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ARTICLE

Evaluation of selected cider apple (*Malus domestica* Borkh.) cultivars grown in Ontario. II. Juice attributes[1]

Derek J. Plotkowski and John A. Cline

Abstract: Twenty-eight apple cultivars were selected for their potential for hard cider production in Ontario; their juice characteristics were measured in 2017 and 2018, beginning two years after planting in 2015. After being harvested and pressed, each juice sample underwent analyses to determine soluble solids concentration (SSC), titratable acidity (TA), pH, yeast assimilable nitrogen (YAN), and polyphenolic concentration. Soluble solids concentration ranged from 10.6 °Brix in Brown's Apple to 18.3 °Brix in Ashmead's Kernel. Titratable acidity ranged from 31 as mg malic acid per 100 mL juice in Sweet Alford to 191 as mg malic acid per 100 mL juice in Bramley's Seedling. The pH ranged from 2.88 in Breakwell to 4.76 in Sweet Alford. Yeast assimilable nitrogen concentration ranged from 60 mg YAN·L^{-1} juice in Medaille d'Or to 256 mg YAN·L^{-1} juice in Bulmer's Norman. Polyphenols in juice ranged from 131 μg gallic acid equivalents (gae)·mL^{-1} juice in Tolman Sweet to 1042 μg gae·mL^{-1} juice in Stoke Red. Firmness ranged from 6.3 kg in Yarlington Mill to 11.7 kg in GoldRush. The relationships between these variables were also analyzed, showing a connection between acidity and juicing efficiency as well as a relationship between polyphenol concentration and fruit weight. Exploratory analyses indicated that juice attributes can be used to distinguish between cultivars and their origins. Cider producers can use these data to determine what to expect in juice from these cultivars.

Key words: YAN, titratable acidity, pH, soluble solids, polyphenols, apple juice, hard cider, cider cultivars.

Résumé : Les auteurs ont choisi 28 cultivars de pomme susceptibles de servir à la production de cidre en Ontario, puis ont mesuré les propriétés de leur jus en 2017 et 2018, soit deux ans après la plantation, en 2015. Après récolte et extraction, le jus a subi diverses analyses qui ont permis d'établir la concentration de solides solubles, l'acidité totale, le pH, la quantité d'azote assimilable par les levures et la concentration de polyphénols. La concentration de solides solubles varie de 10,6 °Brix pour la variété Brown's Apple à 18,3 °Brix pour la variété Ashmead's Kernel. L'acidité totale fluctuait pour sa part de 31 mg d'acide malique par 100 ml pour le jus de Sweet Alford à 191 mg d'acide malique par 100 ml pour celui de Bramley's Seedling. Le pH variait de 2,88 chez Breakwell à 4,76 pour Sweet Alford. La concentration d'azote assimilable par les levures allait de 60 mg par litre de jus chez Medaille d'Or à 256 mg par litre de jus pour Bulmer's Norman. La concentration de polyphénols dans le jus fluctuait de 131 μg en équivalent d'acide gallique par millilitre de jus chez Tolman Sweet à 1 042 μg en équivalent d'acide gallique par millilitre de jus pour Stoke Red. Enfin, la fermeté variait de 6,3 kg pour Yarlington Mill à 11,7 kg pour GoldRush. Les auteurs ont également analysé les liens entre ces variables et découvert une relation entre l'acidité et l'efficacité d'extraction du jus, de même qu'un lien entre la concentration de polyphénols et le poids du fruit. Les premières analyses indiquent qu'on pourrait utiliser les paramètres du jus pour différencier les cultivars et leurs origines. Les cidriculteurs pourront se servir de ces données pour déterminer à quoi s'attendre avec le jus des variétés étudiées. [Traduit par la Rédaction]

Mots-clés : azote assimilable par les levures, acidité totale, pH, solides solubles, polyphénols, jus de pomme, cidre, pommes à cidre.

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Introduction

Cider production

When making cider, producers usually blend the juices of several apple cultivars to achieve the desired physicochemical characteristics for the best fermentation and final product. Many cider makers choose apples using the cider apple classification system developed by the former Long Ashton Research Station (LARS) in the United Kingdom (Lea 2015). This approach was useful when the system was developed at the beginning of the 20th century; however, with more accurate and complex analytical methods to determine juice components, there is greater ability to discriminate between juices destined for cider production.

The year-to year variation in juice attributes like polyphenols and titratable acidity (TA) make the juice of apple cultivars somewhat difficult to categorize. An apple juice characterized as bittersharp one year may be a classified as bittersweet the next. Ideally, classification based on data from several seasons would be used, but it is even better for cider makers to conduct these measurements each year to make decisions for that season. Nevertheless, the aim of classifying cultivars is to determine what is expected from the orchard. If the cider maker desires a consistent cider from year to year, then knowing the averages will be helpful. This study was conducted to provide more information to cider producers on the attributes of the juices extracted from the 28 cultivars when grown in Ontario, while a concurrent study was conducted to evaluate the horticultural attributes of those same cultivars (Plotkowski and Cline 2021).

Juice attributes

Juice composition affects both the production and flavour of cider. Nitrogen availability, sugar concentration, and pH influence the growth and metabolism of fermentation microorganisms (Kelkar and Dolan 2012). Titratable acidity and polyphenols have traditionally been used to classify apple cultivars for their flavour (Mangas Alonso and Blanco Gomis 2010; Lea 2015).

In cider production, the first role of sugar is to act as a substrate for yeast to convert to pyruvate via glycolysis and then to ethanol and CO_2 via alcoholic fermentation (Mangas Alonso 2010). Post-fermentation residual sugar is the source of the perception of sweetness in cider. Measuring sugar in juice by refractometry or specific gravity, a measure of juice density, before fermentation allows cider makers to predict alcohol production, plan how to blend ciders, and make any desired corrections through exogenous sugar addition (Merwin et al. 2008).

The two main functions of acids in cider production, similar to those of sugar, are to influence fermentation, which is associated with pH, and to influence the flavour of the final cider, which is associated with TA. The pH of a juice affects the survival of yeast, beneficial bacteria, like *Leuconostoc* spp., and spoilage microorganisms, like *Pedioccus* spp. and *Lactobacillus* spp., in addition to influencing the formation of H_2S, biogenic amines, and volatile acids (Toit and Pretorius 2000). The pH in alcoholic fermentation media is considered to be high if it is above 3.5. Below this concentration, the pH favours the growth of desirable microorganisms (Toit and Pretorius 2000). Titratable acidity, on the other hand, is a metric that describes the quantity of molecules or functional groups that can lose protons (that is, be titrated) (Iland 2004). These acids, primarily malic acid in apple juice, as well as lactic and acetic acid in finished ciders, are perceived as a sour flavour when consumed in a cider (González San José 2010; Wu et al. 2007).

Polyphenols are a class of compounds that include tannins. All polyphenols contain multiples of the aromatic organic chemical structures known as phenols. Historically, polyphenols were measured with the Lowenthal–Permanganate method as tannic acid (Alexander et al. 2016). These measurements were used to establish juice classifications of bittersharp and bittersweet. Other methods, like the Folin–Ciocalteu, bovine serum albumin, and dimethylaminocinnamaldehyde methods, are also used to assess polyphenols, though they may lack sensitivity or specificity to polyphenol compounds and still do not discriminate amongst the compounds as effectively as high-performance liquid chromatography. Direct comparisons among these methods are complicated by the varying ratios they produce when performed on the same samples (Ma et al. 2019).

In addition to the low polyphenol concentrations of most apple cultivars used for North American cider production (WIlson et al. 2003; Thompson-Witrick et al. 2014; Peck et al. 2016; Cline et al. 2021), there is significant variation between years when comparing fruit from the same orchard (Alexander et al. 2016). The major phenolics in these apples, which are primarily for culinary use, are chlorogenic acid and protocatechuic acid (Wu et al. 2007). Although procyanidins and catechin polymers are known to contribute to the perception of bitterness and astringency, it is difficult to quantify sensory impact based on polyphenol composition and total polyphenol concentration (Le Quéré et al. 2006; Thompson-Witrick et al. 2014). Martin et al. (2017) investigated the idea of adding commercial tannin to make up for the lack of high-tannin cider apples in North America. In their sensory study, the most highly rated ciders were those with some tannins and moderate residual sugar concentrations (Martin et al. 2017). In addition to being affected by the competing flavours of acidity and sweetness, polyphenol perception is affected by the degree of polymerization of procyanidins (Symoneaux et al. 2014*a*, 2014*b*). Astringency is associated with greater polymerization of procyanidins in cider, while bitterness is higher in medium- than in short- or long-chain polymers (Symoneaux et al. 2014*a*, 2014*b*). Adding exogenous polyphenols to influence

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these flavours has not improved cider taste; however, horticultural and oenological methods of improving polyphenols to achieve desirable sensory characteristics show promise. On the horticultural side, increasing crop load in the orchard has been demonstrated to increase post-fermentation polyphenol concentration in York apples (Peck et al. 2016). On the oenological side, addressing fruit processing could allow for greater polyphenol extraction from apple peels, which usually have more polyphenols compared with the flesh (Thompson-Witrick et al. 2014).

While important from a plant nutrition perspective, nitrogen in cider production is most often discussed in terms of yeast assimilable nitrogen (YAN) and the fermentation process. yeast assimilable nitrogen comprises ammonium and primary amino acids, which make up the fraction of nitrogen in a fermentation medium that is biologically available to yeast (Bell and Henschke 2005). Yeast require nitrogen as a nutrient for growth and reproduction, which is key for a consistent fermentation. Amino acids are not used in a consumptive way in cider production; rather, they are recycled through yeast autolysis and reuptake (Suárez Valles et al. 2005). yeast assimilable nitrogen is measured by enzymatic assay, formol titration, or ammonium ion electrodes (for ammonium) (Bell and Henschke 2005).

Most cultivars for cider production produce juice with low YAN. Cider producers often correct for these low levels by adding nitrogen in the cellar, via the addition of either diammonium phosphate or commercial yeast nutrient formulations (Jolicoeur 2013; Merwin et al. 2008). Horticultural and oenological practices also influence YAN. In contrast to N supplementation, many cider producers manipulate nitrogen concentrations by reducing the amount of nitrogen to induce a longer fermentation (Le Quéré et al. 2006).

Other places of study

Some North American studies have looked at the juice parameters of cider apples in specific regions, such as New York (Valois et al. 2006), Virginia (Thompson-Witrick et al. 2014), Québec (Provost 2018), Vermont (Bradshaw et al. 2018), and Washington (Miles et al. 2017). The variations in parameters among the cultivars examined across studies point to differences in climate, terrain, and horticultural practices. In the aforementioned studies, researchers analyzed the juice by measuring sugars, acids, polyphenols, and nitrogenous compounds. At Washington State University, researchers compared and contrasted Brown Snout, Dabinett, Kingston Black, and Yarlington Mill apples grown in northwest and central Washington (Alexander et al. 2016). It was observed that the growing region, cultivar, and annual variation did not influence juice SSC, pH, TA, or tannins (Alexander et al. 2016). Moreover, the cultivars in question did not align with the Long Ashton Research Station (LARS) classification of the same apples grown in Britain. Nevertheless, testing the attributes every year was considered important to account for the juice attributes of a particular growing season (Alexander et al. 2016).

Objectives of the study

The objectives of this study were to determine the juice characteristics of 28 apple cultivars selected for cider production in Ontario and specifically to measure sugar concentration, TA, pH, polyphenol concentration, and YAN concentration. A second, exploratory objective, was to examine the relationships among the juice attributes across cultivars.

Materials and Methods

Plant materials

The main experiment consisted of 28 apple cultivars grafted onto M.9 T337 rootstock. The budwood was sourced from Canada and trees were propagated and grown by a commercial nursery in Watford, Ontario (Warwick Orchards & Nursery). The cultivars were Ashmead's Kernel, Breakwell, Brown's Apple, Bulmer's Norman, Binet Rouge, Bramley's Seedling, Brown Snout, Calville Blanc d'Hiver, Crimson Crisp®, Cox Orange Pippin, Cline Russet, Dabinett, Enterprise, Esopus Spitzenberg, Fréquin Rouge, GoldRush, Grimes Golden, Golden Russet, Kingston Black, Michelin, Muscadet de Dieppe, Medaille d'Or, Porter's Perfection, Sweet Alford, Stoke Red, Tydeman Late, Tolman Sweet, and Yarlington Mill. The apple cultivars were selected by consultation with members of the Ontario Craft Cider Association, with special attention being paid to cultivars that had a historical reputation for cider production in Europe and North America as well as those with a noted tannin concentration. These cultivars were then sourced within Canada, as no virus-free certified budwood was available outside of Canada at the time of propagation, which limited the breadth of available cultivars.

Orchard management

In the spring of 2015, the trees were planted at the Simcoe Research Station (Simcoe, ON). They received regular treatment and care and integrated pest management for disease and insect pests according to the local recommendations of the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA 2016). The trees in this experiment were planted in a randomized complete block, with four blocks of five trees for each of 28 cultivars. The five-tree blocks of each cultivar consisted of two guard trees at either and three data trees in the middle. Trees were spaced 1 m within and 4.5 m between rows (1667 trees·ha^{-1}). At planting, the trees were headed and trained to a wire trellis in a vertical axis training system. The trellis system was equipped with drip irrigation for each tree to supplement natural rainfall.

Fruit collection

In the fall of 2017 and 2018, fruit at the Simcoe location were collected from the guard trees before harvest to determine maturity. Ripeness analyses were done by harvesting a total of five fruit taken from the two guard trees in each block, usually consisting of two fruit from one tree and three fruit from the other. These were generally taken two weeks before their projected harvest date based on data from other sites, although some trees were harvested ahead of the projected schedule. These five fruit were weighed and photographed whole with a digital camera (Nikon, Tokyo). They were then halved transversely and seeded. Half of each apple was photographed, as were its seeds. Notes were taken on seed and fruit colour. Half of each apple was then dipped in iodine, rated, and photographed.

All fruit on the data trees, which were the centre three trees in the set of five trees, were harvested when the guard tree fruit was measured at 40% flesh stain on the Cornell generic starch–iodine test scale, which corresponds to a rating of 6 (Blanpied and Silsby 1992). After harvesting, apples were either processed into juice immediately or stored at 0–1 °C until processing, typically within a week.

Juicing

For juicing, five representative fruit from each tree were selected from each replicate for a total of 15 fruit per replicate. Fruit weight of the 15 apples was recorded on an analytical scale (LC 3200D, Sartorius, Bohemia, NY). Afterward, the fruit were sectioned to fit into the feed tube and ground in the fruit juicer (Model 8006, Omega, Harrisburg, PA) using the grinding attachment, which does not separate the juice from the pomace. The ground fruit was then placed in cheesecloth (Grade #50, Fisher Scientific, Whitby, ON) on a custom-made stainless-steel rack-and-cloth set (Allingham Machining Inc., Stoney Creek, ON). This was used in conjunction with a PowerFist hydraulic press (Princess Auto, Hamilton, ON). Any separated juice from the juicer was poured over the ground fruit before closing the cheesecloth packet. Once the cheesecloth packet was closed, another steel plate was placed on top along with a pressing plate. The hydraulic press was pressed down to 17 000 kPa, released once the juice stopped running freely into a graduated cylinder, and pressed down to 17 000 kPa once more. The volume of juice production was recorded and used in conjunction with the fruit weight to calculate the juice extraction efficiency as mL juice per g fruit. The racks were washed between each use. A 50-mL aliquot of juice was set aside and frozen at −80 °C for downstream polyphenol analysis. All other juice analyses were performed immediately or within a day of pressing while storing the juice at 0–1 °C.

Juice analyses

The soluble solid concentration was measured using a temperature compensating refractometer (Pocket 7105 PALBXIAcid5, Atago, Tokyo, Japan). The lens was washed with distilled water between measurements and wiped with a delicate task wiper (Kimwipes, Kimberly-Clark, Mississauga, ON).

For polyphenol analysis, a 2-mL aliquot of each juice sample was transferred to an Eppendorf tube and centrifuged for 10 min in a centrifuge (Legend Micro 21, Thermo Fisher, Mississauga, ON). Thereafter, 0.5 mL of the supernatant was transferred to a new Eppendorf tube containing 1.5 g of polyvinylpolypyrrolidone (PVPP), with the rest of the supernatant reserved. The mixture of supernatant and PVPP was then centrifuged for 10 min. The PVPP was used to precipitate out the polyphenols to measure interfering compounds. The samples, along with water blanks and gallic acid standards (0–500 $mg \cdot L^{-1}$ gallic acid in water), were plated onto a 96-well microplate (Thompson-Witrick et al. 2014). Folin–Ciocalteu reagent (Sigma Aldrich) was added to the samples on the plate. The plate was incubated for an hour before adding sodium bicarbonate solution and being read in the microplate reader (Epoch 2, BioTek, Winooski, VT) at 765 nm. The polyphenol concentration was calculated by taking the difference between the untreated samples and samples treated with PVPP. These differences were transformed using a standard curve created using the standard solutions (Thompson-Witrick et al. 2014).

Each time it was used, the pH meter (pH 700 Benchtop Meter, Oakton Instruments, Vernon Hills, IL) was calibrated using standards (Fisher Scientific, Whitby, ON) of 4.0, 7.0, and 10.0. The pH electrode was rinsed with distilled water and wiped with a Kimwipe in between measurements, which were taken directly by placing the electrode in the juice sample. Titratable acidity was measured using an autotitrator (G20 Compact Titrator, Mettler Toledo, Mississauga, ON) programmed to an endpoint of pH = 8.2 using a 0.01 M NaOH solution. The titrator was calibrated with pH standards of 4.0, 7.0 and 8.0. Five millilitres of juice was then mixed with 45 mL of distilled water and run through the autotitrator. The volume of 0.01 M NaOH required to titrate the medium to the endpoint pH of 8.2 was used to calculate TA with the acid millequivalence (meq.) factor for malic acid (eq 1).

$$\text{(1)}\quad \text{Titratable acidity(TA)} = \frac{\text{mL NaOH} \times \text{N(NaOH)} \times 0.067\ \text{acid meq. factor} \times 100}{\text{mL juce titrated}}$$

Table 1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017 (University of Guelph, Simcoe, Ontario, 2017).

Cultivar	Titratable acidity (as mg malic acid per 100 mL juice)		Soluble solids (°Brix)		Juice pH		Juice yeast assimilable nitrogen (mg YAN·L^{-1} juice)		Corrected juice polyphenols (µg gae per mL juice)[a]	
Ashmead's Kernel	95	ef	18.3	a	3.45	hi	148	bcd	366	fgh
Binet Rouge	37	k	15.1	d–h	4.44	c	104	d–g	915	ab
Bramley's Seedling	145	bc	12.7	jkl	3.00	n	73	fg	276	gh
Breakwell	158	b	11.4	lm	3.08	mn	69	fg	446	e–h
Brown Snout	58	ij	16.4	bcd	4.09	ef	170	ab	580	c–f
Brown's Apple	102	e	10.6	m	3.33	jk	116	c–f	781	bc
Bulmer's Norman	36	k	11.7	kl	4.07	ef	152	bcd	738	bcd
Calville Blanc d'Hiver	132	cd	14.1	g–j	3.19	lm	91	fg	317	fgh
Cline Russet	60	hi	14.5	fgh	3.74	g	82	fg	230	h
Cox Orange Pippin	82	fg	15.7	c–f	3.49	hi	146	bcd	256	gh
Crimson Crisp®	74	gh	13.7	hij	3.54	h	104	d–g	271	gh
Dabinett	82	fg	14.9	e–h	3.50	hi	145	b–e	256	gh
Enterprise	102	e	14.2	ghi	3.41	ijk	118	c–f	246	h
Esopus Spitzenberg	97	ef	15.4	d–g	3.38	ijk	113	c–f	250	gh
Frequin Rouge	32	k	16.0	b–e	4.61	b	148	bcd	515	d–g
Golden Russet	85	fg	17.2	ab	3.48	hi	174	ab	380	fgh
GoldRush	92	ef	12.9	ijk	3.29	kl	82	fg	246	h
Grimes Golden	93	ef	13.8	hij	3.48	hi	81	fg	275	gh
Kingston Black	86	efg	14.0	g–j	3.49	hi	80	fg	437	e–h
Medaille d'Or	137	cd	15.3	d–g	3.18	lm	60	g	557	def
Michelin	43	jk	13.0	ij	4.17	e	145	b–e	564	c–f
Muscadet De Dieppe	40	k	12.9	ijk	3.98	f	97	efg	693	b–e
Porter's Perfection	121	d	14.6	fgh	3.30	kl	104	d–g	925	ab
Stoke Red	101	e	12.8	ijk	3.42	hij	78	fg	1042	a
Sweet Alford	31	k	15.7	c–f	4.76	a	82	fg	208	h
Tolman Sweet	34	k	14.6	e–h	4.45	c	155	bc	185	h
Tydeman Late	176	a	17.1	abc	3.18	lm	206	a	314	fgh
Yarlington Mill	40	k	14.1	g–j	4.30	d	83	fg	737	bcd
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

Note: Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means. Colour scale is used to indicate value as a visual aid. Red is used for the lowest values, which scales up to blue for the highest values. YAN, yeast assimilable nitrogen; gae, gallic acid equivalents.

[a]Corrected juice polyphenols = uncorrected juice polyphenols – juice ascorbic acid interference.

The YAN concentration was measured using a formol titrator and associated parts (HI84533, Hanna Instruments, Laval, QC) at formol calibration standards. The instrument's pH meter was calibrated with pH standards of 4.1, 7.1, and 8.2. The injector was calibrated on the low concentration setting. For each assay, 10 mL of juice was diluted with 40 mL of distilled water, and then titrated to pH = 8.2. Once the solution was titrated, 4 mL of formaldehyde was added and the solution was re-titrated. The machine calculated and reported the final value as the formol number.

Firmness was measured by slicing off 1–2 mm of skin with a sharp razor to create flat surfaces on opposite equatorial ends of the apple. Each cut end was then placed on a Fruit Texture Analyzer (Güss Instruments, South Africa), which recorded the firmness by determining the force required to penetrate fruit flesh with an 11-mm diameter probe (Abbott et al. 1976). This was repeated on both sides of each of five apples in every sample before the fruit was juiced.

Statistical analyses

Data were analyzed using a generalized linear mixed model (the GLIMMIX procedure) in SAS 9.4 (The SAS Institute, Cary, NC). Significance was evaluated at a *p* value of 0.05 and residuals were analyzed for normality and outliers. Post-hoc means separation was analyzed

Table 2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 (University of Guelph, Simcoe, Ontario, 2018).

Cultivar	Titratable acidity (as mg malic acid per 100 mL juice)		Soluble solids (°Brix)		Juice pH		Juice yeast assimilable nitrogen (mg YAN·L^{-1} juice)		Corrected juice polyphenols (μg gae per mL juice)[a]		Fruit firmness (N)	
Ashmead's Kernel	108	cde	16.1	abc	3.31	i–l	169	bcd	372	e–i	9.4	bcd
Binet Rouge	43	jk	13.8	def	4.41	ab	185	bc	880	ab	10.7	ab
Bramley's Seedling	191	a	11.9	ef	2.70	p	133	c–f	373	e–i	9.3	b–f
Breakwell	190	a	12.8	def	2.88	o	103	def	436	e–h	7.4	g–j
Brown Snout	77	gh	17.6	a	4.01	ef	158	b–e	577	def	6.8	hij
Brown's Apple	114	cd	11.8	f	3.39	h–k	154	b–e	799	a–d	6.4	ij
Bulmer's Norman	63	hi	13.3	def	4.15	de	256	a	923	a	8.3	d–h
Calville Blanc d'Hiver	125	bc	12.9	def	3.21	lmn	104	def	258	ghi	6.7	hij
Cline Russet	86	fg	14.0	cde	3.53	gh	123	c–f	188	hi	8.5	c–g
Cox Orange Pippin	110	cde	12.3	ef	3.08	mn	167	b–e	230	ghi	7.5	f–j
Crimson Crisp®	86	fg	11.9	ef	3.40	hij	128	c–f	180	hi	8.7	c–g
Dabinett	104	c-f	13.0	def	3.19	lmn	151	b–f	188	hi	6.8	hij
Enterprise	102	def	13.9	c–f	3.54	gh	139	b–f	225	ghi	7.8	f–j
Esopus Spitzenberg	116	cd	14.9	bcd	3.60	g	152	b–e	222	hi	9.3	b–f
Frequin Rouge	53	ijk	16.4	ab	4.39	bc	149	b–f	639	b–e	9.6	bc
Golden Russet	113	cd	16.4	ab	3.48	ghi	207	ab	315	f–i	11.7	a
GoldRush	123	bcd	13.8	def	3.42	hi	145	b–f	189	hi	9.9	bc
Grimes Golden	91	efg	12.4	ef	3.44	ghi	82	f	277	ghi	8.1	d–h
Kingston Black	112	cde	14.1	cde	3.23	klm	110	def	493	efg	9.2	b–f
Medaille d'Or	171	a	16.8	ab	3.03	no	120	c–f	875	abc	10.8	ab
Michelin	50	ijk	12.8	def	3.95	f	168	bcd	585	cde	7.8	e–i
Muscadet De Dieppe	46	ijk	14.0	cde	4.11	def	101	def	567	def	7.0	hij
Porter's Perfection	138	b	14.0	c–f	3.24	j–m	138	b–f	865	abc	9.1	c–f
Stoke Red	120	bcd	13.6	def	3.39	h–k	148	b–f	876	ab	7.5	f–j
Sweet Alford	35	k	13.0	def	4.57	a	98	ef	131	i	7.6	f–j
Tolman Sweet	49	ijk	13.5	def	4.26	bcd	134	c–f	228	ghi	10.0	bc
Tydeman Late	179	a	16.3	ab	3.12	mn	157	b–e	259	ghi	9.2	b–f
Yarlington Mill	57	hij	16.7	ab	4.24	cd	132	c–f	640	b–e	6.3	j
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

Note: Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means. Colour scale is used to indicate value as a visual aid. Red is used for the lowest values, which scales up to blue for the highest values. YAN, yeast assimilable nitrogen; gae, gallic acid equivalents.

[a]Corrected juice polyphenols = uncorrected juice polyphenols – juice ascorbic acid interference

using the Tukey–Kramer grouping for least square means ($\alpha = 0.05$).

To understand the relationships among juice variables, exploratory statistical analyses including principal component analysis, cluster analysis,and discriminant analysis were (the PRINCOMP, FASTCLUS, and DISCRIM procedures) performed in SAS 9.4 (The SAS Institute, Cary, NC). The suitability of the discriminant analyses was analyzed with a χ^2 test.

Results

Juice attributes

In 2017, SSC ranged from 10.6 °Brix for Brown's Apple to 18.3 °Brix for Ashmead's Kernel (Table 1). The five cultivars with the highest soluble solid contents were Ashmead's Kernel (18.3 °Brix), Golden Russet (17.2 °Brix), Tydeman Late (17.1 °Brix), Brown Snout (16.4 °Brix), and Fréquin Rouge (16.0 °Brix). In 2018, SSC ranged from 11.8 °Brix for Brown's Apple to 17.6 °Brix for Brown Snout (Table 2). The five cultivars with the highest soluble solid contents were Brown Snout (17.6 °Brix), Medaille d'Or (16.8 °Brix), Yarlington Mill (16.7 °Brix), Golden Russet (16.4 °Brix), and Fréquin Rouge (16.4 °Brix).

In 2017, juicing efficiency ranged from 0.48 mL juice·g^{-1} fruit for Muscadet de Dieppe to 0.72 mL juice·g^{-1} fruit for GoldRush (Table 3). The five cultivars with the highest juicing efficiency in 2017 were GoldRush (0.72 mL juice·g^{-1} fruit), Bramley's Seedling (0.69 mL juice·g^{-1} fruit), Bulmer's Norman (0.68 mL juice·g^{-1} fruit), Crimson Crisp® (0.68 mL juice·g^{-1} fruit), and Cline Russet (0.67 mL juice·g^{-1} fruit). In 2018, juicing efficiency ranged from 0.36 mL juice·g^{-1} fruit for

Table 3. Historical titratable acidity of 28 apple cultivars grown for cider production harvested.

Cultivar	Titratable acidity at Simcoe (mg malic acid·100 mL^{-1} juice)	Historical titratable acidity	References[a]
Ashmead's Kernel	95–108	1.17% malic; 10.40–10.78 g·L^{-1} malic	5; 2
Binet Rouge	37–43	0.15% malic	7
Bramley's Seedling	145–191	1.05–1.21% acid; 1.54% malic; 10.07 g·L^{-1}	4; 5; 9
Breakwell	158–190	0.64% malic; 7.82 g·L^{-1}	7; 9
Brown Snout	58–77	0.47 g malic acid·100 g^{-1} juice; 3.37 g·L^{-1} malic; 1.05 g·L^{-1} malic	13; 9; 2
Brown's Apple	102–114	0.67% malic; 7.29 g· L^{-1} malic; 8.0–12.5 g·L^{-1} malic	4; 9; 6
Bulmer's Norman	36–63	0.24% malic; 2.16 g·L^{-1} malic; 2.2–4.9 g·L^{-1} malic	7; 9; 6
Calville Blanc d'Hiver	125–132	0.73 g malic acid·100 g^{-1} juice; 0.76 %–1.17 malic; 9.97 g·L^{-1} malic	12; 5; 2
Cline Russet	60–86	New cultivar, no historical data available	
Cox Orange Pippin	82–110	0.68%–0.76% acid; 0.90% malic	4; 5
Crimson Crisp	74–86	8.85 g·L^{-1} malic	2
Dabinett	82–104	0.10–16 g malic acid·100 g^{-1} juice; 2.55 g malic·L^{-1}; 1.10–1.88 g·L^{-1} malic	12; 9; 2
Enterprise	102	9.35 g·L^{-1} malic	11
Esopus Spitzenberg	97–116	7.10 g·L^{-1} malic	2
Frequin Rouge	32–53	2.62 g·L^{-1} malic	9
Golden Russet	85–113	0.46%–0.54 g malic acid·100 g^{-1} juice; 0.73% malic; 6.64 g malic·L^{-1}	12; 5; 9
GoldRush	92–123	0.61–0.78 g malic acid·100 g^{-1} juice; 9.35 g·L^{-1} malic	12; 11
Grimes Golden	91–93	6.6 g·L^{-1} malic; 6.75 g·L^{-1} malic	10; 9
Kingston Black	86–112	0.67 g malic acid·100 g^{-1} juice; 6.45 g malic·L^{-1}; 1.5–2.6 g·L^{-1} malic	12; 9; 3
Medaille d'Or	137–171	0.27% malic; 3.43 g·L^{-1} malic; 2.1 g·L^{-1} malic	7; 9; 1
Michelin	43–50	0.24–0.27 g malic acid·100 g^{-1} juice; 3.25 g malic·L^{-1}; 2.5 g·L^{-1} malic	12; 9; 3
Muscadet De Dieppe	40–46	2.72 g·L^{-1} malic; 2.8 g·L^{-1} malic	9; 6
Porter's Perfection	121–138	0.70–88 g malic acid·100 g^{-1} juice; 13 g·L^{-1} malic; 8.2 g·L^{-1} malic	12; 6; 3
Stoke Red	101–120	0.64% malic; 6.13 g·L^{-1} malic	7; 9
Sweet Alford	31–35	0.22% malic; 1.86 g·L^{-1} malic	7; 9
Tolman Sweet	34–49	No historical data found	
Tydeman Late	176–179	No historical data found	
Yarlington Mill	40–57	0.22% malic; 2.7 g·L^{-1} malic; 2.59 g·L^{-1} malic; 1.67 g·L^{-1} malic; 1.3–4.5 g·L^{-1} malic	7; 10; 8; 2; 6

[a]Historical values are reported in the same order as the source listing cited the following numbers: (1) Boré and Fleckinger 1997; (2) Bradshaw et al. 2018; (3) Copas 2001; (4) Copas 2010; (5) Eisele and Drake 2005; (6) Jolicoeur 2013; (7) Lea 2015; (8) Gottschalk et al. 2017; (9) Miles et al. 2013; (10) Raboin 2016; (11) Thompson-Witrick et al. 2014; (12) Valois et al. 2006.

Muscadet de Dieppe to 0.68 mL juice·g^{-1} fruit for Crimson Crisp® (Table 4). The five cultivars with the highest juicing efficiency in 2018 were Crimson Crisp® (0.68 mL juice·g^{-1} fruit), Brown's Apple (0.66 mL juice·g^{-1} fruit), Grimes Golden (0.66 mL juice·g^{-1} fruit), GoldRush (0.66 mL juice·g^{-1} fruit), and Enterprise (0.65 mL juice·g^{-1} fruit).

In 2017, the concentration of polyphenols (corrected for interfering compounds) in juice ranged from 185 μg gallic acid equivalents (gae)·mL^{-1} juice for Tolman Sweet to 1042 μg gae·mL^{-1} juice for Stoke Red (Table 1). The five cultivars with the highest polyphenol concentrations in 2017 were Stoke Red (1042 μg gae·mL^{-1} juice), Porter's Perfection (925 μg gae·mL^{-1} juice), Binet Rouge (915 μg gae·mL^{-1} juice), Brown's Apple (781 μg gae·mL^{-1} juice), and Bulmer's Norman (738 μg gae·mL^{-1} juice). In 2018, the corrected concentration of polyphenols in juice ranged from 131 μg gae·mL^{-1} juice for Tolman Sweet to 923 μg gae·mL^{-1} juice for Bulmer's Norman (Table 2). The five cultivars with the highest polyphenol concentrations in 2018 were Bulmer's Norman (923 μg gae·mL^{-1} juice), Binet Rouge (880 μg gae·mL^{-1} juice), Stoke Red (876 μg gae·mL^{-1} juice), Medaille d'Or (875 μg gae·mL^{-1} juice), and Porter's Perfection (865 μg gae·mL^{-1} juice).

In 2017, the pH ranged from 3.00 for Bramley's Seedling to 4.76 for Sweet Alford (Table 1). The five

Table 4. Historical pH of 28 apple cultivars grown for cider production.

Cultivar	pH at Simcoe	Historical pH	References[a]
Ashmead's Kernel	3.31–3.45	3.55; 3.03–3.25	3; 1
Binet Rouge	4.41–4.44	No historical data found	
Bramley's Seedling	2.70–3.00	2.95–3.08; 3.37; 3.26	2; 3; 4
Breakwell	2.88–3.08	3.23	4
Brown Snout	4.01–4.09	3.95; 3.87; 3.78	7; 4; 1
Brown's Apple	3.33–3.39	3.28	4
Bulmer's Norman	4.07–4.15	4.04	4
Calville Blanc d'Hiver	3.19–3.21	3.28; 3.64; 3.13	7; 3; 1
Cline Russet	3.53–3.74	New cultivar, no historical data available	
Cox Orange Pippin	3.08–3.49	3.30-3.48; 3.70	2; 3
Crimson Crisp	3.40–3.54	3.37	1
Dabinett	3.19–3.50	4.39; 4.37; 4.13–4.15	7; 4; 1
Enterprise	3.41–3.54	3.76	6
Esopus Spitzenberg	3.38–3.60	3.48	1
Frequin Rouge	4.39–4.61	4.19	4
Golden Russet	3.48	3.61–3.65; 3.79; 3.67	7; 3; 4
GoldRush	3.29–3.42	3.19–3.22; 3.49	7; 6
Grimes Golden	3.44–3.48	3.57; 3.42	5; 4
Kingston Black	3.23–3.49	3.47; 3.45	7; 4
Medaille d'Or	3.03–3.18	4.19	4
Michelin	3.95–4.17	4.04–4.08; 3.98	7; 4
Muscadet De Dieppe	3.98–4.11	4.12	4
Porter's Perfection	3.24–3.30	3.31–3.36	7
Stoke Red	3.39–3.42	3.67	4
Sweet Alford	4.57–4.76	4.43	4
Tolman Sweet	4.26–4.45	No historical data found	
Tydeman Late	3.12–3.18	No historical data found	
Yarlington Mill	4.24–4.30	4.49; 4.13; 3.78	5; 4; 1

[a]Historical values are reported in the same order as the source listing cited the following numbers: (1) Bradshaw et al. 2018; (2) Copas 2010; (3) Eisele and Drake 2005; (4) Gottschalk et al. 2017; (5) Raboin 2016; (6) Thompson-Witrick et al. 2014; (7) Valois et al. 2006.

cultivars with the lowest pH in 2017 were Bramley's Seedling (2.99), Breakwell (3.08), Tydeman Late (3.17), Medaille d'Or (3.17), and Calville Blanc d'Hiver (3.19). In 2018, the pH ranged from 2.88 for Breakwell to 4.57 for Sweet Alford (Table 2). The five cultivars with the lowest pH in 2018 were Bramley's Seedling (2.70), Breakwell (2.88), Medaille d'Or (3.03), Cox Orange Pippin (3.08), and Tydeman Late (3.12).

In 2017, TA ranged from 31 as mg malic acid per 100 mL juice for Sweet Alford to 176 as mg malic acid per 100 mL juice for Tydeman Late (Table 1). The top five cultivars in 2017 were Tydeman Late (176 as mg malic acid·100 mL^{-1} juice), Breakwell (158 as mg malic acid·100 mL^{-1} juice), Bramley's Seedling (145 as mg malic acid·100 mL^{-1} juice), Medaille d'Or (137 as mg malic acid·100 mL^{-1} juice), and Calville Blanc d'Hiver (132 as mg malic acid·100 mL^{-1} juice). In 2018, TA ranged from 35 as mg malic acid per 100 mL juice for Sweet Alford to 191 as mg malic acid per 100 mL juice for Bramley's Seedling (Table 2). The top five cultivars in 2018 were Bramley's Seedling (191 as mg malic acid·100 mL^{-1} juice), Breakwell (190 as mg malic acid·100 mL^{-1} juice), Tydeman Late (179 as mg malic acid·100 mL^{-1} juice), Medaille d'Or (171 as mg malic acid·100 mL^{-1} juice), and Porter's Perfection (138 as mg malic acid·100 mL^{-1} juice).

In 2017, the YAN concentration ranged from 60 mg YAN·L^{-1} juice for Medaille d'Or to 206 mg YAN·L^{-1} juice for Tydeman Late (Table 1). The five cultivars with the highest concentrations of YAN in 2017 were Tydeman Late (206 mg YAN·L^{-1} juice), Golden Russet (174 mg YAN·L^{-1} juice), Brown Snout (170 mg YAN·L^{-1} juice), Tolman Sweet (155 mg YAN·L^{-1} juice), and Bulmer's Norman (152 mg YAN·L^{-1} juice). In 2018, the YAN concentration ranged from 82 mg YAN·L^{-1} juice for Kingston Black to 256 mg YAN·L^{-1} juice for Bulmer's Norman (Table 2). The five cultivars with the highest concentrations of YAN in 2018 were Bulmer's Norman (256 mg YAN·L^{-1} juice), Golden Russet (207 mg YAN·L^{-1} juice), Binet Rouge (185 mg YAN·L^{-1} juice), Ashmead's Kernel (169 mg YAN·L^{-1} juice), and Michelin (168 mg YAN·L^{-1} juice).

While fruit firmness was not measured in 2017, in 2018, it ranged from 6.3 N for Yarlington Mill to 11.7 N for GoldRush (Table 2). The five firmest fruit in 2018 were

Fig. 1. The association among juice attributes of fruits measured in 28 apple cultivars grown on M.9. rootstock for cider production. (Polyphenols refers to the concentration of polyphenols found in juice samples; Brix refers to the measured soluble solids concentration in juice samples; DaysToHarvest refers to the number of days between the start of full bloom and the harvest of a cultivar; Formol refers to the yeast assimilable nitrogen concentration measured in juice samples; JuiceEff refers to the amount of juice obtained per weight of fruit that was pressed; pH refers to the pH found in juice samples; TA refers to the titratable acidity measured in juice samples). University of Guelph, Simcoe, Ontario, 2018.

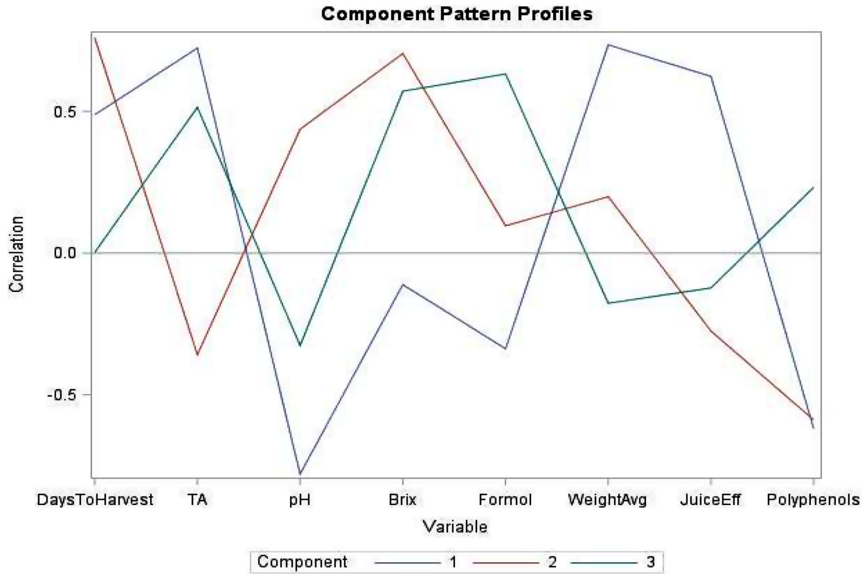


Table 5. Classification summary for the juice attributes of cider cultivars based on geographical origin. University of Guelph, Simcoe, Ontario, 2018.

From origin	France	North America	United Kingdom	Total
France	30[a]	10	7	47
	64[b]	21	15	100
North America	3	58	2	63
	5	92	3	100
United Kingdom	32	16	79	127
	25	13	62	100
Total	65	84	88	237
	27	35	37	100
Priors	0.3333	0.33333	0.33333	

[a]Number of observations classified onto origin.
[b]Percent classified into origin.

Golden Russet (11.7 N), Medaille d'Or (10.8 N), Binet Rouge (10.7 N), Tolman Sweet (10.0 N), and GoldRush (9.9 N). The five softest cultivars in 2018 were Yarlington Mill (6.3 N), Brown's Apple (6.4 N), Calville Blanc d'Hiver (6.7 N), Brown Snout (6.8 N), and Dabinett (6.8 N).

Multivariate analyses

The principal component analysis indicated that 83% of the horticultural variance among the cultivars could be attributed to four clusters. The first cluster explained 35% of the variance and was mostly influenced by TA, fruit weight, and juicing efficiency (Fig. 1). The second cluster explained 23% of the variance and it was most influenced by the number of days until harvest, SSC, and pH. The third cluster explained 15% of the variance and was mostly influenced by YAN, soluble solids, and TA. The fourth cluster accounted for 10% of the variance and was influenced by YAN, juicing efficiency, and fruit weight.

The discriminant analyses showed that using juice attributes, classification by origin was successfully predicted in 73% of observations and that classification by cultivar was successfully predicted in 90% of observations. A χ^2 test at 95% confidence indicated a goodness of fit for both origin and cultivar (Table 5).

Table 6. Historical soluble solids concentrations of 28 apple cultivars grown for cider production.

Cultivar	Soluble solids (°Brix) at Simcoe	Historical soluble solids	References[a]
Ashmead's Kernel	16.1–18.3	15.98 °Brix; 17.6–18.0 °Brix	5; 2
Binet Rouge	13.8–15.1	14.2 °Brix	10
Bramley's Seedling	11.9–12.7	40–51 sg[y], 13.18 °Brix; 11.1 °Brix	4; 5; 8
Breakwell	11.4–12.8	10.9 °Brix	8
Brown Snout	16.4–17.6	18.06 °Brix; 15.4 °Brix; 13.5 °Brix; 18.2 °Brix	12; 10; 8; 2
Brown's Apple	10.6–11.8	48 sg; 13.6 °Brix; 10.8 °Brix; 45–65 sg	4; 10; 8; 6
Bulmer's Norman	11.7–13.3	13.6 °Brix; 11.4 °Brix; 14.6 °Brix; 48–66 sg	10; 8; 7; 6
Calville Blanc d'Hiver	12.9–14.1	13.85 °Brix; 14.70–14.96 °Brix; 15.3 °Brix	12; 5; 2
Cline Russet	14.0–14.5	New cultivar, no historical data available	
Cox Orange Pippin	12.3–15.7	50–75 sg; 15.32 °Brix; 13.0 °Brix	4; 5; 7
Crimson Crisp	11.9–13.7	14.4 °Brix	2
Dabinett	13.0–14.9	13.22–13.83 °Brix; 14.0 °Brix; 15.1 °Brix; 13.1–15.3 °Brix	12; 8; 7; 2
Enterprise	13.9–14.2	13.0 °Brix	11
Esopus Spitzenberg	14.9–15.4	14.9 °Brix; 15.3 °Brix	7; 2
Frequin Rouge	16.0–16.4	17.0 °Brix; 11.7 °Brix	10; 8
Golden Russet	16.4–17.2	15.14–18.05 °Brix; 18.32 °Brix; 16.9 °Brix	12; 5; 8
GoldRush	12.9–13.8	11.52–14.30 °Brix; 15.0	12; 11
Grimes Golden	12.4–13.8	14.0 °Brix; 12.8 °Brix	9; 8
Kingston Black	14.0–14.1	16.16 °Brix; 13.4 °Brix; 52–56 sg	12; 8; 3
Medaille d'Or	15.3–16.8	15.8 °Brix; 58 sg	8; 1
Michelin	12.8–13.0	11.74 °Brix, 14.9 °Brix; 12.0; 50sg	12; 10; 3
Muscadet De Dieppe	12.9–14.0	14.7 °Brix; 46–63 sg	8; 6
Porter's Perfection	14.0–14.6	13.87–14.97 °Brix; 53–66 sg	12; 6
Stoke Red	12.8–13.6	12.3° Brix; 52 sg	8; 3
Sweet Alford	13.0–15.7	11.9 °Brix	8
Tolman Sweet	13.5–14.6	15.0 °Brix	7
Tydeman Late	16.3–17.1	No historical data found	
Yarlington Mill	14.1–16.7	15 °Brix; 12.3 °Brix; 12.2 °Brix; 53–75 sg	9; 8; 2; 6

[a]Historical values are reported in the same order as the source listing cited the following numbers: (1) Boré and Fleckinger 1997; (2) Bradshaw et al. 2018; (3) Copas 2001; (4) Copas 2010; (5) Eisele and Drake 2005; (6) Jolicoeur 2013; (7) Gottschalk et al. 2017; (8) Miles et al. 2013; (9) Raboin 2016; (10) Rothwell 2012; (11) Thompson-Witrick et al. 2014; (12) Valois et al. 2006.

Discussion

Evaluation criteria for juice

Given that any attribute of juice can be balanced by blending, a high-quality juice is one that is rich in a specific attribute, be it an attribute measured in this study or another factor such as aroma (Merwin et al. 2008). Cultivars that are rich in a specific attribute can be added to a more neutral base to create the desired concentration of that attribute. For example, for a cider lacking in acidity, a cider maker may choose to blend in additional Bramley's Seedling juice, whereas Bulmer's Norman would be a good addition for needed polyphenols. Microbial stability based on pH, alcohol potential based on sugars, and fermentation capability based on nitrogen should also be considered. The attributes of the juice must be considered in conjunction with horticultural attributes for an orchardist to make the best decisions for planting in the orchard.

Historical TA measurements range from 1.86 $g \cdot L^{-1}$ juice as malic acid in Sweet Alford to 12.5 $g \cdot L^{-1}$ juice as malic acid in Brown's Apple (Jolicoeur 2013; Miles et al. 2017) (Table 3), while historical pH measurements range from 2.95 in Bramley's Seedling to 4.49 in Yarlington Mill (Copas 2013; Miles et al. 2017) (Table 4). In this study, most of the apple cultivars were more acidic than suggested by historical data, having higher TA values, although units and methodology did differ across studies. The pH values were typically in the same range as historical data, though Dabinett, Enterprise, Golden Russet, Medaille d'Or, and Stoke Red had low pH values and Fréquin Rouge had a high pH value when compared with other sources (Eisele and Drake 2005; Valois et al. 2006; Thompson-Witrick et al. 2014; Miles et al. 2017; Bradshaw et al. 2018) (Tables 1, 2, and 4).

Historical sugar concentrations in the apple cultivars in this study range from 10.9 °Brix in Breakwell to 18.2 °Brix in Brown Snout (Miles et al. 2017; Bradshaw et al.

Table 7. Historical polyphenol and tannin concentrations of 28 apple cultivars grown for cider production.

Cultivar	Corrected juice polyphenols (μg gae·mL^{-1} juice) at Simcoe	Historical polyphenols	References[a]
Ashmead's Kernel	366–372	0.07%–0.075% tannin	2
Binet Rouge	880–915	0.21% tannin	6
Bramley's Seedling	276–373	0.09%–0.14% tannin; 0.12% tannin	4; 7
Breakwell	436–446	0.23% tannin; 0.27% tannin	6; 7
Brown Snout	577–580	310 ± 58 gae·100 g^{-1}; 0.19% tannin; 0.21% tannin	10; 7; 2
Brown's Apple	781–799	0.14% tannin; 0.16% tannin; 0.58 g/L gae	4; 7; 5
Bulmer's Norman	738–923	0.27% tannin; 0.22% tannin; 1.8 g/L gae	6; 7; 5
Calville Blanc d'Hiver	258–317	210 ± 16 gae·100 g^{-1}; 0.07% tannin	10; 2
Cline Russet	188–230	New cultivar, no historical data available	
Cox Orange Pippin	230–256	0.04%–0.05% tannin	4
Crimson Crisp	180–271	0.11% tannin	2
Dabinett	188–256	346 ± 42 gae·100 g^{-1}, 297 ± 63 gae·100 g^{-1}; 0.29% tannin; 0.109%–37% tannin	10; 7; 2
Enterprise	225–246	398 mg gae·L^{-1}	9
Esopus Spitzenberg	222–250	0.035% tannin	2
Frequin Rouge	515–639	0.38 % tannin	7
Golden Russet	315–380	236 ± 30 gae·100 g^{-1}, 148 ± 17 gae·100 g^{-1}; 0.13% tannin	10; 7
GoldRush	189–246	150 ± 31 gae·100 g^{-1}, 324 ± 32 gae·100^{-1}; 359 mg gae·L–^{1}	10; 9
Grimes Golden	275–277	0.12% tannin; 0.08% tannin	8
Kingston Black	437–493	308 ± 37 gae·100 g^{-1}; 0.17% tannin; 1.9 g·L^{-1} tannic acid	10; 7; 3
Medaille d'Or	557–875	0.64% tannin; 1.05% tannin; 4.4 g·L^{-1} tannic acid	6; 7; 1
Michelin	564–585	253 ± 35 gae·100 g^{-1}, 641 ± 68 gae·100 g^{-1}; 0.16% tannin; 2.3 g·L^{-1} tannic acid	10; 7; 3
Muscadet De Dieppe	567–693	0.19% tannin; 1.0 g·L^{-1} gallic acid	7; 5
Porter's Perfection	865–925	246 ± 16 gae·100 g^{-1}, 328 ± 12 gae·100 g^{-1}	10
Stoke Red	876–1042	0.31% tannin; 0.32% tannin	6; 7
Sweet Alford	131–208	0.15% tannin; 0.10% tannin	6; 7
Tolman Sweet	185–228	No historical data found	
Tydeman Late	259–314	No historical data found	
Yarlington Mill	640–737	0.32% tannin; 0.20% tannin; 0.21% tannin; 0.35% tannin; 1.9 g·L^{-1} gae	6; 8; 7; 2; 5

Note: gae, gallic acid equivalents.

[a]Historical values are reported in the same order as the source listing cited the following numbers: (1) Boré and Fleckinger 1997; (2) Bradshaw et al. 2018; (3) Copas 2001; (4) Copas 2010; (5) Jolicoeur 2013; (6) Lea 2015; (7) Gottschalk et al. 2017; (8) Raboin 2016; (9) Thompson-Witrick et al. 2014; (10) Valois et al. 2006.

2018) (Table 6). Cultivars in the current study that were higher in sugar compared with historical data were Breakwell, Enterprise, Stoke Red, and Sweet Alford. Cultivars that were lower in sugar compared with historical data were Muscadet de Dieppe and Tolman Sweet (Copas 2001; Jolicoeur 2013; Thompson-Witrick et al. 2014; Gottschalk et al. 2017; Miles et al. 2017) (Tables 1, 2, and 6). The range of sugar concentrations in all other cultivars overlapped with historical data. When compared with historical data, most cultivars were within or close to the range of sugar concentrations reported elsewhere, though both Sweet Alford and Stoke Red had higher sugar concentrations in Simcoe than in other locations.

Historical tannin concentrations in cider apples range from 0.04% tannin in Esopus Spitzenberg to 1.05% tannin in Medaille d'Or (Miles et al. 2017; Bradshaw et al. 2018) (Table 7). Differences in methodology make it challenging to directly compare the current polyphenol results and historical tannin data. Because polyphenol measurement methods vary so greatly, direct comparisons between historical data sources and these data can only be made where methodologies were comparable. Of those, five cultivars had higher polyphenol concentrations in Simcoe than at other North American sites: Brown Snout, Calville Blanc d'Hiver, Golden Russet, Kingston Black, and Porter's Perfection. Two cultivars had lower polyphenol concentrations in Simcoe than at other North American sites: Dabinett, and Enterprise (Copas 2001; Valois et al. 2006; Thompson-Witrick et al. 2014; Miles et al. 2017; Bradshaw et al. 2018) (Tables 1, 2, and 7).

Table 8. Historical yeast assimilable nitrogen (YAN) concentrations of 28 apple cultivars grown for cider production.

Cultivar	Juice formol (mg YAN·L^{-1} juice) at Simcoe	Historical YAN concentrations	References[a]
Ashmead's Kernel	148–169	166.3–262.6 mg YAN·L^{-1}	1
Binet Rouge	104–185	No historical data found	
Bramley's Seedling	73–133	No historical data found	
Breakwell	69–103	No historical data found	
Brown Snout	158–170	94 ± 19 mg YAN·L^{-1}; 97 mg YAN·L^{-1}	2; 1
Brown's Apple	116–154	No historical data found	
Bulmer's Norman	152–256	No historical data found	
Calville Blanc d'Hiver	91–104	45.2 ± 8.5 mg YAN·L^{-1}; 86.31 g YAN·L^{-1}	2; 1
Cline Russet	82–123	New cultivar, no historical data available	
Cox Orange Pippin	146–167	No historical data found	
Crimson Crisp	104–128	170 mg YAN·L^{-1}	1
Dabinett	145–151	13.3 ± 1.9 mg YAN·L^{-1}, 45 ± 20 mg YAN·L^{-1}; 31.79–60.6 g YAN·L^{-1}	2; 1
Enterprise	118–139	No historical data found	
Esopus Spitzenberg	113–152	113.4 mg YAN·L^{-1}	1
Frequin Rouge	148–149	No historical data found	
Golden Russet	174–207	66 ± 11 mg YAN·L^{-1}, 76.1 ± 9.5 mg YAN·L^{-1}	2
GoldRush	82–145	13.8 ± 2.7 mg YAN·L^{-1}, 36.3 ± 2.5 mg YAN·L^{-1}	2
Grimes Golden	81–82	No historical data found	
Kingston Black	80–110	24.4 ± 5.6 mg YAN·L^{-1}	2
Medaille d'Or	60–120	No historical data found	
Michelin	145–168	20.3 ± 1.9 mg YAN·L^{-1}, 58.2 ± 9.0 mg YAN·L^{-1}	2
Muscadet De Dieppe	97–101	No historical data found	
Porter's Perfection	104–138	50 ± 23 mg YAN·L^{-1}, 110 ± 12 mg YAN·L^{-1}	2
Stoke Red	78–148	No historical data found	
Sweet Alford	82–98	No historical data found	
Tolman Sweet	134–155	No historical data found	
Tydeman Late	157–206	No historical data found	
Yarlington Mill	83–132	8.88 mg YAN·L^{-1}	1

[a]Historical values are reported in the same order as the source listing cited the following numbers: (1) Bradshaw et al. 2018; (2) Valois et al. 2006.

Most cultivars for cider have low YAN, with historical measurements ranging from 9 mg YAN·L^{-1} in Yarlington Mill to 262 mg YAN·L^{-1} in Ashmead's Kernel. All YAN measurements in this study were higher than those found in other sources, but methodology differed among the sparse historical data sources (Valois et al. 2006; Bradshaw et al. 2018) (Tables 1, 2, and 8).

Associations among attributes

To understand how juice attributes were related to one another, a cluster analysis was run on the dataset. Some notable attribute associations included average fruit weight and juicing efficiency, as well as sugar concentration and the number of days from full bloom to harvest (Fig. 2).

Component pattern charts of the principal components detailed in Fig. 1 indicated natural groups of associated variables that are reflective of the above-listed components (Fig. 3). In contrast to our hypothesis, polyphenols were not a major factor in any of the components. This indicates that polyphenol concentration acts somewhat independently of the other factors, which supports its use as a criterion for juice classification and distinction.

A discriminant analysis (Table 5) of origin based on juice attribute data indicated that North American cultivars were distinct enough from British and French cultivars to be classified as North American 92% of the time. French cultivars were classified as French 64% of the time and British cultivars correctly classified 62% of the time, which supports the prediction the juice attributes of the cultivars are distinct based on their origin. The distinguishing attributes of North American cultivars are large fruit size, long length of time to harvest, low pH, high juicing efficiency, and low polyphenol values. French cultivars are often distinguished based on their low TA, high pH, low fruit weight, low juicing efficiency, and high polyphenols. British cultivars could be distinguished by their high polyphenols, low pH, and high TA.

Fig. 2. The correlation of juice attributes to principal components derived from the juice attribute data of 28 apple cultivars grown on M.9. rootstock for cider production. (DaysToHarvest refers to the number of days between the start of full bloom and the harvest of a cultivar; TA refers to the titratable acidity measured in juice samples; pH refers to the pH found in juice samples; Brix refers to the measured soluble solids concentration in juice samples; Formol refers to the yeast assimilable nitrogen concentration measured in juice samples; WeightAvg refers to the average weight of the individual apples that were pressed; JuiceEff refers to the amount of juice obtained per weight of fruit that was pressed; polyphenols refers to the concentration of polyphenols found in juice samples). University of Guelph, Simcoe, Ontario, 2018.

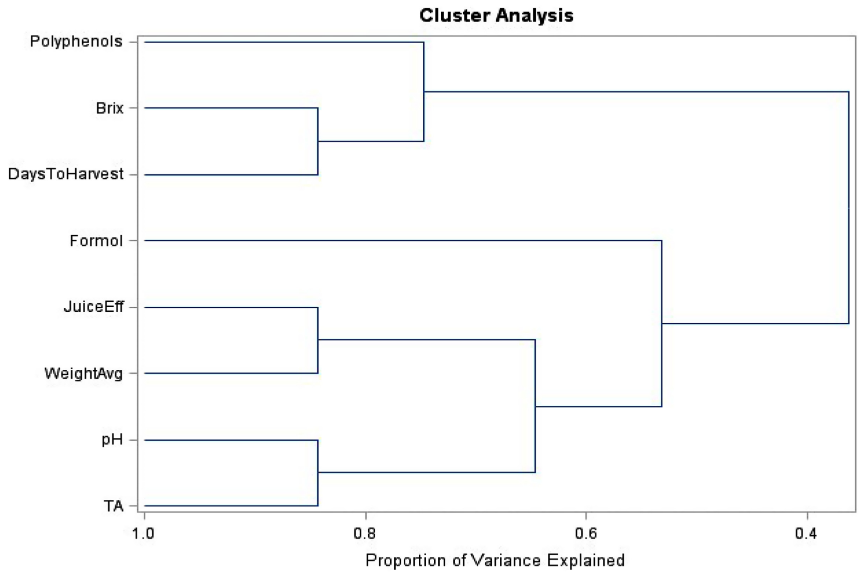


Fig. 3. Plot of juice attributes based on the first two principal components derived from the juice attribute data of 28 apple cultivars grown on M.9. rootstock for cider production. (DaysToHarvest refers to the number of days between the start of full bloom and the harvest of a cultivar; TA refers to the titratable acidity measured in juice samples; pH refers to the pH found in juice samples; Brix refers to the measured soluble solids concentration in juice samples; Formol refers to the yeast assimilable nitrogen concentration measured in juice samples; WeightAvg refers to the average weight of the individual apples that were pressed; JuiceEff refers to the amount of juice obtained per weight of fruit that was pressed; polyphenols refers to the concentration of polyphenols found in juice samples). University of Guelph, Simcoe, Ontario, 2018.

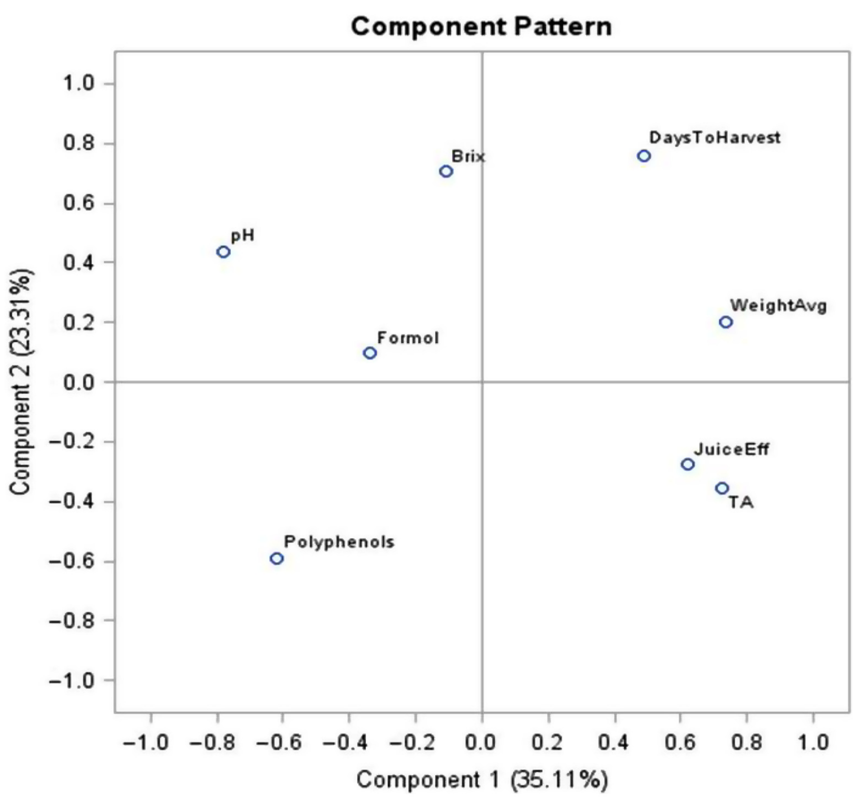


Table 9. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin (University of Guelph, Simcoe, Ontario, 2018).

Cultivar origin	Soluble solids (°Brix)	Titratable acidity (mg malic acid·100 mL^{-1} juice)[a]	Juice pH	Juice formol (mg YAN·L^{-1} juice)	Corrected juice polyphenols (μg gae · mL^{-1} juice)[b]	Fruit firmness (kg)
France	12.6	74b	3.91a	123	771a	8.7ab
North America	12.4	88b	3.59b	126	409b	9.2a
United Kingdom	12.4	101a	3.56b	136	684a	7.9b
P value	0.7879	0.0006	<0.0001	0.1308	<0.0001	<0.0001

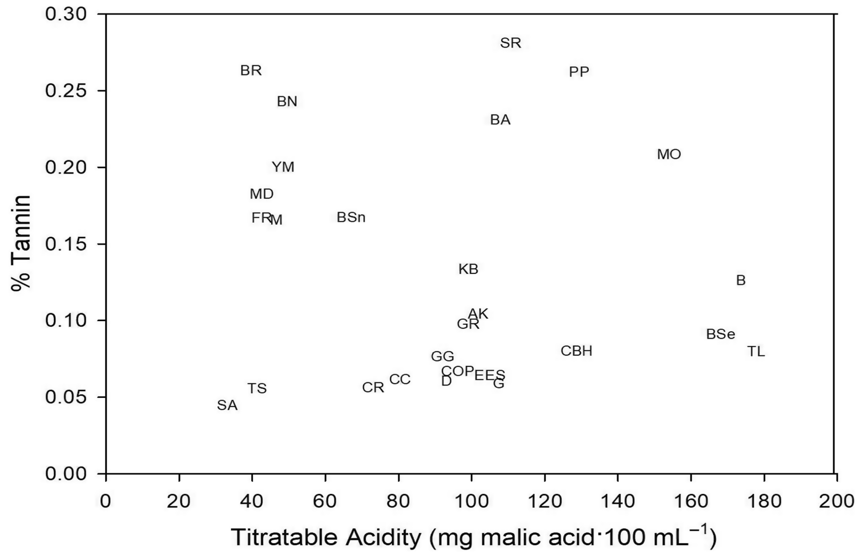
Note: YAN, yeast assimilable nitrogen; gae, gallic acid equivalents.
[a]Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means.
[b]Corrected juice polyphenols = uncorrected juice polyphenols – juice ascorbic acid interference

Table 10. Juice classifications of 28 apple cultivars grown on M.9 rootstock for cider production (University of Guelph, Simcoe, Ontario, 2018).

Cultivar	Titratable Acidity (as mg malic acid per 100 mL juice) 2017	2018	Polyphenols (μg gae per mL juice) 2017	2018	Classification
Ashmead's Kernel	95	108	366	372	Sharp
Binet Rouge	37	43	915	880	Bittersweet
Bramley's Seedling	145	191	276	373	Sharp
Breakwell	158	190	446	436	Sharp
Brown Snout	58	77	580	577	Sharp
Brown's Apple	102	114	781	799	Bittersharp
Bulmer's Norman	36	63	738	923	Bittersharp
Calville Blanc d'Hiver	132	125	317	258	Sharp
Cline Russet	60	86	230	188	Sharp
Cox Orange Pippin	82	110	256	230	Sharp
Crimson Crisp®	74	86	271	180	Sharp
Dabinett	82	104	256	188	Sharp
Enterprise	102	102	246	225	Sharp
Esopus Spitzenberg	97	116	250	222	Sharp
Frequin Rouge	32	53	515	639	Sweet
Golden Russet	85	113	380	315	Sharp
GoldRush	92	123	246	189	Sharp
Grimes Golden	93	91	275	277	Sharp
Kingston Black	86	112	437	493	Sharp
Medaille d'Or	137	171	557	875	Bittersharp
Michelin	43	50	564	585	Sharp
Muscadet De Dieppe	40	46	693	567	Bittersweet
Porter's Perfection	121	138	925	865	Bittersharp
Stoke Red	101	120	1042	876	Bittersharp
Sweet Alford	31	35	208	131	Sweet
Tolman Sweet	34	49	185	228	Sweet
Tydeman Late	176	179	314	259	Sharp
Yarlington Mill	40	57	737	640	Bittersharp

Note: Colour scale is used to indicate value as a visual aid. Red is used for the lowest values, which scales up to blue for the highest values. gae, gallic acid equivalents.

Fig. 4. Plot of cultivars by titratable acidity and calculated tannin concentrations 28 apple cultivars grown on M.9. rootstock for cider production. (AK is Ashmead's Kernel; B is Breakwell; BA is Brown's Apple; BN is Bulmer's Norman; BR is Binet Rouge; BSe is Bramley's Seedling; CBH is Calville Blanc d'Hiver; CC is Crimson Crisp®; COP is Cox's Orange Pippin; CR is Cline Russet; D is Dabinett; E is Enterprise; ES is Esopus Spitzenberg; FR is Fréquin Rouge; G is GoldRush; GG is Grimes Golden; GR is Golden Russet; KB is Kingston Black; M is Michelin; MD is Muscadet de Dieppe; MO is Medaille d'Or; PP is Porter's Perfection; SA is Sweet Alford; SR is Stoke Red; TL is Tydeman Late; TS is Tolman Sweet; and YM is Yarlington Mill) University of Guelph, Simcoe, Ontario, 2018.



A discriminant analysis of cultivar based on juice attribute data indicated that most cultivars are easily distinguishable when looking at combined juice attributes, with 90% of data points being classified as the correct cultivar. Cultivars that were frequently classified as one another due to similar horticultural characteristics included two pairs: Cox's Orange Pippin and Dabinett; and Michelin and Muscadet de Dieppe. These pairs of cultivars have similar juice profiles based on measured characteristics, though there are unmeasured aromatic and flavour attributes.

Associations based on place of origin

The 28 cultivars were selected because of their reputation or potential for cider, especially those that were traditionally grown in France, the United Kingdom, and parts of North America with a history of cider production. Separating cultivars by their country of origin revealed that some juice attributes were significantly influenced by the origin of the cultivar. There were no differences among the average SSC or YAN concentrations in the cultivars based on their origin. North American apples were the firmest, while British apples were the softest. French and English cultivars both had significantly higher polyphenol concentrations than North American ones, even when grown in North America. British apples had significantly higher TA values than American or French apples, while the French cultivars had the highest average pH. This reflects the styles of cider that have been typical of these regions. French ciders are typically naturally fermented and have biomass removed through keeving, which may be aided by the high pH. French and English ciders both have bitter and astringent properties that are associated with their high polyphenol concentrations. Producers who wish to make a specific style of cider should use apples that reflect that style and should be able to recreate those properties in North America (Table 9).

The results enumerated in this study will give cider producers and apple growers the necessary information to determine which apple cultivars they should plant to produce high-quality cider. Many cider producers choose to use traditional LARS classifications to guide their plantings and cider blends. In the current study, polyphenol concentrations were used to estimate percent tannins using a lab-developed standard curve to place the 28 cultivars on the LARS classification scale (Table 10, Fig. 4). However, the classification system may need updating to better reflect current research and understanding of juice composition. Further research should be undertaken to establish the composition of aromatics in the juices, and particularly the effect of fermentation on those compounds. This research forms the basis on which further cider apple research in the region can be conducted. Once apple cultivars with good horticultural and juice production qualities in Ontario are planted, other aspects of orchard management can be examined for their effects on juice quality. The effects of these aspects of terroir on juice can help us to understand the origins of the physicochemical qualities of apple juice and better control those in the future for continued improvement in cider production.

The exploratory analyses show that differences in juice attributes exist among apple cultivars grown in Ontario based on the cultivar's origin and on the cultivars themselves. In addition to continued evaluation at the Simcoe site, future experiments could compare the juice attributes of the same cultivars grown in different regions, particularly those with different climatic and biotic pressures.

Author Contributions

DP wrote the original draft of the manuscript. DP carried out the investigations (experiments and data analyses). DP and JC were involved in the initial concept development. Both authors reviewed, edited and approved the final manuscript. DP and JC were involved in developing the methodology. DP and JC secured the funding for this research.

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