FINAL REPORT

August 15, 2016

Virginia Wine Board

Effects of Harvest Maturity and Post-Harvest Storage on Fruit, Juice, and Cider Quality

Principal Investigators (Team project):

Gregory M. Peck (50%), Assistant Professor of Pomology, School of Integrative Plant Science, Horticulture Section, Cornell University, 121 Plant Science Building, Ithaca, NY 14853
Phone: 607.255.7122
Email: gmp32@cornell.edu

Amanda Stewart (45%), Assistant Professor of Enology and Fermentation, Department of Food Science & Technology, Virginia Tech, 1230 SW Washington St. HABB1 401F, Blacksburg, VA 24061
Phone: 540.231.0868
Email: amanda.stewart@vt.edu

Andrew Neilson (5%), Assistant Professor of Food Science & Technology, Department of Food Science & Technology, Virginia Tech, 1230 SW Washington St., HABB1 402, Blacksburg, VA 24061
Phone: 540.231.8391
Email: andrewn@vt.edu

Start date: June 1, 2015
Type of Project: Research
Amount Funded: $34,041

A. INTRODUCTION

The increased popularity of hard apple cider in recent years has created the opportunity for both large and small brands alike to compete in the alcoholic beverage market. As with beer and wine, there are ciders of varying quality and styles to appeal to a variety of consumers. Relatively little research has been done in cider production, especially when compared to the body of research-based knowledge available to commercial producers of beer and wine. In order for Virginia cidermakers to compete in the cider market, it is important that their cider production practices be informed by research specific to cider production. We aim to better understand the relationship between cider production practices and resulting product quality in order to provide practical resources and suggestions.

One area of interest to cider producers is the relationship between harvest maturity and cider quality. There have been decades of research dedicated to wine grape maturity and its impact on the resulting wines, but there is a lack of these studies for apples and ciders. It is therefore difficult to assess the extent to which orchard management practices influence cider quality. Apples at varying stages of maturity have different chemical compositions, with riper apples having higher sugar levels, higher levels of aroma compounds, and lower acidity. However, unripe apples may have a greater long-term storage potential due to lower ethylene concentrations at the onset of storage. Apples are able to be stored for long periods of time before processing, but the chemistry of apples may change during storage, making it necessary to understand the effects storage will have on apple, juice, and cider quality.

B. OBJECTIVE

Overall Objective: to understand how fruit maturity at harvest and post-harvest storage time and conditions affect the quality of the fruit, juice, and resulting cider in order to optimize processing conditions and desired cider characteristics.

Specific Objective 1: evaluation of effects of harvest maturity on fruit, juice, and cider quality.

Specific Objective 2: evaluation of effects of post-harvest storage on fruit, juice, and cider quality.

C. SUMMARY

The goal of this research is to better understand how pre-processing practices impact cider quality and how these practices can be applied for optimized cider characteristics. As outlined in the grant proposal, *Managing Apple Maturity and Storage to Increase the Quality of Virginia's Hard Ciders*, three cultivars were selected to study both harvest maturity and post-harvest storage of fruit and the resulting juices. Two of the three cultivars were processed into hard cider. Fruit, juice, and cider were analyzed for specific physical and chemical attributes.

For the harvest maturity study, there were three treatments and four biological replicates per cultivar, resulting in a total of 24 individual ciders between two cultivars. For the post-harvest storage study, there were four treatments and four biological replicates per cultivar, resulting in a total of 32 individual ciders between two cultivars. Therefore, throughout the study, a total of 56 individual ciders were produced and analyzed.

The data collected thus far has indicated that the experimental treatments resulted in substantial differences in the fruit and juice from both studies, with fewer differences persisting into the final ciders. This preliminary data from the first year of this study suggests that though harvest maturity and post-harvest storage of apples may significantly impact fruit and juice quality, these factors may not result in similarly important quality differences in the final cider product. If this result is consistently found in additional studies, it could allow cidermakers to have greater flexibility with their harvesting and fruit processing schedules without sacrificing quality.

D. MATERIALS & METHODS

Fruit: York apples were harvested from the Virginia Tech Alson H. Smith, Jr. Agricultural Research and Extension Center in Winchester, VA and Dabinett and Brown Snout apples were harvested from Cornell University's Research Orchard in Lansing, NY. All cultivars were evaluated for fruit and juice quality parameters for both objectives, and York and Dabinett juices were fermented into ciders. Figures 1 and 2 show the fruit, juice, and cider from each variety.

Figure 1: York juice, fruit, and cider (from left).

Figure 2: Dabinett cider, fruit, and juice (from left).

Experimental Treatments: For the maturity study, there were three treatments: fruit harvested 2 weeks before maturity, fruit harvested at maturity, and fruit harvested 2 weeks after maturity. "Maturity" harvest date was determined based on standard fruit maturity parameters for dessert fruit production. These treatments are outlined in Figure 3.

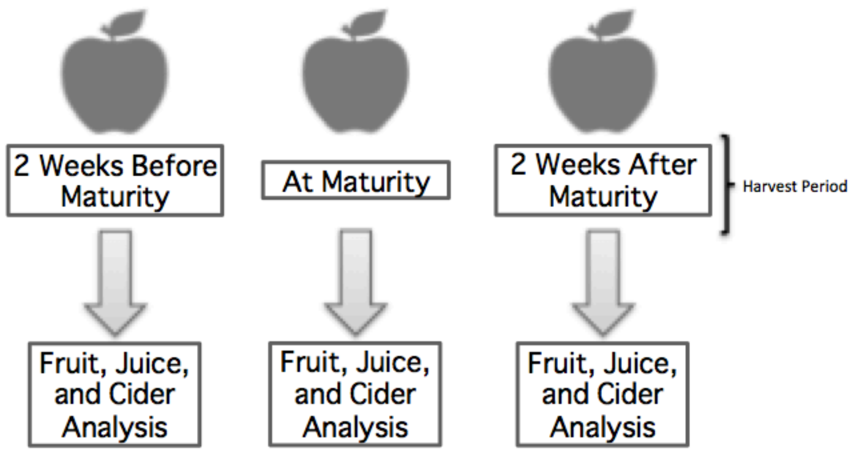

Figure 3: Outline of Harvest Maturity Experiment

For the storage study, fruit was harvested at standard fruit maturity and then stored, analyzed, and processed in four different treatments: at harvest, after 6 weeks of storage in 1°C conditions plus 24 hours at room temperature, after 6 weeks of storage in 10°C conditions plus 24 hours at room temperature, and after 4 months of storage in 1°C conditions plus 24 hours at room temperature. These experimental treatments are outlined in Figure 4.

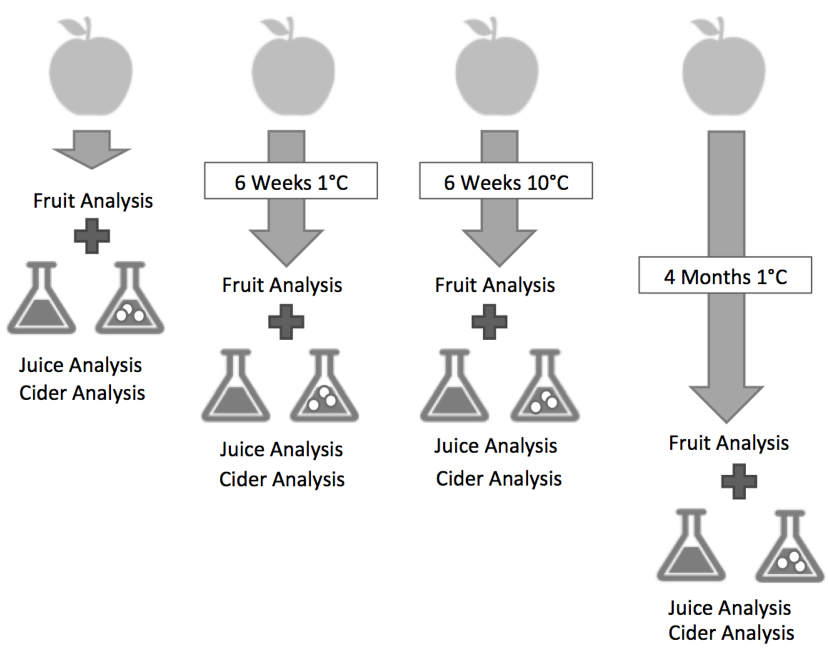

Figure 4: Outline of Post-Harvest Storage Experiment

Quality Parameters: Fruit quality was analyzed by measuring fruit firmness, fruit diameter, fruit weight, starch-iodine index, color, and ethylene concentration.

Juice quality was analyzed by measuring soluble solid concentration (SSC), pH, titratable acidity (TA), SSC to TA ratio (SSC:TA), total polyphenols, primary amino nitrogen (PAN), and ammonia.

Cider quality was analyzed by measuring residual sugar (RS), pH, TA, total polyphenols, total procyanidins, individual polyphenols, PAN, ammonia, free sulfites, and total sulfites.

Cider Fermentation: Juice was clarified using pectinase and settled overnight, then 750mL of juice was racked into 1L flasks. The juice was then treated with potassium metabisulfite, per standard commercial cidermaking practice. Then, the juice was inoculated using EC1118 yeast and a Fermaid K nutrient addition. The flasks were sealed using airlocks and then placed in a 18℃ temperature-controlled environmental chamber. Fermentation was monitored by weighing the flasks daily to measure CO_2 loss, then determining residual sugar levels when the rate of mass loss approached zero.

E. RESULTS AND DISCUSSION

Objective 1: Harvest Maturity

Fruit Quality

Table 1: Effects of Harvest Date on Fruit Maturity and Quality. Mean separation was analyzed separately for each cultivar.

	Treatment (harvest date)	Fruit Firmness (lbs)	Fruit Diameter (mm)	Fruit Weight (g)	Starch-Iodine Index (1-8)	Color*	Ethylene (ppm)
York	9/11/15	22.26±2.10 a	72.58±5.98 b	148.7±32.63 b	1.175±0.50 b	45.88±22.33 b	1.711±5.54 b
	9/25/15	19.52±1.75 b	77.86±5.93 a	179.9±41.97 a	1.85±1.16 a	75.25±15.48 a	8.08±51.06 ab
	10/9/15	19.62±1.82 b	78.17±6.65 a	185.3±42.85 a	2.288±1.24 a	81.25±13.34 a	11.73±23.16 a
Dabinett	9/9/15	28.97±2.08 a	50.55±4.60 a	49.2±12.58 b	1.25±0.49 b	30.5±18.53 b	0.0697±0.04 b
	9/23/15	25.94±2.47 b	52.74±5.05 a	59.93±16.23 a	2.225±0.90 a	57.63±18.94 a	5.97±35.34 ab
	10/6/15	26.64±2.29 b	52.34±4.68 a	57.2±14.79 a	2.6±1.15 a	57.25±23.91 a	22.96±25.49 a
Brown Snout	9/9/15	22.48±1.72 a	42.78±4.24 b	28.53±8.34 b	1.8±0.41 b	2.225±0.34 c	0.0152±0.06 c
	9/23/15	20.64±2.17 b	45.48±5.49 ab	39.42±14. 34 a	3.288±0.78 a	2.65±0.38 b	6.319±4.08 b
	10/6/15	20.1±1.94 b	48.15±5.7 a	44.45±14.39 a	3.513±0.8 a	2.913±0.49 a	17.5±16.47 a

* For York and Dabinett, Red Color is measured on a 0-100% scale, and for Brown Snout, Green Background Color is measured on a 1-4 scale.

As shown in Table 1, there were several quality parameters that showed significant differences between treatments. Fruit firmness generally decreased as maturity advanced, and fruit diameter increased with later harvest dates in both York and Brown Snout apples, but not in Dabinett apples. Fruit weight increased with later harvest dates in all three cultivars and starch-iodine index values decreased across all three cultivars. Both color and ethylene concentration increased with later harvest dates in all three cultivars. These findings are consistent with previous apple maturity studies [1-4].

Juice Quality

Table 2: Effects of Harvest Date on Juice Quality. Mean separation was analyzed separately for each cultivar.

	Treatment (harvest date)	**SSC (°Brix)**	pH	TA (g/L Malic Acid)	SSC:TA	Total Polyphenols (mg/L)	PAN (g N/L	Ammonia (g/L)
York	9/11/15	9.35±1.04 ab	3.483±0.10 a	1.299±0.21 a	1.889±0.20 a	75.57±3.65 b	0.078±0.07 a	ND
	9/25/15	7.875±0.50 b	3.53±0.13 a	1.277±0.12 a	1.511±0.12 a	88.33±1.82 a	0.05±0.01 a	ND
	10/9/15	9.5±0.42 a	3.402±0.20 a	1.252±0.17 a	1.957±0.33 a	60.89±8.10 c	0.038±0.02 a	ND
Dabinett	9/9/15	11.13±0.77 a	4.475±0.11 a	4.955±0.28 a	8.748±1.57 a	327.0±56.25 a	0.046±0.01 a	ND
	9/23/15	11.33±0.05 a	4.402±0.28 a	5.23±0.41 a	8.932±0.83 a	267.5±49.92 a	0.031±0.01 a	ND
	10/6/15	10.6±0.74 a	4.333±0.36 a	4.941±0.69 a	8.612±1.57 a	221.5±64.46 a	0.036±0.02 a	ND
Brown Snout	9/9/15	11.5±0.25 a	4.23±0.19 a	1.998±0.32 a	5.879±1.03 a	231.0±35.83 a	0.065±0.01 a	ND
	9/23/15	10.3±0.55 b	4.1±0.34 ab	2.413±0.27 a	4.292±0.31 a	203.5±45.15 a	0.041±0.02 ab	ND
	10/6/15	11.68±0.45 ab	3.78±0.27 b	2.788±0.46 a	4.288±0.82 a	159.0±40.28 a	0.031±0.01 b	ND

As shown in Table 2, Soluble solids concentration did not significantly differ between treatments in Dabinett juice, but was highest in the juice from fruit harvested 2 weeks after maturity for York and the juice from fruit harvested at maturity for Brown Snout. There were no significant differences in pH between treatments in York and Dabinett apples, but pH in Brown Snout juice was significantly highest in the juice from fruit harvested 2 weeks before maturity. There were no significant differences across cultivars in titratable acidity and SSC:TA. Significant differences in total polyphenols were only found in York apples with the highest concentration found in juice from fruit harvested at maturity and the lowest concentration found in juice from fruit harvested 2 weeks after maturity. PAN concentration significantly differed only in Brown Snout juice with the highest concentration found in juice from fruit harvested 2 weeks before maturity and the lowest concentration found in juice from fruit harvested 2 weeks after maturity. Ammonia was not detectable in any of the treatments across all three cultivars.

Cider Quality

Table 3: Effects of Harvest Maturity on Cider Quality (Condensed)

	Treatment (harvest date)	Residual Sugar (g/L)	Total Procyanidins (mg/L)
Dabinett	9/9/15	0.5083±0.43 b	0.0122±0.002 ab
	9/23/15	1.6400±0.01 a	0.0127±0.002 a
	10/6/15	1.4810±0.38 a	0.0064±0.004 b

Table 3 lists only the cider parameters measured with significant differences across experimental treatments. There were no parameters measured for York with significant differences between treatments, and only residual sugar and total procyanidins differed between treatments in Dabinett. There were higher residual sugar levels found in the ciders made from fruit harvested at maturity and fruit harvested 2 weeks after maturity. Higher concentrations of total procyanidins were found in cider made from fruit harvested at maturity and lower concentrations of total procyanidins were found in cider made from fruit harvested 2 weeks after maturity.

Summary of Objective 1 Results

From this data, fruit quality significantly differs between treatments in all three cultivars, and juice chemistry shows several significant differences between treatments. However, very few differences persist into the cider after fermentation despite the differences observed in the fruit and the juice.

Objective 2: Post-Harvest Storage

Fruit Quality

Table 4: Effects of Post-Harvest Storage on Fruit Maturity and Quality. Mean separation was analyzed separately for each cultivar.

	Treatment (Storage Condition)	Fruit Firmness (lbs)	Fruit Diameter (mm)	Fruit Weight (g)	Starch (1-8)	Color*	Ethylene (ppm)
York	At Harvest	20.10±1.54 a	74.65±6.22 a	160.18±38.19 a	2.063±1.46 c	65.38±19.92 b	1.47±1.01 c
	6 Weeks Storage 1°C	18.42±1.79 b	73.24±5.48 a	150.80±36.06 ab	4.262±1.29 b	89.1±101.17 ab	98.48±128.57 b
	6 Weeks Storage 10°C	15.82±1.59 c	73.54±5.18 a	155.50±35.25 ab	6.875±1.11 a	73.33±18.64 ab	236.56±227.51 a
	4 Months Storage 1°C	14.63±1.76 d	73.06±5.36 a	143.93±28.79 b	6.000±3.51 a	77.35±19.36 a	71.56±54.19 b
Dabinett	At Harvest	28.45±1.94 a	47.13±4.33 b	42.68±11.39 b	3.250±1.21 d	47.25±19.25 b	19.62±36.08 c
	6 Weeks Storage 1°C	22.47±3.09 b	48.01±5.37 b	45.68±14.27 ab	5.150±1.25 c	56.73±24.49 ab	51.52±100.94 b
	6 Weeks Storage 10°C	15.98±3.13 c	50.25±6.01 a	51.10±17.83 a	7.675±0.40 b	59.93±27.69 ab	304.0±264.24 a
	4 Months Storage 1°C	16.73±1.47 c	51.24±4.45 a	50.80±13.29 a	8.000±0.0 a	61.25±23.25 a	239.15±177.92 a
Brown Snout	At Harvest	23.06±2.98 a	43.04±5.83 a	34.55±12.57 ab	3.380±0.98 c	3.00±0.44 b	14.87±10.28 b
	6 Weeks Storage 1°C	18.28±1.83 b	45.36±3.85 a	38.90±8.14 a	6.090±1.27 b	2.91±0.32 b	133.64±186.74 b
	6 Weeks Storage 10°C	14.28±2.54 c	44.89±5.01 a	38.40±11.02 a	8.000±0.0 a	3.43±0.54 a	324.06±373.86 a
	4 Months Storage 1°C	ND	44.05±4.39 a	31.28±9.22 b	8.000±0.0 a	3.53±0.54 a	151.94±131.27 b

* For York and Dabinett, Red Color is measured on a 0-100% scale, and for Brown Snout, Green Background Color is measured on a 1-4 scale.

As shown in Table 4, fruit firmness was greatest at harvest for all three cultivars then significantly decreased with increased storage time. Fruit diameter was not significantly different between treatments in York and Brown Snout apples, but in Dabinett was significantly higher in the fruit stored for 6 weeks at 10°C and fruit stored for 4 months at 1°C. Fruit weight was greatest for York apples analyzed at harvest but was greatest in Dabinett fruit stored for 6 weeks at 10°C and fruit stored for 4 months at 1°C. Brown Snout fruit weight was greatest in the fruit stored for 6 weeks at 1°C and fruit stored for 6 weeks at 10°C. Both Starch-Iodine Index values and color values were lowest in fruit analyzed at harvest for all three cultivars. Ethylene concentration was lowest in fruit analyzed at harvest for all three cultivars. Both York and Brown Snout fruit had the highest ethylene concentrations in fruit stored for 6 weeks at 10°C, and Dabinett ethylene concentrations were highest in fruit stored for 6 weeks at 10°C and 4 months at 1°C

Juice Quality

Table 5: Effects of Post-Harvest Storage on Juice Quality. Mean separation was analyzed separately for each cultivar.

	Treatment (storage condition)	SSC (°Brix)	pH	TA (g/L malic acid)	SSC:TA	Total Polyphenols (mg/L)	PAN (g N/L)	Ammonia (g/L)
York	At Harvest	9.73±0.35 b	3.656±0.047 a	4.478±0.479 ab	2.191±0.254 b	94.74±9.98 b	0.060±0.020 a	ND
York	6 Weeks Storage 1C	9.3±0.90 ab	3.406±0.091 b	4.799±0.308 a	1.95±0.291 b	113.96±7.21 ab	0.073±0.041 a	ND
York	6 Weeks Storage 10C	10.23±0.48 ab	3.441±0.358 ab	2.668±0.408 bc	3.927±0.841 ab	93.13±10.82 b	0.051±0.014 a	ND
York	4 Months Storage 1C	10.80±0.497 a	3.434±0.250 ab	3.264±0.304 c	3.342±0.471 a	122.6±13.03 a	0.040±0.013 a	ND
Dabinett	At Harvest	11.80±0.80 b	4.698±0.023 a	1.114±0.140 a	10.69±1.18 a	335.5±44.85 b	0.038±0.016 a	ND
Dabinett	6 Weeks Storage 1°C	11.48±0.57 b	4.656±0.084 a	1.316±0.288 a	9.101±2.373 a	323.0±35.87 b	0.034±0.020 a	ND
Dabinett	6 Weeks Storage 10°C	11.6±1.29 ab	4.484±0.153 ab	1.059±0.216 a	11.19±1.965 a	343.5±65.21 b	0.030±0.018 a	ND
Dabinett	4 Months Storage 1°C	14.3±1.374 a	4.372±0.075 b	1.374±0.140 a	10.51±1.594 a	482.0±67.75 a	0.029±0.016 a	ND
Brown Snout	At Harvest	12.85±0.24 c	4.306±0.151 a	2.298±0.051 b	5.594±0.148 a	243.5±11.36 a	0.031±0.012 a	ND
Brown Snout	6 Weeks Storage 1°C	12.35±1.29 c	3.947±0.188 ab	2.603±0.229 b	4.80±0.863 a	248.0±59.96 a	0.020±0.008 a	ND
Brown Snout	6 Weeks Storage 10°C	15.93±0.56 b	4.029±0.192 b	2.78±0.275 ab	5.767±0.551 a	322.0±81.68 a	0.040±0.011 a	ND
Brown Snout	4 Months Storage 1°C	17.03±0.32 a	4.156±0.111 ab	3.186±0.129 a	5.35±0.227 a	281.0±21.21 a	0.024±0.013 a	ND

As shown in Table 5, SSC was highest in the juice from fruit stored for 4 months at 1°C across all three cultivars. The pH in York and Brown Snout juice was lowest in juice from fruit processed at harvest, and pH was lowest in Dabinett apples in both the juice from fruit processed at harvest and juice from apples stored for 6 weeks at 1°C. TA did not significantly differ between treatments in Dabinett apples, but was significantly highest in York juice made from fruit stored for 6 weeks at 1°C and in Brown Snout juice made from fruit stored for 4 months at 1°C . There were no significant differences in SSC:TA between Dabinett and Brown Snout treatments. However, for York juice, SSC:TA was highest in the juice made from apples stored for 4 months at 1°C. Total polyphenols concentrations in York and Dabinett juices were highest in juice made from fruit stored for 4 months at 1°C. Brown Snout juice did not show significant differences in polyphenol concentrations between treatments. There were no significant differences in PAN concentration between treatments in any of the three cultivars. Ammonia was not detectable in any of the York, Dabinett, or Brown Snout juices.

Cider Quality

Table 6: Effects of Post-Harvest Storage on Cider Quality (Condensed). Mean separation was analyzed separately for each cultivar.

	Treatment (storage condition)	Residual Sugar (g/L)	Total Polyphenols (mg/L)	Total Procyanidins (mg/L)	Free SO_2 (mg/L)	Total SO_2 (mg/L)
York	At Harvest	0.418±0.07 a	50.92±5.64 b	ND	0.469±0.31 a	12.504±1.53 a
York	6 Weeks Storage 1C	0.384±0.22 a	71.09±12.96 a	ND	0.469±0.18 a	11.488±1.56 b
York	6 Weeks Storage 10C	0.010±0.01 b	55.87±8.55 ab	ND	0.021±0.04 a	6.460±0.902 c
York	4 Months Storage 1C	0.213±0.20 ab	61.58±10.34 ab	ND	0.313±0.36 a	7.424±1.581 c
Dabinett	At Harvest	1.285±0.284 a	412.2±49.81 a	0.010±0.002 b	0.547±0.156 a	19.538±1.64 a
Dabinett	6 Weeks Storage 1°C	1.319±0.131 a	423.2±38.26 a	0.016±0.003 ab	0.313±0.0 ab	7.503±3.31 b
Dabinett	6 Weeks Storage 10°C	0.920±0.58 a	401.70±36.16 a	0.012±0.001 ab	0.313±0.0 ab	11.645±3.12 b
Dabinett	4 Months Storage 1°C	0.508±0.43 a	495.20±82.51 a	0.017±0.001 a	0.156±0.18 b	11.176±1.21 b

Table 6 shows those parameters with significant differences in one or more cultivar. Many of the parameters showed no significant differences between treatments. York cider residual sugar was lowest in the cider made from apples that were stored for 6 weeks at 10°C. Total polyphenols in York cider was lowest in the cider made from apples processed at harvest and highest in cider made from apples stored for 6 weeks at 1°C. Dabinett ciders made from apples stored for 4 months at 1°C had the greatest concentration in total procyanidins. Free sulfites in Dabinett cider was highest in the cider made from apples processed at harvest and lowest in the cider made from apples stored for 4 months at 1°C. Total sulfites in York and Dabinett were highest in the cider made from apples processed at harvest.

Summary of Objective 2 Results

Though there were many differences between treatments concerning fruit and juice characteristics, there were fewer differences found in the different cider storage treatments. This indicates that though storage conditions may greatly influence the physical and chemical characteristics of the fruit and juice, few differences persist into the final cider.

F. CONCLUSIONS AND FUTURE WORK

The first year of data indicates that harvest timing and storage durations and conditions may have a limited impact on the cider quality even when there are significant impacts on fruit and juice quality. The data also show that certain quality parameters are cultivar-dependent. Therefore, further research is necessary to ascertain the effects of harvest maturity and post-harvest storage on additional cultivars used for cidermaking. Furthermore, the impact of the growing season cannot be assessed within one year. For example, seasons with colder weather during the harvest window may result in smaller differences between treatments, while warmer growing season could lead to greater changes in fruit chemistry during the harvest window. Growing season conditions were not expected to influence the post-harvest storage experiment, however fruit maturity when fruit is placed into storage is expected to significantly influence the outcome. For these reasons, we will continue this project investigating new cultivars important for cider production in a second year, with continuing funding from the Virginia Wine Board.

G. IMPACT STATEMENT

The results of this study were presented to 60 commercial apple growers and cider makers on June 16, 2016 at a Commercial Cider Production Workshop organized by Virginia Tech Cooperative Extension (organizers were Dr. Greg Peck, Dr. Amanda Stewart, and Mark Sutphin) at the Virginia Tech Alson H. Smith, Jr. Agriculture Research and Extension Center. Published research results and research-based recommendations with regards to the influence of orchard management and pre-processing practices on cider quality are not currently available. This research project represents an important first step toward developing practical research-based recommendations for cider makers, taking into account both crop production and processing systems.

H. PUBLICATIONS/PRESENTATIONS OF THIS AND RELATED RESEARCH

Ewing, B. *Effect of Harvest Maturity and Post-Harvest Storage on Fruit, Juice, and Cider Quality.* Food Science and Technology Poster Session. 2016. Virginia Tech.

Ewing, B. *Effect of Harvest Maturity and Post-Harvest Storage on Fruit, Juice, and Cider Quality*. 2016. Commercial Cider Production Workshop. Virginia Tech Cooperative Extension.

REFERENCES

1. Lea, A.G.H. and J.-F. Drilleau, *Cidermaking*, in *Fermented Beverage Production*, A.G.H. Lea and J.R. Piggot, Editors. 2003, Springer Science+Business Media New York: New York. p. 59-87.

2. Burg, S.P. and E.A. Burg, *Ethylene Action and the Ripening of Fruits.* Science, 1965. **148**(3674): p. 1190-1196.

3. Song, J. and F. Bangerth, *The effect of harvest date on aroma compound production from 'Golden Delicious' apple fruit and relationship to respiration and ethylene production.* Postharvest Biology and Technology, 1996. **8**(4): p. 259-269.

4. Girard, B. and O.L. Lau, *Effect of maturity and storage on quality and volatile production of 'Jonagold' apples.* Food Research International, 1995. **28**(5): p. 465-471.