Comparative Mechanical Harvest Efficiency of Six New Mexico Pod-type Green Chile Pepper Cultivars

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SUMMARY. New Mexico pod-type green chile (*Capsicum annuum*) is one of New Mexico's leading horticultural commodities. Cultivated acreage of green chile in New Mexico is threatened because of the high cost and insufficiently available labor for hand harvest. Therefore, mechanization is necessary to sustain the industry. Successful mechanization depends on harvester design coupled with plant architecture that optimizes harvest yield and quality. Harvested green fruit must be whole, unbroken, and unblemished for fresh and processed markets, so harvester design and plant architecture must maximize yield while minimizing fruit damage. In two trials conducted at the New Mexico State University Agricultural Science Center in Los Lunas, six cultivars (AZ-1904, Machete, PHB-205, E9, PDJ.7, and RK3-35) were evaluated for plant architecture and harvest efficiency with a double, open-helix mechanical harvester with two counter-rotating heads. Cultivars were direct seeded on 17 Apr. 2015 and 14 Apr. 2016 and managed according to standard production practices. Plant architecture traits, plant width, plant height, height to first primary branch, distance between first primary branch and first node, basal stem diameter, and number of basal branches were measured before harvest. Mechanical harvest yield components, which included marketable fruit, broken fruit, ground fall losses, unharvested fruit remaining on branches, and nonpod plant material, were assessed after once-over destructive harvests on 2 Sept. 2015 and 31 Aug. 2016. Fruit width, fruit length, and pericarp thickness were measured from a representative sample of 10 marketable fruit. In 2015, 'AZ-1904' and 'PDJ.7' had significantly ($P \leq 0.05$) more marketable yield than 'Machete' that had the least marketable yield. No statistically significant differences were found in marketable yield in 2016. When both years were combined, 'PDJ.7' had significantly more nonpod plant material harvested and the plants were taller than all other cultivars. We found mechanical harvest performance to be significantly affected by plant height, with shorter plants yielding less marketable fruit. Despite differences in fruit wall thickness, no significant differences were measured in broken fruit. In 2015, 'AZ-1904' had significantly less basal branches per plant, reducing obstruction for the picking mechanism. Harvest efficiencies (marketable harvested fruit yield as a percentage of total plot yields) ranged from 64.6% to 39.3% during this 2-year trial, with the highest harvesting cultivars PDJ.7 and AZ-1904. In the future, all new Mexico pod-type green chile breeding efforts for mechanical harvest must incorporate desirable plant architecture traits to increase harvest efficiencies.

Demand for new Mexico pod-type green chile in the United States has been rising for decades (Gandonou and Waliczek, 2013), yet domestic production has been declining because of both limited

availability of labor and associated costs (Funk and Walker, 2010). Coinciding with reduction in New Mexico acreage (New Mexico Department of Agriculture, 2015) is a dramatic increase in imports of green chile from Mexico to the United States since

2009 (U.S. Agency for International Development, 2014). Hand labor accounts for an estimated 50% of green chile production costs in the United States (Eastman et al., 1997; Hawkes et al., 2008). Lower cost of hand labor in other countries has given a competitive advantage in overall lower production costs as compared with production in the United States. Red chile production labor costs were reduced to $\approx 10\%$ (Eastman et al., 1997) when the crop was transitioned to mechanical harvest. If green chile production shifted to mechanical harvest, like red chile, this would level the playing field with competing countries.

In New Mexico, processing industries exist for both green and red chile. The red chile crop consists of physiologically mature fruit that is predominantly dried and ground into powders or used for extraction of red pigments to produce oleoresin paprika; the dried red fruit does not have to be whole or unblemished after harvest. The acceptability of fruit damage for red chile processors has driven the adoption of mechanization of red chile harvest. In New Mexico, 80% of the red chile crop is currently mechanically harvested (Bosland and Walker, 2004). By contrast, the new Mexico green chile crop is 100% hand-harvested. High-quality green chile for the fresh market and processing must be undamaged, thick-walled fruit, ≈ 15 – 18 cm in length (Walker and Funk, 2014). Quality green chile is important because blemished or broken fruit will rot before reaching the fresh market or it will not move efficiently in a processing production line developed for whole unbroken fruit.

Transitioning new Mexico green chile production to a mechanical harvest system has major challenges, primarily the unacceptability of broken or blemished fruit due to mechanical damage (Funk et al., 2011) and lack of an efficient method to mechanically

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1.1209	lb/acre	kg·ha ⁻¹	0.8922
2.2417	ton(s)/acre	t·ha ⁻¹	0.4461

remove the stems from the fruit (Herbon et al., 2009). To overcome these obstacles, a whole systems

Fig. 1. New Mexico pod-type green chile plant architecture measurement locations: (A) plant width, (B) plant height, (C) first primary branch height, (D) basal stem diameter measurement location, and (E) distance between the first primary branch and the first node; 1 cm = 0.3937 inch and 1 mm = 0.0394 inch.

Fig. 2. Broken new Mexico pod-type green chile fruit caused by a mechanical harvester.

Fig. 3. New Mexico pod-type green chile nonpod plant material (sticks and leaves) collected from a mechanical harvester along with fruit.

approach must be used (Rasmussen, 1968) as was seen in the 1960s when processing tomato (*Solanum lycopersicum*) production progressed into mechanical harvest. Tomato mechanical harvest success was propelled forward by the joint effort of engineers, horticulturists, and agronomists. Engineers created picking mechanisms, horticulturists developed cultivars for efficient mechanical harvest, and agronomists determined optimum field growing conditions. The same whole systems approach is being used for efficient mechanical harvest of green chile.

Joint research between New Mexico State University horticulturists and the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Cotton Ginning Research Laboratory (Las Cruces, NM) determined that the inclined double open-helix picking head design was the most efficient green chile harvesting mechanism out of the several tested picking mechanisms (Funk and Walker, 2010). During this research in 2010, yield differences were identified between several new Mexico pod-type green chile cultivars. Anecdotally, it was observed that plant architecture contributed to improved mechanical harvest efficiency; however, additional research was needed to identify the most important determinants of mechanical harvest quality/efficiency, such as plant height, plant width, number of basal branches, basal stem diameter, and height to first primary branch.

Mechanical harvest efficiency is the marketable fruit as a percentage of total plot yields. In an initial study of green chile mechanical harvest efficiency with the double open-helix

picking mechanism, Funk and Walker (2010) reported 78% harvest efficiency of total plot yield. Research on mechanical harvest of green chile is limited, so determination of an acceptable benchmark for harvest efficiency has not been reported. Local farmers state that they would benefit from an 80% harvest efficiency for new Mexico pod-type green chile (V. Hernandez, personal communication). As a benchmark for our study on new Mexico pod-type green chile, 80% harvest efficiency was used.

Mechanical harvest efficiencies of red chile have been reported to be anywhere from 70% to 98% (Funk and Walker, 2010). Previous research on mechanical harvest of red chile found that certain plant architecture traits would improve mechanical harvest efficiency. These included upright plant habit with narrow branch angles and fruit set higher than the junction of the first primary branch (Marshall, 1984, 1997), fewer basal branches to reduce branch breakage and allow the picker to harvest without obstruction (Palevitch and Levy, 1984), and larger basal stem diameter at the soil level to lessen plant lodging (Kahn, 1985). Pendulous fruit that is evenly spread throughout the plant canopy with a low detachment force of the calyx from the fruit is also ideal for mechanical harvest (Wall et al., 2003). As a result of this research, a red new Mexico pod-type 'NuMex Garnet' was released specifically for mechanical harvest traits (Walker et al., 2004). However, knowledge is lacking on whether plant architecture traits beneficial for red chile mechanical harvest would also benefit new Mexico pod-type green chile mechanical harvest and on general information comparing mechanical harvest efficiency of currently available green chile cultivars. Identifying desirable plant architecture traits for mechanical harvest of green chile will improve harvest efficiency and drive breeding efforts in a direction that develops cultivars improved for mechanical harvest. In addition, data on mechanical harvest performance of current green chile cultivars would give growers and processors advice on which chile cultivars to grow when trying to transition their green chile crops to mechanical harvest.

The aim of this study was to evaluate six new Mexico pod-type

green chile cultivars consisting of breeding lines and common cultivars with various fruit and plant architecture traits and to determine their relative suitability for mechanical harvest. A whole systems approach was demonstrated in this research by incorporating previous engineering results on the most efficient picking mechanism (Funk and Walker, 2010) and agronomic results on best field management practices (Paroissien and Flynn, 2004; Wall et al., 2003) into the materials and methods for ideal assessment of these cultivars in a mechanical harvest system.

Materials and methods

Field experiments were conducted during 2015 and 2016 at the New Mexico State University Agricultural Science Center at Los Lunas (lat. 34°46'08.09"N, long. 106°45'40.63"W, 4840 ft elevation). Soils at the study site were Bluepoint loamy fine sand (Natural Resources Conservation Services, 2017). Fertilization during both years consisted of nitrogen (Helena Chemicals, Collierville, TN) at 200 lb/acre and phosphorus (Helena Chemicals) at 100 lb/acre. A quarter of all fertilizer was applied as a preplant broadcast and three-quarters equally distributed in the irrigation water over the course of season at three different growth stages: first bloom, peak bloom, and fruit set.

FIELD CULTIVATION. The field was plowed, disked, laser-leveled, and listed before planting. Six new mexico pod-type green chile cultivars, AZ-1904, Machete, both common commercial cultivars, and PHB-205, E9, PDJ.7, and RK3-35 (Curry Chile and Seed Co., Pearce, AZ), were seeded on cultivated ridges at a rate of 5 lb/acre on 17 Apr. 2015 and 14 Apr. 2016 in a randomized complete block design with five replications over an area of 3000 ft² (12.5 × 240 ft) and a row of border plants on all sides of the field. The field consisted of 30 plots; each plot was 100 ft² (2.5 × 40 ft). The plants were thinned to 8-inch spacing on 11 June 2015 [55 d after planting (DAP)] and 14 June 2016 (61 DAP). The field was furrow-irrigated, and crop management followed standard, local grower practices (Bosland and Walker, 2004). Irrigations were scheduled weekly using alternate furrow irrigation until

Fig. 4. Fruit characteristics of six mechanically harvested new mexico pod-type green chile cultivars in 2015. All values are means of observations $\pm$ SE. Means within a graph followed by the same letters are not significantly different by the least significant difference test at $P \leq 0.05$. Means within a graph with no letters are not significantly different; 1 cm = 0.3937 inch and 1 mm = 0.0394 inch.

Aug. 2015 and 2016. Weeds were managed with cultivation and hoeing.

PLANT DATA COLLECTION. Before harvest, plant architecture measurements and plant counts were made on 1 Sept. 2015 (137 DAP) and 30 Aug. 2016 (138 DAP). Within each plot, all healthy plants were counted. Plant heights (centimeters) were obtained in the field by measuring from the soil level to the upper most meristem (Fig. 1B). Plant widths (centimeters) were measured at the widest point on the top of the canopy (Fig. 1A). Basal stem diameter (millimeters) was measured with a digital caliper (500-171-30; Mitutoyo, Kawasaki, Japan) at the base of the stem right above the soil line (Fig. 1D). Height to the first primary branch (centimeters) was measured from the soil level to the first branch bifurcation (Fig. 1C). Distance to the first node (centimeters) was measured between the first primary branch and the first node (Fig. 1E). The number of basal lateral branches large enough to bear fruit within 10 cm of the soil line was counted.

MECHANICAL HARVEST. The picking mechanism used for the trials was a power take-off driven single row, counter-rotating, double open-helix model (Moses 1010; Yung-Etgar, Bet-Lehem-Hglilit, Israel). The crops were harvested as a once-over destructive harvest on 2 Sept. 2015 (138 DAP) and 31 Aug. 2016 (139 DAP). From each plot, a sample area of 75 ft² (2.5 × 30 ft) was harvested. The tractor with the picking mechanism was driven at 1 mph in a creeper gear. Harvested material was conveyed into two 16-gal buckets lined with plastic bags. Between each plot, the plastic bags were removed from the collection bins and transferred to the laboratory for sorting. Immediately after the mechanical harvest of each plot, fruit left on the ground (ground fall loss) and fruit left on the plant (unharvested remaining on plants) by the machine were hand-harvested to quantify field yield losses.

YIELD DATA COLLECTION. Harvested materials from each plot were sorted into categories to characterize the quality of the machine-harvested chile and were measured by fresh weight. The categories included 1) marketable green, 2) machine broken fruit (Fig. 2), 3) immature fruit, 4) diseased fruit, 5) nonpod plant

Fig. 5. Fruit characteristics of six mechanically harvested new Mexico pod-type green chile cultivars in 2016. All values are means of observations $\pm$ SE. Means within a graph followed by the same letters are not significantly different by the least significant difference test at $P \leq 0.05$. Means within a graph with no letters are not significantly different; 1 cm = 0.3937 inch and 1 mm = 0.0394 inch.

material (Fig. 3), 6) ground fall fruit loss, and 7) unharvested fruit remaining on plants. Fruit classified as marketable green yield were intact, whole, and unblemished green fruit. Fruit classified as machine broken were fruit that were severed, damaged, or both by the machine. Fruit classified as immature were healthy fruit less than 4-inch length with a malleable pericarp. Fruit classified as diseased had disease blemishes or discoloration on more than 40% of the fruit. Yield classified as nonpod plant material were the sticks and leaves the machine harvested into the collection buckets. All of the sorted materials were placed into bins and weighed (SVI-110E; Sartorius Stedim North America, Bohemia, NY). Ten representative fruit from the marketable green fruit category were selected for fruit measurements. Fruit width (centimeters) was measured across the top at the shoulder but below the calyx. Fruit length (centimeters) was measured from the top of the shoulder to the apex. If the fruit was curled, the entire length of the fruit was measured by rolling the fruit from the shoulder to the apex on the ruler. The fruit was cut in half at the shoulder and pericarp thickness (millimeters) was measured at three representative points with a digital caliper.

DATA ANALYSIS. The parameters in this study were designed to measure and compare the machine-harvested yield, plant architecture, and fruit characteristics from each of the six cultivars. When variables were not significantly different between years (cultivar $\times$ year interaction was not significant), the data for those variables were combined from 2015 and 2016; if variables were significantly different between years (cultivar $\times$ year interaction was significant), the data were analyzed from each year separately. All data were subjected to statistical analysis using SAS (version 9.3; SAS Institute, Cary, NC). Plant architecture measurements, fruit characteristics, and yield categories were analyzed using an analysis of variance (ANOVA) test. Least significant difference tests ($P \leq 0.05$) were used to separate the means when ANOVA tests were significant. Covariance analysis (Kuehl, 2000) was conducted using each plant architecture trait individually as covariates to determine the

effect of architectural traits on mechanical harvest efficiency.

Results

FRUIT CHARACTERISTICS. Fruit characteristic variables were significantly different between 2015 and 2016 ($P \leq 0.05$), so each variable was analyzed separately by year. In both years, 'PDJ.7' had the widest fruit and 'Machete' had the narrowest fruit (Figs. 4A and 5A). 'AZ-1904' and 'Machete' had longer fruit in both years, but in 2015, 'PDJ.7' was not significantly different from 'AZ-1904' and 'Machete' (Figs. 4B and 5B). 'RK3-35' had shortest fruit in both years, but in 2016, it was not significantly different from 'PHB-205' (Figs. 4C and 5C).

PLANT ARCHITECTURE TRAITS. Plant height ($P = 0.33$) and stem diameter ($P = 0.89$) were not significantly different ($P \leq 0.05$) between 2015 and 2016; data from both years were combined for those two variables. In both years, the tallest cultivar was PDJ.7 and AZ-1904 was intermediate, whereas E9, Machete, PHB-205, and RK3-35 were the shortest cultivars (Fig. 6). In both years, 'Machete' had the thinnest basal stem diameter, whereas 'AZ-1904', 'E9', 'PDJ.7', and 'PHB-205' had the

thickest basal stem diameters (Fig. 7). The other plant architecture traits were significantly different between 2015 and 2016 ($P \leq 0.05$), so the data for these variables were analyzed separately. In 2015, 'PDJ.7' had the widest plants (Fig. 8A) and in 2016, 'E9' had the narrowest plants (Fig. 9A). 'PDJ.7', in both years, had the tallest height to the first primary branch (Figs. 8C and 9C). In 2015, 'RK3-35' had the most basal branches, whereas 'AZ-1904' had the least (Fig. 8D). In 2015, 'PDJ.7' and 'AZ-1904' had the largest distance to the first node (Fig. 8B). In 2016, distance to the first node and number of basal branches were not significantly different (Fig. 9B and D).

When using covariate analysis to further evaluate the effect of plant architecture traits on mechanical harvest efficiency, each plant architecture trait was added to the model individually. All plant architecture traits, i.e., plant width, first primary branch height, distance to first node, and number of basal branches, were not significant when used as a covariate. Plant height was significant in 2015 ($P = 0.05$) and 2016 ($P = 0.02$) when using covariance analysis to determine the effect of plant architecture traits on mechanical harvest of marketable green yield.

YIELD COMPONENTS. Nonpod plant material ($P = 0.20$) was not significantly different between 2015

Fig. 6. Plant height measurements for each new Mexico pod-type green chile cultivar mechanically harvested in 2015 and 2016. Mean values of plant height $\pm$ SE. All values are means of 60 observations. Means separated within a graph by the least significant difference test at $P \leq 0.05$. Means with a common letter do not differ significantly; 1 cm = 0.3937 inch.

and 2016 ($P \leq 0.05$); therefore, data were combined and analyzed together. Other yield component variables were significantly different between 2015 and 2016; thus, data were analyzed

separately for each year. In both years, 'PDJ.7' had the most harvested non-pod plant material and 'Machete' had the least (Fig. 10). In 2015, differences were found in harvest

efficiency: 'AZ-1904' and 'PDJ.7' had the highest harvest efficiencies, whereas 'Machete' had the lowest (Table 1). No differences between the means were observed in broken harvested fruit yields in either 2015 or 2016 (Tables 1 and 2). Ground fall losses were not statistically significant only in 2016; 'RK3-35' had more ground yield losses than 'AZ-1904' (Table 2). Unharvested fruit remaining on plants were not statistically significant in 2016, but in 2015, 'PHB-205' had more than six times more fruit remaining on the plants after mechanical harvest than 'AZ-1904' (Tables 1 and 2). 'AZ-1904' had the highest harvest efficiency at 60% and 65% in 2015 and 2016, respectively, and 'Machete' had the lowest harvest efficiency in both years (Tables 1 and 2). The amount of immature and diseased fruit was minimal and not different among the cultivars; therefore, the data are not included in this report.

Discussion

Successful mechanization of new mexico pod-type green chile requires

Fig. 7. Basal stem diameter measurements for each new mexico pod-type green chile cultivar mechanically harvested in 2015 and 2016. Mean values of plant height $\pm$ SE. All values are means of 60 observations. Means separated within a graph by the least significant difference test at $P \leq 0.05$. Means with a common letter do not differ significantly; 1 mm = 0.0394 inch.

Fig. 8. Plant architecture traits of six mechanically harvested new mexico pod-type green chile cultivars in 2015. All values are means of observations $\pm$ SE. Means within a graph followed by the same letters are not significantly different by the least significant difference test at $P \leq 0.05$. Means within a graph with no letters are not significantly different; 1 cm = 0.3937 inch.

Fig. 9. Plant architecture traits of six mechanically harvested new mexico pod-type green chile cultivars in 2016. All values are means of observations $\pm$ SE. Means within a graph followed by the same letters are not significantly different by the least significant difference test at $P \leq 0.05$. Means within a graph with no letters are not significantly different; 1 cm = 0.3937 inch.

Fig. 10. Mechanical harvest of new mexico pod-type green chile nonpod plant material for each cultivar in 2015 and 2016. Mean values of harvested nonpod plant material $\pm$ SE reported in metric tons per hectare. All values are means of 10 observations. Means separated within a graph by the least significant difference test at $P \leq 0.05$. Means with a common letter do not differ significantly; 1 t·ha⁻¹ = 0.4461 ton/acre.

that growers have access to cultivars most suited for mechanical harvest. To obtain optimal yield and quality for a mechanical harvest system, crops

must be selected for specific characteristics (Eastman et al., 1997). The best plant architecture traits for mechanical harvest of red chile research

included taller plants and greater height for the first primary branch, fewer basal branches, and thicker basal stem diameter (Marshall, 1984, 1997; Wall et al., 2003). These same traits were identified as advantageous traits for mechanical harvest for green chile in this research when making quantitative comparisons between each cultivar evaluated.

In 2015, 'PDJ.7' and 'AZ-1904' had the highest efficiencies of 55% and 60%, respectively; although neither reached the proposed benchmark of 80%, they are much closer than 'Machete' with the lowest harvest efficiency of 36%. The differences in harvest efficiencies point out that some cultivars have traits that make them better suited for mechanical harvest. 'PDJ.7' and 'AZ-1904' had some of the horticultural traits that contribute to increased mechanically harvested marketable green yield such as taller plants and first primary branch height. Primary branch height would also be an approximate measurement of fruit set height; therefore, 'PDJ.7'

Table 1. Mechanical harvest yield components of six new mexico pod-type green chile cultivars at Los Lunas, NM, in 2015.

Cultivar	Total yield (t·ha ⁻¹) ^z	Harvest efficiency [marketable harvested fruit] (%) ^y	Broken harvested fruit (%) ^x	Ground fall losses (%) ^w	Unharvested remaining on plants (%) ^v
AZ-1904	30.9	59.9 a ^u	21.0	16.8	2.3 b
E9	29.5	47.8 ab	22.0	21.0	9.2 ab
Machete	18.6	36.2 b	28.0	23.1	9.7 b
PDJ.7	32.5	54.5 a	16.9	24.3	4.3 b
PHB-205	27.3	40.3 ab	16.5	24.2	19.0 a
RK3-35	25.1	45.0 ab	12.7	30.7	11.6 ab
	NS ^t		NS	NS	

^zTotal green chile mechanical harvest yield in kilograms per 6.9 m² (74.27 ft²) reported as metric tons per hectare; 1 t·ha⁻¹ = 0.4461 ton/acre.

^yCalculated percentage = 100 × [marketable yield/(marketable yield + broken yield + ground fall losses + unharvested remaining on plants)]; value of five replications.

^xBroken fruit caused by mechanical damage; broken fruit as a percentage of total plot yields; value of five replications.

^wFruit left on the ground after mechanical harvest; ground fall losses as a percentage of total plot yields; value of five replications.

^vFruit left on plants after mechanical harvest; unharvested fruit remaining on plants as a percentage of total plot yields; value of five replications.

^uMeans within a column followed by the same letters are not significantly different according to the least significant difference (LSD) test ($P \leq 0.05$).

^tNot significantly different via the LSD test at $P \leq 0.05$.

Table 2. Mechanical harvest yield components of six new mexico pod-type green chile cultivars at Los Lunas, NM, in 2016.

Cultivar	Total yield (t·ha ⁻¹) ^z	Harvest efficiency [marketable harvested fruit] (%) ^y	Broken harvested fruit (%) ^x	Ground fall losses (%) ^w	Unharvested remaining on plants (%) ^v
AZ-1904	30.9	59.9 a ^u	21.0	16.8	2.3 b
E9	29.5	47.8 ab	22.0	21.0	9.2 ab
Machete	18.6	36.2 b	28.0	23.1	9.7 b
PDJ.7	32.5	54.5 a	16.9	24.3	4.3 b
PHB-205	27.3	40.3 ab	16.5	24.2	19.0 a
RK3-35	25.1	45.0 ab	12.7	30.7	11.6 ab
	NS ^t		NS	NS	

^zTotal green chile mechanical harvest yield in kilograms per 6.9 m² (74.27 ft²) reported as metric tons per hectare; 1 t·ha⁻¹ = 0.4461 ton/acre.

^yCalculated percentage = 100 × [marketable yield/(marketable yield + broken yield + ground fall losses + unharvested remaining on plants)]; value of five replications.

^xBroken fruit caused by mechanical damage; broken fruit as a percentage of total plot yields; value of five replications.

^wFruit left on the ground after mechanical harvest; ground fall losses as a percentage of total plot yields; value of five replications.

^vFruit left on plants after mechanical harvest; unharvested fruit remaining on plants as a percentage of total plot yields; value of five replications.

^uMeans within a column followed by the same letters are not significantly different according to the least significant difference (LSD) test ($P \leq 0.05$).

^tNot significantly different via the LSD test at $P \leq 0.05$.

had the higher fruit set that is better for mechanical harvest (Marshall, 1984). The lack of differences in marketable harvested fruit yield in 2016 could be due to weather conditions in 2016 such as warmer maximum temperatures earlier in the season (New Mexico Climate Center, 2015, 2016), increasing overall yield of all cultivars.

The significant effect of height on mechanical harvest efficiency on each cultivar suggests that plant height may be one of the primary factors for marketable yield differences among the cultivars trialed. Shorter plants were observed to have lower marketable yields. This does not indicate that chile plants should be selected for height only; instead, height should be one of the main considerations when selecting plants for mechanical harvest. In addition, height can become a limiting factor. If the plants become too tall, they will not fit properly into the mechanical harvester (Marshall and Boese, 1998). The ideal plant height for

a red chile mechanical harvest is 60–80 cm (Marshall, 1997; Wolf and Aper, 1984).

It must be noted that the differences observed in height during this study could have been due to environmental factors and genotype × environmental ($G \times E$) interactions. Field plant height has a genetic component, but it can be representative of environmental conditions and how $G \times E$ interactions are affecting plant height expression (Acquaah, 2012). Plant height can also be influenced by cultivation practices: the higher the planting density, the taller the plants (Wall et al., 2003). To reduce environmental impact on plant height, plants in this study were all thinned to a consistent within-row spacing of 8 inches.

Other plant traits to be considered for mechanical harvest plant selection are basal stem diameter and fruit characteristics. Previous research on chile has found that larger basal stem diameters reduce lodging (Kahn,

1985) and have a positive effect on mechanical harvest efficiency (Wall et al., 2003). In our research, the cultivars with significantly larger basal stem diameters had more marketable yield. No previous research on the effect of fruit characteristics on mechanical harvest yield has been carried out. Our results indicate that longer and wider fruit may contribute to a higher marketable yield. As seen in 2015, ‘PDJ.7’ had the widest fruit and ‘AZ-1904’ had the longest fruit and both of these had the highest marketable yield. Longer and wider fruit may increase yield mainly because of their larger size, but larger size may also increase or decrease mechanical fruit breakage. No statistically significant differences in broken harvested fruit were detected in this study in 2015 or 2016, despite differences in fruit characteristics such as pericarp thickness and fruit width. Because no other previous research on the relationship between fruit characteristics and broken harvested fruit

has been conducted, further investigation may be warranted.

Conclusions

In this study, differences were found; the machine harvest efficiency in 2015 was highest for 'AZ-1904' and 'PDJ.7', followed by 'E9', 'RK3-35', 'PHB-205', and 'Machete'. Although no significant differences were found in the marketable yield in 2016, the plant architecture data support that 'PDJ.7' has the tallest plant height, and height to primary branch to make it a possible candidate for mechanical harvest. 'AZ-1904' is another potential selection for mechanical harvest because of the low number of basal branches. Both 'PDJ.7' and 'AZ-1904' have harvest efficiencies that are closer to our 80% benchmark. However, there is a need for future breeding efforts to enhance characteristics such as plant height, basal stem diameter, and number of basal branches before releasing a new mexican pod-type green chile cultivar for mechanical harvest.

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