is reasonable to wonder why the green chile and cayenne pepper crops have resisted mechanization for so long. One issue is the lack of a mechanical de-stemmer [an issue being addressed by research engineers at New Mexico State University (NMSU)]. Both pepper types destined for processing require de-stemming. A second issue confronting green chile harvest mechanization is fruit damage. For peppers that will be dehydrated or that will be processed into sauce, bruises and cracks do not substantially reduce their value. But for green chile, either fresh or for canning, even low levels of injuries greatly reduce their market value.

**Materials and Methods**

Seeking higher picking efficiency and less mechanical damage in a wider range of field conditions and plant types, five experimental harvest mechanisms were tested in 2008 in green chile at the NMSU Leyendecker Plant Science Research Center near Las Cruces. To preserve all material captured by experimental harvest mechanisms for analysis, there was no field cleaning. To individually quantify mechanical damage and extraneous matter each mechanism’s product stream was handled and collected separately.
A 1978 John Deere cotton stripper harvester became the platform used to power and propel four of the experimental harvest mechanisms. Converting it from a commercial to an experimental purpose involved replacing the product basket with an expanded metal deck $3 \times 3.6$ m ($10 \times 12$ ft), adding hydraulic system components powered by the existing OEM 77-kW (104-hp) diesel engine and adding conveyors that separately delivered harvested material from each mechanism (fig. 2). Two sets of harvest mechanisms were modified to interchangeably attach to the front of the platform.

Frank E. Eaton developed a harvest mechanism for the NMSU Chile Task Force (ca. 2004) with vertical motion instead of the horizontal motion disclosed by Urich and Urich (1999). Eaton’s design featured a plurality of rubber fingers on long bars. Four bars were attached to bearings spaced around the edges of two upright, parallel disks (spider reels) forming an offset double-crank mechanism similar to an inclined hay rake. The disks were set $45^\circ$ to the harvester’s direction of travel. As the disks rotated, the bars moved up in an oblique circular motion while the rubber fingers remained parallel to the ground. A second set of two disks moving four bars mirrored the first on the other side of the crop row (see Appendix A: Sketch showing disk finger mechanism). The bars moved through a circular path such that opposing fingers entered the crop area, lifted the peppers to separate them from the plants and then returned downward when withdrawn, similar to a mechanism developed in Florida ca. 1973 (the ‘Side Delivery Rake Reel Harvester’ described by Shaw and Ozaki, 1976, and evaluated by Wilhoit et al., 1990). Though promising, it had not been tested in a head that captured and conveyed fruit in green chile production. A compact version of this disk finger mechanism was built by the USDA-ARS-Southwestern Cotton Ginning Research Laboratory [SWCGRRL solves problems pertaining to cotton production and processing, especially Western irrigated cottons, decreasing inputs, improving fiber value, and reducing environmental impact. Because chile is grown in rotation with cotton in the region served, and because mechanization issues are similar, stakeholders asked the SWCGRRL to help solve harvest mechanization problems.) in 2008.

A second rubber finger mechanism was also built by the SWCGRRL. It had a single bar on either side of the crop row that chains drove through a vertical path. The bars each held six rubber fingers in a horizontal orientation perpendicular to the crop row. As the bars moved they thrust the rubber fingers into the plant space near ground level, lifted them by combing vertically up through the crop area (to lift peppers from plants), then withdrew the rubber fingers at the top of their motion to return to ground level, similar to a hay-tine combing mechanism developed at The University of Arizona ca. 1974 (Gentry et al., 1978; see Appendix B: Sketch showing chain finger mechanism) Both mechanisms used rubber fingers approximately 2 cm (0.75 in.) in diameter by 11 cm (4.5 in.) long (LB Products, LLC, Libertyville, Iowa). The fingers were made of 60-durometer prime natural rubber.

For these trials both the disk-driven and chain-driven rubber finger mechanisms were fitted inside McClendon harvester heads (fig. 3). The McClendon heads had paddle-chain conveyors on either side. Hinged paddles were moved by a loop of roller chain on either side of the head. The paddles traveled down to the front of the picking head in a vertical position and then dropped to their horizontal working position for the return trip. While horizontal, they slid on a flat surface parallel to the ground in front of and under the picking mechanism, and inclined behind it, to convey harvested material. The paddles discharged material approximately 1 m (39 in.) above the ground. Using existing heads that had proven capturing and conveying technology permitted the research design and construction effort to focus on the harvest mechanism itself. This approach had its disadvantages. The mechanisms were made smaller than ideal to fit these existing heads; there was little clearance for harvested material to make its way safely to the conveyors.

The second pair of experimental harvest mechanisms was similar to that first patented by Creager (1971) and improved by Cosimati (1998). They had vertical open-helixes formed of 13-mm (0.5-in.) diameter steel rod in a 4.5 turn coil 20 cm (8 in.) in diameter by 66 cm (26 in.) tall (fig. 4). Although
these heads had been tested in the past, succulent green chile results for them were not found in the literature.

The unmodified (Creager) head contained eight counter-rotating open-helixes, four on each side in an orthogonal pattern. The first pair rotated so that they helped plants into the picking head, the remaining open-helixes turned in the opposite direction so the side contacting the plants opposed the plant’s relative motion. The modified (Hernandez) head contained seven helixes, four on one side and three on the other in a staggered pattern (Appendix C; Sketch depicting Creager heads). The Hernandez head also had a wider opening to admit plants into the picking chamber, with nylon brushes angled slightly inward to help prevent peppers being ejected from the picking head. Both heads had rigid paddle-chain conveyors on either side. The paddles traveled downward at the front of the head (occasionally knocking peppers to the ground), discharging harvested material approximately 75 cm (30 in.) above the ground at the back of the head.

The fifth harvest mechanism evaluated in these trials was purchased abroad (Yung-Etgar, Bet-Lehem-Hgilit, Israel) and was attached to a power and propulsion unit by Oxbo International Corporation (Clear Lake, Wis.). It used the counter-rotating double open-helix picking mechanism first described by Fullilove and Futral (1972) and improved by Wolf and Alper (1984). Three pairs of inclined opposite hand open-helixes approximately 10 cm (4 in.) in diameter and 2 m (6 ft) in length were spaced 0.5 m (20 in.) on center in its 2-m (80-in.) wide head; just the outer two were used. The coils intermeshed with a 5-cm (2-in.) gap as they counter rotated 180° out of phase at 300 rpm (Appendix D). Built by Yung-Etgar, a farmer and custom harvester who also manufactures equipment, this model has been in commercial production for several years and is a mature, robust design. Chiles fall directly onto a flat surface and are conveyed with little subsequent damage by low profile paddles powered by a belt-chain, dropping onto a common conveyor for delivery to a separate vehicle (fig. 5).

For the green chile mechanical harvester trials, two fields were prepared at New Mexico State University’s Leyendecker Plant Science Research Center. Each was direct seeded 3 April 2008, thinned to one plant every 25 to 30 cm (10 to 12 in.) on 1-m (40-in.) rows, irrigated with a season total of approximately 91- to 122-cm (36- to 48-in.) water and fertilized, all in accordance with standard local practices for green chile. Field One contained seven blocks, Field Two eight, for a total of 15 blocks two rows wide, with an additional two guard rows, one on each side. Each block was randomly planted in five cultivars. The cultivars included ‘AZ-20’ (Curry Chile and Seed Co., Pearce, Ariz.) and ‘NuMex Joe E. Parker’ (JEP), both standard commercial green chile varieties, and breeding lines ‘Despanado’ (DESP), ‘PHB 109’, and a green chile accession from Texas A&M University’s chile breeding program (TAM). Thus there were potentially 150 observations (a one-variety half plot one row wide) in 15 random complete blocks. However, poor stand establishment resulted in insufficient plant populations in 13 of the plots. Four blocks had five viable plots, nine blocks had four plots, and two blocks had only three viable plots, resulting in 124 viable one-row plots 1 × 8 m (40 in. × 26.25 ft).

The rubber finger harvest mechanisms were operated in 21 plots, the Creager and Hernandez coils in 26 plots (separation data for broken peppers, leaf trash, etc. was available for 20). The Israeli harvester merged harvested material together from two rows onto one conveyor. It was operated in 15 plots (four cultivars).

All material harvested by an experimental head in a particular plot was captured in plastic bags. The material was hand sorted and weighed (fig. 6). Fresh weights were recorded for each category: red, green, immature and diseased peppers, and plant material (leaves and stems). Fruit remaining on plants and fruit lying on the ground were collected separately, bagged, and also weighed fresh.

Statistical analysis was performed using PC-SAS 9.1 (SAS Institute, Inc., Cary, N.C.) with a 5% significance level. The cultivar JEP was omitted from this analysis because of variety-specific poor stand establishment due to a weak seed lot. The general linear model procedure was used to calculate the statistical significance of two controlled class variables (harvest mechanism and cultivar) and two uncontrolled continuous variables (days after planting and yield) on seven response variables (gross harvest efficiency, mechanical damage, net marketable portion, peppers remaining on plant, ground fall, the ratio of whole-to-damaged fruit and the marketable yield). Response means were pair-wise
Figure 6. Separating and weighing components of harvested material for each plot.

RESULTS AND DISCUSSION

Table 1 presents harvest results for each tested mechanism and cultivar as measured by harvest efficiency and mechanical damage. Gross harvest efficiency quantifies how well a harvest mechanism removes peppers from plants without dropping them on the ground. Gross harvest efficiency was calculated by dividing all fruit harvested by all fruit in the plot (total plot yield) whether ground-fall, left on plants, or harvested. In all columns, means with the same letter are not statistically different.

Values in the column ‘mechanical damage’ were calculated by dividing damaged harvested peppers by all harvested peppers. As it was not possible to isolate damage by source, e.g., whether caused by picking mechanism or conveyance, presented results are for head combination and not just picking principle. The last column, net marketable portion, indicates the undamaged whole pepper weight removed from the field as a percentage of each plot’s total yield.

Harvest mechanism was the most influential parameter, being strongly significant in the general linear model across all response variables. Cultivar contributed to the general linear model for Gross Harvest Efficiency, but was not significant for Mechanical Damage or Net Marketable Portion.

Due to several rain delays, trials were spread out from 26 August through 22 September 2008. Even so, “days from planting to harvest” had no statistically significant influence on any harvest response variable. The general linear models of the response variables were not significantly impacted by yield, either. For these particular trials, harvest response variables were so strongly determined by harvest mechanism that pepper maturity (days from planting) and quantity (plot yield) appeared to have little influence.

Mechanical damage was noticeably less with the Yung-Elgar (Israeli) harvester, an inclined helix, compared to the two vertical helix mechanisms (11% compared to about 48%). Much of this is likely explained by the fact that the tip speed of the 20-cm (8-in.) diameter vertical helices, turning at from 300 to 400 rpm, was much higher than the tip speed of the 10-cm (4-in.) diameter inclined helices turning at 300 rpm. The bars of the vertical helices struck the fruit at 3 to 4 m s\(^{-1}\) (56 to 75 ft min\(^{-1}\)) while the Israeli harvester’s inclined helices contacted the fruit at a more gentle 1.6 m s\(^{-1}\) (28 ft min\(^{-1}\)). Predicting mechanical damage as a function of helix tip speed had a reasonable correlation; the R\(^2\) was 0.769. However, the relationship between tip speed and mechanical damage was not established with statistical confidence since the tip speeds were not varied in a controlled manner.

Mechanical damage may have come from the conveying systems as well as the picking mechanisms. In these trials four heads had similar internal conveying systems and one

<table>
<thead>
<tr>
<th>Harvest Mechanism</th>
<th>Cultivar</th>
<th>Parameter</th>
<th>Gross Harvest Efficiency(^{[a]}) (%)</th>
<th>Mechanical Damage(^{[a]}) (%)</th>
<th>Net Marketable Portion(^{[b]}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>88.3 a</td>
<td>11.2 c</td>
<td>78.4 a</td>
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<td></td>
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<td>81.1 a</td>
<td>48.1 a</td>
<td>41.6 b</td>
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<td>48.9 a</td>
<td>40.7 b</td>
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<td></td>
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<tr>
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<td>16.6 c</td>
<td>36.0 b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chain</td>
<td>41.1 b</td>
<td>39.4 b</td>
<td>25.7 c</td>
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</tbody>
</table>

Table 1. Gross harvest efficiency as a percentage of plot yields, mechanical damage as a percentage of gross harvest, and net marketable portion as a percentage of plot yields.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mechanism</th>
<th>Gross Harvest Efficiency(^{[a]}) (%)</th>
<th>Mechanical Damage(^{[a]}) (%)</th>
<th>Net Marketable Portion(^{[b]}) (%)</th>
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<td>0.1700(^{[c]})</td>
<td>0.3380(^{[c]})</td>
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Significance (Pr > F) in General Linear Model

<table>
<thead>
<tr>
<th>Significance (Pr &gt; F)</th>
<th>Mechanism</th>
<th>Cultivar</th>
<th>Days</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;0.0001</td>
<td>0.9145(^{[c]})</td>
<td>0.2295(^{[c]})</td>
<td>0.3380(^{[c]})</td>
</tr>
</tbody>
</table>

No. of observations used (n)

| harv_mech | 100 | 94 | 94 |

\(^{[a]}\) Means grouped with the same letter are not statistically different from each other.

\(^{[b]}\) Marketable whole peppers as a percentage of total plot yields.

\(^{[c]}\) This parameter was not significant at the 5% level.
common external conveying system. (The Israeli harvester’s external conveying system was part of its propulsion unit; its head had a flat conveyor that used low profile paddles driven by a flexible belt.) Of the four, the disk finger had the lowest level of fruit damage. Hypothetically, if the disk finger mechanism did no damage to the peppers at all, then any mechanical damage by that head came from its conveying system. Thus the maximum contribution the conveying system may have made to mechanical damage was 16.6%.

While it is unrealistic to assume that the picking mechanism caused no damage at all, this provides an upper bound for the conveyors’ contribution to damage. Mechanical damage was over twice as much with the chain finger mechanism and three times as much with the Creager and Hernandez mechanisms. Lacking quantitative data, by this argument it appears that the conveying systems’ contribution to fruit damage was a fraction of that ascribable to picking mechanism for at least three of the tested systems. Field observations corroborate this hypothesis, as only occasionally were peppers seen to be broken by conveying systems. In all likelihood, mechanical damage caused by the conveyors was less than 15% by mass of the harvested portion. The research focus and analysis effort was picking mechanism. Since four mechanisms had a common conveying system quite similar to the fifth mechanism’s conveyance, the errors that may have been introduced by not analyzing the conveying systems separately were nearly uniformly distributed as well as small.

The most important measure of harvester performance is ‘net marketable portion,’ presented in the third column. This quantity accounts for mechanical damage as well as field losses by counting whole fruit alone as successfully harvested. Minor differences between mechanisms’ gross harvest efficiency become major differences when accounting for damage; by this measure, only the Israeli inclined helix picking mechanism even approached an acceptable level of performance.

Table 2 presents plant and ground losses as a percentage of total plot yields, the ratio of whole-to-damaged fruit harvested, and the mechanically harvested marketable (undamaged) yield. Again, means with the same letter are not statistically different.

Where plant losses were high the harvest mechanism was clearly unsatisfactory (experimental disk finger and experimental chain finger). Most mechanisms left more fruit on the ground than on the plant. Where ground losses were exceptionally high, the fault may lie with the conveying mechanism as well as the harvest mechanism, and even with other elements of the head design such as crop divider size and shape. However, the chain and disk finger mechanisms were fitted inside identical heads. Differences in ground losses in this case are due to the chain finger mechanism knocking down peppers on its return stroke. The Israeli harvester had the lowest field losses and the highest ratio of whole to damaged peppers, confirming that it was very effective at removing fruit and that it did so with comparatively little mechanical damage. The two vertical helix mechanisms were statistically in the same group as the Israeli harvester when it came to removing fruit from the plant, and similar as far as ground losses were concerned. However, and more importantly, fruit damage was significantly higher with the vertical helix mechanisms as indicated by near unity whole-to-damaged fruit ratios.

While the two rubber finger mechanisms had nearly identical gross harvest efficiencies, it is interesting to observe the differences between them when it comes to how those losses were apportioned. The disk finger left approximately 20% more on the plant, the chain finger left approximately 40% more on the ground. There is also a clear distinction between them in “marketable harvested fruit” yields due to the greater amount of mechanical damage caused by the chain finger mechanism, which had a whole-to-damaged fruit ratio that was only a third as much as that of the disk mechanism.

The quantity of undamaged (marketable) fruit harvested in kg ha⁻¹ (lb acre⁻¹) is perhaps the most dramatic indication of the differences between harvest mechanisms. The Israeli harvester’s close helix spacing and low to the ground helix

<table>
<thead>
<tr>
<th>Harvest Mechanism</th>
<th>Cultivar</th>
<th>Parameter</th>
<th>Unharvested Remaining on Plants [%]</th>
<th>Ground Fall Losses [%]</th>
<th>Whole to Damaged Fruit Ratio</th>
<th>Marketable Harvested Fruit (kg ha⁻¹)</th>
<th>Marketable Harvested Fruit (lb acre⁻¹)</th>
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<tbody>
<tr>
<td>Israeli</td>
<td></td>
<td></td>
<td>3.8 c</td>
<td>7.9 d</td>
<td>8.37 a</td>
<td>14,200 a</td>
<td>15,900 a</td>
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<td>Hernandez</td>
<td></td>
<td></td>
<td>6.9 c</td>
<td>15.5 c</td>
<td>1.14 c</td>
<td>8,130 b</td>
<td>9,110 b</td>
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<td>Creager</td>
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<td></td>
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<td>12.3 cd</td>
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<td>19.7 ab</td>
<td>2.58 b</td>
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<td>12.4 bc</td>
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<td>‘PHB109’</td>
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<td>18.4 a</td>
<td>23.2 a</td>
<td>4.36 a</td>
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Significance (Pr > F) in General Linear Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cultivar</th>
<th>Days</th>
<th>Yield</th>
<th>Significance (Pr &gt; F)</th>
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</table>

[a] Means grouped with the same letter are not statistically different from each other.

[b] This parameter was not significant at the 5% level.
placememt helped it achieve high removal rates, the proximity of the conveyor to the helix minimized ground fall, and its unobstructed product path combined with the relatively low tip speed of the smaller diameter inclined helix minimized fruit damage. Its 70% higher marketable yield (compared to other tested mechanisms) could be the difference between economic viability and disaster.

When comparing different cultivars, higher plant losses may indicate greater stem attachment force or fruit concentration nearer the center of the plant. For example, the TAM variety had the lowest plant-calyx attachment force but the highest level of damage. This variety also exhibited the most concentrated fruit set, with many of the fruit wedged between the branches. Perhaps more importantly, the TAM variety also had the highest number of three-locule peppers (about half). This may explain its lower whole-to-damaged fruit ratio. Fruit tended to be broken when they were pulled through the branches off of the plant. In addition, the wider, blockier fruit may have been more susceptible to mechanical damage. Plot yields in this climate and set of production practices had a greater influence than other factors in determining marketable yield. Cultivar responses will be discussed in detail in the companion paper “Field Evaluation of New Mexican-type Green Chile Cultivars for Mechanical Harvest” by S. J. Walker and P. A. Funk (Hort Sci); paper submitted to ASHS.

CONCLUSIONS

An important aspect of the 2008 harvester experiment was that of providing feedback to support chile breeding efforts at New Mexico State University. Upon correlating “whole-to-damaged fruit ratio” and marketable harvested fruit yield to plant characteristics for each variety, breeding objectives for new mechanical harvest efficient varieties will be determined. In the growing conditions found in this climate zone the cultivar TAM produced fruit that was concentrated towards the center of the plants to such an extent that peppers were entwined with the stalk and branches. This characteristic made it difficult for any mechanism to harvest it without damaging it, indicating that very concentrated fruit set is counter to successful mechanical harvest of green chile. In this study, relative fruit attachment force for each variety was much less important than the harvest mechanism in predicting successful fruit removal from the plant. For this study, plant spacing followed standard green chile practices to preserve fruit size and quality, not the high plant densities used for mechanized paprikas.

Performance of the rubber finger mechanisms was disappointing. This was at least partly due to crowding a complex mechanism into a small head without leaving space for harvested fruit to escape. The vertical helix mechanisms were likewise unacceptable for green chile harvest. While they approached viable harvest efficiencies, nearly half the peppers were damaged, most likely by the high tip speed of the large diameter helix. The inclined helix (Israeli) mechanism was the only one of the five tested that at this point appeared to be suitable for harvesting green chile.

Key features of the successful design included a clear, open product path and relatively low tip speed providing minimal opportunity for fruit damage; closely spaced helixes starting close to ground level that left few peppers on plants; and conveyors that were immediately proximate to the helixes, minimizing ground fall losses. The Yung-Elgar (Israeli) head also had air cylinders that allowed the operator to vary the force pressing the helixes together, while still letting them spread apart in thicker foliage.

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The authors wish to express their gratitude to the New Mexico Chile Association for partial financial support and for the pleasure of working with a team of congenial colleagues. Special thanks to Vince Hernandez, who provided the harvest platform as well as substantial technical and moral support.

REFERENCES


Appendix A. Sketch of the disk finger, an inclined, oblique offset double-crank or hay-rake type mechanism. Only two of each sets of four bars are depicted in this plan view. Hydraulic motors plumbed in series turn each side at roughly the same speed. Rubber fingers travel upward in the crop area (center) and downward at each side. The hydraulic motor end was higher than the front, inclining the bars 20°.
Appendix B. Sketch of the chain finger mechanism. Plan views show finger bar segment in rising position (top) and returning position (center). Elevation section (bottom) with arrow indicates chain sprockets rotation. The intention of this device was to harvest by combing vertically, especially to also harvest low hanging fruit near ground level that other designs miss. The disk finger mechanism (Appendix A) fully engaged the crop 1/2 disk diameter above ground level (~15 cm), while this chain finger design engaged the crop 1/2 of the lower sprocket diameter above ground level (~5 cm).

Appendix C. Sketch depicting Creager heads. Sectional plan views illustrate the original (orthogonal eight, at left) and the Hernandez modification (staggered seven, at right, with a slightly wider space between helixes for the plants). Arrows indicate the direction of rotation of each helix that results in an upward relative helix motion (there were left hand and right hand helixes in each head). Front elevations present the single open helixes formed of 13-mm (0.5-in.) diameter steel rod in a 4.5 turn coil 20 cm (8 in.) in diameter by 66 cm (26 in.) tall.

Appendix D. Sketch illustrating the Israeli harvester (Yung-Etgar, Bet-Lehem-Hgllit, 36007, Israel) with its inclined counter-rotating double open-helixes. Left hand and right hand (shaded) helixes are powered by a common gear box to synchronize their rotation, maintaining a constant gap between lobes (plan view, top). This gap can be adjusted by moving the helixes with respect to each other. Harvested fruit was caught by the low-profile conveyor proximate to the helixes, shown just below them in the side elevation section view (bottom). A belt near the top (not shown, see fig. 5) cleared branches away.