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Review

Fungus resistant grape varieties as a suitable alternative for organic wine production: Benefits, limits, and challenges

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ABSTRACT

Areas dedicated to organic wine production have significantly increased over the last few years. The vast majority of organic wine is made from *Vitis vinifera* varieties that are highly susceptible to fungal diseases and pests, making organic management difficult for growers. Depending on the growing area, 20–70% of organic growers declare issues with fungal diseases in Europe. Recently, fungus-resistant grape (FRG) varieties have been recommended as the most suitable choice in organic viticulture, especially in areas where disease pressure necessitates high rates of fungicides. FRG varieties could contribute to improved disease management in organic as well as conventional viticulture, reduce production costs and decrease copper accumulation in soils. Recently, many FRG varieties presenting advantageous agronomic attributes and enological characteristics have been developed in North America and Europe for conventional and sustainable farming. In this review, we present an overview of the benefits and limits associated with FRG varieties in addition to the current knowledge regarding berry and wine composition, canopy management, and winemaking challenges and practices.

Contents

Abbreviations: FRG, fungus resistant grape; M3GE, malvidin-3-glucoside equivalents; MDGE, malvidin-3,5-diglucoside equivalents; DW, dry weight; FW, fresh weight; LC–MS/MS, liquid chromatography coupled to mass spectrometry; UPLC–MS, ultraperformance liquid chromatography coupled to mass spectrometry; HPLC-DAD, high performance liquid chromatography coupled to diode-array detector; CE, catechin equivalent; B2E, procyanidin B2 equivalent; RE, resveratrol equivalent; TA, titratable acidity; TSS, total soluble solids; YAN, yeast assimilable nitrogen.

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1. Introduction

Organic wine production considerably increased over the last ten years and accounts for nearly 5% of total production of today's wine market (Bonn et al., 2015; Willer and Lernoud, 2015). Reasons driving consumers toward organic wine varies from health concerns to environmental awareness and interest for *terroir*, and the overall perception that organic wines are of higher value than conventional ones (Bonn et al., 2015).

Organic wines are expected to be free of synthetic pesticides, fertilizers or other synthetic inputs that could pose a higher risk than conventional farming to human health or the environment (Mann et al., 2010; Bonn et al., 2015). However, the vast majority of organic wine is made from *Vitis vinifera* varieties highly susceptible to fungal diseases and pests, making organic management difficult for growers (Wiedemann-Merdinoglu and Hoffmann, 2010). Depending on the country origin, 20–70% of organic growers declare issues with botrytis and powdery mildew in Europe (Collective, 2008).

In contrast with conventional viticulture that integrates a wide range of synthetic pesticides in pest management programs, organic viticulture mostly relies on sulfur- and copper-based fungicides such as the Bordeaux mixture to control major diseases like downy and powdery mildews, as well as a wide range of other diseases and insect pests (Provenzano et al., 2010). Copper-based formulations have been used for more than a hundred years in European vineyards (Flores-Vélez et al., 1996), but copper has a low mobility in soil and was later found to accumulate to levels that could threaten the environment (Komárek et al., 2010). Indeed, copper concentration is typically much higher in vineyard soils (20–665 mg/kg) compared to arable land (5–30 mg/kg) (Besnard et al., 2001; Komárek et al., 2010). Such accumulation is likely to occur in perennial crops like grapevines because copper fungicides are continuously sprayed on the same land (Komárek et al., 2010). Correspondingly, vineyards located in wet areas show higher copper concentration than those from dry areas, which suffer less pressure from diseases (Komárek et al., 2010). Copper concentration reached 93 mg/kg in the 0–20 cm soil layer of a Mediterranean organic vineyard with a dry climate, whereas values between 200 and 297 mg/kg have been reported in conventional vineyards located in wet areas from Northern Italy (Provenzano et al., 2010).

The European Union recently established premium goals to reduce pesticides, particularly copper, in viticulture (Rousseau et al., 2013). One of the strategies is to shift from a treatment-oriented approach to a disease prevention approach by the development of fungus-resistant varieties (Rousseau et al., 2013). Fungus-resistant grapes (FRG) result from interspecific cross-breeding between the Mediterranean species *V. vinifera* and North American and Asian *Vitis spp*. such as *V. riparia*, *V. amurensis* and *V. rupestris* that carries high resistance to fungal diseases, including powdery and downy mildews, and grey rot. The firsts FRG varieties, issued from traditional breeding, carried a significant percentage of non-*V. vinifera* species in their genetic and were therefore considered as “interspecific hybrids” (Sivčev et al., 2010). Recently, marker-assisted selection combined with multiple back-crossing with *V. vinifera* varieties allowed the development of FRG carrying both disease-resistance genes and a significant percentage (more than 85%) of *V. vinifera* in their pedigree; those are generally referred to as “PIWI” (from German: *Pilzwiderstandsfähige*, “disease resistant”) and are accepted as *V. vinifera* varieties in European catalogues (Sivčev et al., 2010). In some cases though, “PIWI” indistinctly refers to both interspecific hybrids and newer “disease-resistant *V. vinifera*” varieties (Collective, 2008; Siegfried and Temperli, 2008).

Optimal variety selection is a key factor for successful implementation of organic grape production (Fragoulis et al., 2009; Sivčev et al., 2010). Recently, FRG varieties have been recommended as the most suitable choice for organic viticulture (Pavloušek, 2010; Sivčev et al., 2010; Becker, 2013). Resistance to major diseases such as powdery mildew significantly reduces the need for pesticides and thus represents a major advantage in organic farming, especially in humid areas such as Bordeaux (Galbrun, 2008; Sivčev et al., 2010; Wiedemann-Merdinoglu and Hoffmann, 2010; Fuller et al., 2014; Weigle and Carroll, 2015).

Superficies devoted to organic wine production from FRG varieties are not well documented. In Germany, FRG occupied 7.9% of organic vineyard surface areas in 2003 but projections were that 40% of the new plantings planned from 2010 to 2015 would be FRG cultivars (Sloan et al., 2010). In contrast, both old and recent FRG varieties have spread extensively over the last 30 years in areas presenting challenging growing conditions such as wet summers and cold winters with most of these varieties grown using conventional management practices (Table 1). Very little research has been done to compare vineyard practices and pesticide use for FRG varieties grown under conventional vs. organic management. In addition, the large genetic pool found in FRG varieties makes them highly variable in terms of viticulture (e.g., vigor, canopy management, berry ripening), berry composition (e.g., sugars, acids, phenolic compounds) and winemaking (e.g., aroma). In order to obtain a comprehensive understanding of FRG varieties with regards to organic grape production, this review will present the benefits and limits of FRG for organic wine production, present their agronomic and oenological characteristics, and discuss challenges related to their use in wine production.

2. Benefits and limits of FRG in organic viticulture

2.1. Breeding for disease resistance and quality

In phytopathology, “resistance” refers to the capacity of the plant to defend itself against pathogens (Prell and Day, 2001). Interspecific hybridization of grapevines began in the 19th Century and was initially aimed at introducing pest and disease resistance in offspring (Galet 1999; Avenard et al., 2003; Reynolds, 2015). Many FRG developed at that time carried undesirable “foxy” flavors in their wine, a default that was later attributed to the presence of *V. labrusca* in the breeding process, resulting in the near elimination of this species in recent breeding (Hemstad and Luby 2000; Sun et al., 2011a). Later, several breeding programs implemented worldwide led to the development of varieties showing different characteristics such as cold-hardiness, short/long growing season, and pest resistance (detailed review by Reynolds, 2015).

Table 1
Estimated growing area for significant FRG varieties grown in Europe, North America, and Asia.

Color	Variety	Estimated growing area (ha)	Countries	*Ref.*
red	Chambourcin	200–1000	France, Italy, Switzerland	1[a]
	Baco Noir	200–1000	Canada, United States	2–5
	Frontenac	200–1000	Canada, China, United States	2–4, 6
	Maréchal Foch	200–1000	Canada, United States, France	2–5
	Marquette	200–1000	Canada, United States	2–4
	Regent	>1000	Austria, Belgium, Bulgaria, Czech Republic, Denmark, England, Germany, Hungary, Italy, Netherlands, Sweden, Switzerland	1
white	Baco Blanc	>1000	France	7
	Bianca	>1500	Austria, Belgium, Czech Republic, Denmark, Hungary, Italy, Moldova, Netherlands, Romania, Serbia, Switzerland	1,7
	Cabernet Blanc	200–1000	Austria, Germany, Switzerland	1
	Frontenac Gris	200–1000	Canada, United States	2–4
	Kunleány	>1500	Hungary	1,7
	La Crescent	200–1000	Canada, United States	3, 4
	Vidal	>1000	Canada	2–5
	Villard blanc	200–1000	France	7
	Zala Gyöngye	>2500	Hungary	7

[a] (1) Rousseau et al., 2013; (2) Association des vignerons du Québec, 2013 (Personal communication); (3) Tuck and Gartner, 2013; (4) Mount Kobau Wine Services, 2014; (5) Grape Growers of Ontario, 2015; (6) Li et al., 2015; (7) Eurostat, 1999–2009.

The recent sequencing of the *Vitis* sp. nuclear genome significantly contributed to the implementation of molecular breeding strategies in grapevines (see the review by Di Gaspero and Foria, 2015). These tools assist breeders in the selection of parents or of the most promising offspring (Di Gaspero and Foria, 2015). So far, many markers related to desirable agronomic and enological characteristics (e.g., fruit ripening time, berry size, color, acidity, aroma) have been identified in grapevine, including a number of markers for disease resistance (Emanuelli et al., 2011; Merdinoglu and Caranta, 2013; Di Gaspero and Foria, 2015; Zini et al., 2015). Genes related to disease resistance contribute to the activation of pathogen-specific defense mechanisms (PSDM) that induce a hypersensitive response in plant upon the detection of specific pathogen-encoded Avirulence proteins (Verhagen et al., 2010; Wu et al., 2014). PSDM are among the most effective defenses of plants against pathogens (Wu et al., 2014). The main genetic markers related to PSDM in *Vitis* sp. include markers for downy mildew (*rpv1*, *rpv3*, *rpv10*, *rpv12)* and for powdery mildew (*ren1*, *ren3*, *run1)* (Zini et al., 2015; Di Gaspero et al., 2012).

So far, downy and powdery mildews, and botrytis have been primarily targeted for the development of FRG varieties and several cultivars bearing resistance to these diseases have been developed over the last twenty years (Rousseau et al., 2013). Nevertheless, certain pathogens have been able to bypass the resistance mechanisms of certain FRG in field trials (Di Gaspero and Foria, 2015; Merdinoglu and Caranta, 2013). Recently, the pyramidization of resistance haplotypes from different grape species into new FRG varieties prevented pathogens from bypassing resistance mechanisms, therefore making FRG resistance more durable (Di Gaspero and Foria, 2015; Merdinoglu and Caranta, 2013).

2.2. *Economical and agricultural benefits of disease resistance*

The benefits of growing FRG cultivars go well upon the sector of organic wine production. Indeed, most *V. vinifera* varieties have low to high susceptibility to fungal diseases that result in significant production costs and economic losses (Fuller et al., 2014). In Italy, the annual cost for controlling downy mildew in conventional vineyard typically ranges from 8 to 16 million Euros per year, depending on disease pressure (Salinari et al., 2006). Under medium disease pressure, 12 treatments per season are necessary for traditional *V. vinifera* varieties grown under conventional management (Rousseau et al., 2013). In a study including 183 FRG varieties grown in six different European countries, the number of fungicide treatments was reduced by 73% and 82% in organic vineyards with low and medium disease pressure, respectively (Rousseau et al., 2013). In a survey involving 65 German vineyards under organic management, growers reported having to spray FRG varieties 3.8 times per season on average (Becker, 2013).

Estimations are that growing FRG varieties could cut production costs by two in French vineyards (Galbrun, 2008). In California, it has been estimated that powdery mildew resistant varieties could allow cost savings as high as 48 M$ per year for the production subsets of Crimson Seedless Table grapes, raisin grapes and Central Coast Chardonnay wine grapes (Fuller et al., 2014).

The disease resistance of FRG varies with cultivar's genetic and growing location (Pavloušek et al., 2014). Therefore most FRG varieties show some susceptibility to different pathogens, including downy mildew, powdery mildew, botrytis, black rot and anthracnose (Table 2). In organic management, these diseases are generally controlled using sulfur-based fungicides (i.e., *Myco-San*) (Rousseau et al., 2013; Siegfried and Temperli, 2008). When copper-based formulations are necessary, they are used at a much lower rate than for *V. vinifera* varieties (Van Der Meer and Lévite, 2010). In Québec (Canada), garlic powder suspension (marketed as *Buran*) is known among the local agronomists to efficiently prevent powdery mildew in organic FRG.

2.3. *Yield*

The yield of organic *V. vinifera* grapevines can show 8–16% reduction compared to conventional grapevines (Bayramoglu and Gundogmus, 2008; Guesmi et al., 2012). In contrast, FRG are often more vigorous and may show high productivity (10 000–20 000 T/ha), which could contribute to secure yields in organic production (Reynolds and Vanden Heuvel, 2009; Sun et al., 2011b; Rousseau et al., 2013; Barthe, 2015).

Yields ranging from 7.0 to 11.8 T/ha were reported for FRG grown under conventional management with minimal treatment in Switzerland (Siegfried and Temperli, 2008). In a five years study carried out in New York State, organic Seyval blanc grapevines produced, on average, 30% less crop than vines grown using conventional management (12.7 vs. 19.9 Tons/ha, respectively; Pool, 1995). Such reduction was caused by differences in soil quality (e.g., the organic plots was inferior to that of conventional plots) and by

Table 2
Overview of disease susceptibility, vigor and hardiness/cold tolerance of 41 fungus-resistant varieties.

Variety	Susceptibility to diseases[a,b]								Vigor	Hardiness/Cold tolerance (°F)	Ref.[c]
	DM	PM	BOT	BR	AT	DA	CG	EUT			
reds											
Baco noir	+	++	+	+++		+	+++	++	high	–10 to –20	1–7
Baltica		+		+	+				moderate	–20 to –30	1, 8–10
Cabernet Carbon	–/+	++	–/+								2, 5
Cabernet Jura	–	–/+	–/+								2, 5
Chambourcin	+	+	++	+++		+	++		moderate/high	–5 to –15	1–6, 11
Chancellor	+++	++	+	+	+	+++	++	+	moderate	–10 to –20	1–6, 12, 13
Chelois	+	+++	+	+		+++		++		–10 to –20	6
Concord	+	++	+	+++		+++	+	+++	high	–15 to –25	3, 4, 6
De Chaunac	++	++	+	+	+	++	++	+++	moderate/high	–15 to –25	1–5
Frontenac	–/+	++	++	++	+	++			high	–20 to –30	1, 3, 4, 8–10
Léon Millot	+	++	+	+		+	++	++	high	–15 to –25	1–7, 11
Lucie Kulhmann	+	++			+	+			moderate		1, 12, 13
Maréchal Foch	+	++	+	++		+	+++	+++	moderate	–15 to –25	1–7, 11, 14
Marquette	–	+	+	+	+++				high	–20 to –30	1, 8–10, 14
Petite Perle	+	+	+	+	+				moderate	–20 to –30	1, 8, 9, 14
Regent	+	+	+			+				–5 to –15	2, 5, 7, 15
Sabrevois	+	+		+	+				moderate	–20 to –30	1, 10, 13, 14
Skandia		+	+	+	++				moderate	–20 to –30	1, 8, 9, 14
St. Croix	++	++	++	+	+				moderate/high	–20 to –30	1, 3, 6, 8–10, 12–14
whites											
Aurore	++	++	++	+++		+	++	+++	high	–10 to –20	3–7
Bianca	+	+	–/+			++				–5 to –15	2, 5, 7, 16
Bronner	–/+	+	+								5, 2, 11
Cabernet blanc	++	++	–/+							–5 to –15	2, 5
Frontenac blanc	–/+	+		++	++				high	–20 to –30	1, 8–10, 14
Frontenac gris	–/+	+		++	+				high	–20 to –30	1, 8–10, 14
Geisenheim	+	+++	+		+				moderate		1
Helios	++	+	+								2, 5, 11
Hibernal	++	+	+	+		+			moderate		1, 5, 12, 13
Johanniter	++	–/+	++								2, 5, 11
Kunleány	++	+++	–								5, 16
La Crescent	+	+		++	++				high	–20 to –30	1, 3, 8–10, 14
Louise Swenson	+	+	+	+	++				low	–20 to –30	1, 8–10, 14
Osceola Muscat	++	++	+	+	+				high	–15 to –25	1, 8, 9
Seyval	+	+++	++	++	+	+	++	+	moderate	–10 to –20	1–7, 10, 11, 13, 14
Solaris	++	–/+	++							–10 to –20	2, 5, 11, 14
Soleil blanc	+	–/+	++								2, 5, 11
St. Pepin	+	+	+		+				moderate	–20 to –30	1, 6, 10, 12–14
Traminette	+	+	+	+	+++	++	++	+	moderate/high	–10 to –20	1, 3, 4, 10
Vandal-Cliche	+	+	+		+++				moderate/high	–15 to –25	1, 10, 12, 13
Vidal	+	++	–/+	+	+	+	+++	+	moderate	–5 to –15	1–6, 10, 12, 13
Villard blanc	–	+		+							5, 15

[a] DM: downy mildew; PM: powdery mildew; BOT: *Botrytis*; BR: black rot; AT: anthracnose; DA: dead arm; CG: crown gall; EUT: *Eutypa*.

[b] –/+ = resistant and few susceptible according to several references; – = resistant; + =slightly susceptible; ++ = moderately susceptible; +++ = highly susceptible.

[c] (1) Dubé and Turcotte, 2011; (2) Sivčev et al., 2010; (3) Dami et al., 2005a; (5) Rousseau et al., 2013; (6) Reisch et al., 1993; (7) Lisek, 2010; (8) Provost et al., 2012b; (8) Wolf, 2008; (9) Provost et al., 2013; (10) Carisse and Lefebvre, 2011; (11) Tuchschmid et al., 2006; (12) Khanizadeh et al., 2008; (13) Khanizadeh et al., 2005; (14) Plocher and Parke, 2008; (15) Avenard et al., 2003; (15) Daniela et al., 2013; (16) Pavloušek, 2013.

the competition caused by cover crops in the organic plot (Pool, 1995).

2.4. Marketing and wine quality

FRG varieties are nearly completely absent from wine marketing in major wine producing countries, a situation that limits their expansion because they remain unknown to consumers. In a survey of 255 wineries growing FRG varieties (25% of them being under organic management), 40% of respondents pointed the "problem of unknown varieties" as the biggest handicap for the marketing of FRG wines (Becker, 2013). As FRG varieties carry non-*V. vinifera* genes (even at low levels), they may suffer from the perception that interspecific hybrids produce low-quality wines (Fuller et al., 2014). Similarly, organic wine has suffered from a reputation of average quality until recently (Collective, 2008). The need to educate consumers to organic wines made from FRG varieties is therefore significant.

The quality of FRG wines has been a key topic since their development in the 19th Century. Back then, many French-American hybrids were thought to produce wine of "satisfactory commercial quality" and were winning medals in wine competitions (Paul, 1996a). Recent studies showed that the quality of FRG wines is generally rated as equivalent to that of *V. vinifera* (Van Der Meer and Lévite, 2010; Pedneault et al., 2012; Rousseau et al., 2013). For example, in a blind tasting carried out on 52 FRG wines from Europe, 62% red FRG varieties (24 wines tasted), including Cabernet Jura (VB 5-02), Cabertin (VB 91-26-17) and the old interspecific hybrid Chambourcin (J. Seyve 26-205), were noted as equivalent or superior to Merlot (reference wine), and 31% of white (28 wines tasted) were classified as equivalent or superior to the reference Chardonnay wine, including the interspecific varieties Gf. GA.47-42 (Bacchus Weiss X Seyval blanc), Saphira (Gm 7815-1), and Solaris (Fr 240-75) (Rousseau et al., 2013).

A consumer study conducted in Switzerland concluded that 70–90% of consumers noted Solaris and Maréchal Foch wines as equivalent to *V. vinifera* Riesling and Zweigelt wines (used as reference wines), respectively, and 23–30% of consumers judged the FRG wines as "clearly superior" to the reference *V. vinifera* wines (Van Der Meer and Lévite, 2010). A consumer survey comparing 21 red FRG wines produced in Eastern Canada to three imported *V. vinifera* wines described as major selling products in this area showed that 76% of FRG wines were judged as equivalent or superior to the reference wines (Pedneault et al., 2012). Most FRG wines were blends that included Marechal Foch or Frontenac, with other locally grown FRG varieties (Pedneault et al., 2012).

3. Growing FRG varieties for organic wine production

The chemical composition of FRG is highly variable from one variety to another, which is attributable to their large genetic pool. This entails the need to optimize the relationship between varieties and growing conditions. Knowledge of berry chemical composition and of the impact of canopy management practices is essential to achieve that goal. Studies cited in the following Sections (3.1 and 3.2) were generally conducted under conventional management and in northern areas; this is where most FRG have been grown and studied. To our knowledge, no studies are available yet on canopy management practices for European PIWI varieties. Studies comparing organic to conventional management in *V. vinifera* varieties have been reviewed by Provost and Pedneault (2016) and show that organic management has generally a limited impact on berry and wine composition, and wine quality.

3.1. Berry and juice composition

3.1.1. Juice

An overview of juice characteristics (e.g., TSS, pH, TA) of FRG grown in different locations is presented in Table 3. Certain FRG varieties present high pH and high TA, which causes issues with microbial spoilage and color stability in wines (Morris et al., 1984a). YAN level also varies largely among FRG varieties. The analysis of 30 FRG varieties across Midwestern and Eastern United States showed YAN concentrations ranging between 89 and 938 mg/L (Stewart and Butzke, 2012). High YAN values ($\geq$250 mg/L) are common in *V. riparia*-based FRG such as Frontenac (Mansfield, 2015a; Slegers et al., 2015; Stewart, 2013). In addition, significant variations are observed between years, growing areas and cultural practices (Stewart, 2013).

3.1.2. Berries

Red FRG berries typically show anthocyanin concentrations ranging from 0.5 to 1.5 mg/g M3 G eq. FW in berries with low tannin concentration ranging from 0.07 to 0.95 mg/g berry in seed, and from 0.03 and 0.79 mg/g berry in skin (Tables 4 and 5). Conversely, tannin levels in *V. vinifera* cv. Pinot noir reach 1.2 mg/g berry in seed and 0.56 mg/g berry in skin (Springer and Sacks, 2014). The profile of other phenolic compounds such as flavonols and phenolic acid derivatives varies significantly from one FRG variety to another (Tables 6 and 7). In red European PIWI varieties such as Cabernet Cortis and Regent, isorhamnetin-3-*o*-rutinoside is the major flavonol whereas quercetin-3-*o*-glucoside is the major flavonol in Baco noir and Lucy Khulmann (Ratnasooriya et al., 2011; Ehrhardt et al., 2014). Caftaric acid is the major hydroxycinnamic derivative in most FRG varieties (Zhu et al., 2012; Manns et al., 2013; Ehrhardt et al., 2014).

Stilbenes such as resveratrol are known to be involved in plant defense mechanism against fungal infections (Ehrhardt et al., 2014). *trans*-Resveratrol and its glucoside are the main stilbenes reported in berries of French hybrid FRG varieties grown in Canada, whereas high levels of *trans*- and *cis*-piceid, pallitol and astringin have been reported in PIWI varieties from Italy and Germany (Table 8).

3.2. Impacts of canopy management

3.2.1. Managing yield and berry quality

Controlling yield may contribute to enhance berry and wine quality, especially when the growing season is unfavorable to optimal berry ripening (Berkey et al., 2011). Studies show that either cluster or shoot thinning contribute to increased TSS and pH in FRG berries, but results vary from one year to another and, in many trials, harvest date had a higher impact than yield management (Tables 9 and 10). For example, 36% yield reduction using cluster thinning negatively impacted increased the level of C_6 compounds in juice of Seyval blanc berries during a hot growing season in Quebec (Canada) (Pedneault et al., 2015). Reducing yield significantly increased skin softness in Seyval blanc berries, suggesting that it may impact physical barriers protecting berries from fungal infections (Barthe, 2015).

Geneva Double Curtain (GDC) training contributed to increase yield but conversely reduced TSS and pH in a season-dependent manner in Chancellor (Reynolds et al., 1995). GDC and Umbrella-Kniffin (UK) increased yield in Frontenac and Marquette, respectively, but as UK increased TA and lowered TSS and pH in Marquette, GDC increased TSS and pH, and lowered TA in Frontenac when compared to other training systems (Bavougian et al., 2012; Martinson and Particka, 2013). Both Vertical Shoot Positioning (VSP) and High-Cordon (HC) increased the level of free volatile terpenes in Traminette juice compared to GDC, Smart-Dyson (SD) and Scott-Henry (SH) (Ji and Dami, 2008).

3.2.2. Impact on wine

Shoot thinning significantly decreased yield and the level of C_6 alcohols in Maréchal Foch wines, but did not impacted wine sensory perception (Sun et al., 2011b). In contrast, taste and flavors of wines derived from un-thinned control vines were preferred over those derived from cluster-thinned vines in Vandal-Cliche (Pedneault et al., 2015).

Chancellor wines issues from the GDC scored higher on berry flavor than those issued from the Y-trellis system, whereas wines issues from Hudson River Umbrella (HRU) scored higher on color and lower on earthy note intensities (Tables 9 and 10; Reynolds et al., 2004). GDC increased yield and decrease TSS and pH in Seyval blanc, but GDC wines rated higher on melon notes intensity, and lower on earthy and vegetal flavors and astringency when compared to wines from 6-arms Kniffin (6AK) and Y-trellis systems (Reynolds et al., 2004).

In Traminette, increasing cluster sunlight exposition improved wine color and sensory ratings for linalool, rose and spice aromas (Bordelon et al., 2008; Skinkis et al., 2010). Increasing cluster exposition had little impact on aroma intensity in Seyval blanc wines, but wines from exposed clusters were rated as superior (Reynolds et al., 1986).

3.3. Challenges in FRG wine production

Recent findings (Manns et al., 2013; Slegers et al., 2015; Springer and Sack, 2015) show that many aspects of current enology knowledge may have limited application with FRG varieties, because most of them present particular biochemical characteristics. Therefore, particular winemaking practices should be developed for these grapes.

3.3.1. Juice extraction and methanol

Many FRG varieties contain high levels of pectin that necessitate the use of enzymes to increase juice yield at pressing. High pectin levels have been thought to increase methanol concentration in FRG wine (Lee et al., 1975). However, surveys showed that the level of methanol in FRG wines ranges between 20 and 197 mg/L, which

Table 3
Overview of TSS, TA, pH and YAN levels in the juice of 41 fungus-resistant grape varieties from different growing areas.

Variety	Localization		TSS (Brix)	TA			pH	YAN (mg/L)	Ref.
	Country	Area		Value	Units	Eq.			
reds									
Baco noir	Canada	Nova Scotia	18.5	0.82	%	tartaric acid	2.66		1[a]
Baltica	Canada	Québec	24.9	6.96	g/L	tartaric acid	3.05	179	2
Cabernet Carbon	Switzerland	Stäfa	22.5–22.9	7.8–8.3	g/L	n.a.	3.0–3.1		3
	Switzerland	Wädenswill	21.0	10.7	g/L	n.a.	3.0		4
Cabernet Cortis	Switzerland	Wädenswill	22.3	10.6	g/L	n.a.	3.1		4
Cabernet Jura	Switzerland	Wädenswill	21.2–24.0	8.1–10.2	g/L	n.a.	3.0–3.4		3
Chambourcin	China	Beijing	20.2	4.2	g/L	H_2SO_4	n.a.		5
	Switzerland	Wädenswill	19.0–21.6	12–12.4	g/L	n.a.	n.a.		4
	United States	Michigan	20.6–21.8	7.2–7.9	g/L	n.a.	3.23–3.34		6
	United States	Ohio	20.1–21.3	10.7–11.2	g/L	n.a.	3.20–3.27		7
Chancellor	Canada	British Columbia	18.5–23.5	12.2–16.0	g/L	n.a.	3.12–3.37		8
	United States	Arkansas	14.8–17.1	0.74–0.93	%	tartaric acid	3.47–3.79		9
Chelois	United States	Arkansas	14.8–18.2	0.68–1.07	%	tartaric acid	3.61–3.80		9
Corot noir	United States	New York	15.0–17.8	7.5–11.6	g/L	n.a.	3.34–3.75	213	10, 11
Frontenac	Canada	Québec	21.5–25.3	10.1–17.5	g/L	tartaric acid	3.10–3.35	191–403	2,12–14
	United States	Iowa	21.4	10.4	g/L	tartaric acid	3.39		15
	United States	Minnesota	22.9–26.4	14.9–18.5	g/L	tartaric acid	2.86–3.12		16
	United States	Nebraska	19.7–22.5	14.6–20.9	g/L	n.a.	2.92–3.12		17
Léon Millot	Canada	Nova Scotia	20.6	0.81	%	tartaric acid	3.13		1
	Switzerland	Wädenswill	21.6	7.24	g/L	n.a.	3.46		18
Lucy Khulman	Canada	Nova Scotia	21.1	0.76	%	tartaric acid	3.11		1
Maréchal Foch	Canada	Nova Scotia	23.1	0.94	%	tartaric acid	3.06		1
	Canada	Québec	21.6	7.24–10.3	g/L	tartaric acid	3.18	95–108	12,14
	Switzerland	Wädenswill	21.6	9.7	g/L	n.a.	3.2		4
	United States	Minnesota	24.6–26.1	8.7–11.8	g/L	tartaric acid	2.99–3.05		16
	United States	New York	20.1–25.1	8.67–11.4	g/L	n.a.	3.10–3.70	119	10, 19
Marquette	Canada	Québec	23.7–28.2	8.25–13.1	g/L	tartaric acid	3.09–3.50	210–342	2, 12–14
	United States	Iowa	22.7	8.2	g/L	tartaric acid	3.39		15
	United States	Minnesota	26.2–30.5	11.5–12.0	g/L	tartaric acid	2.84–3.05		16
	United States	New York	21.9	9.37	g/L	n.a.	3.09	329	10
Noiret	United States	New York	19.3	7.2	g/L	tartaric acid	3.45	164	20
Petite Perle	Canada	Québec	22.9	7.38	g/L	tartaric acid	3.33	299	2
Regent	Germany	n.d.	20.1–20.3	8.0–8.3	g/L	n.a.	–		21
	Switzerland	Stäfa	20.3–22.0	6.1–8.4	g/L	n.a.	3.3–3.7		3
Sabrevois	Canada	Québec	18.6–19.2	13.4	g/L	tartaric acid	3.16	213–221	12–14
Skandia	Canada	Québec	29	6.84	g/L	tartaric acid	3.69	351	2
St. Croix	Canada	Québec	19.4–22.7	5.14–9.0	g/L	tartaric acid	3.21–3.39	129–167	2, 12, 14
	United States	Iowa	16.8	6.3	g/L	tartaric acid	3.73		15
	United States	Minnesota	20.9–24.1	3.87–4.96	g/L	tartaric acid	3.08–3.50		16
Villard noir	United States	Arkansas	15.1–17.0	0.75–1.00	%	tartaric acid	3.63–3.73		9
whites									
Adalmiina	Canada	Québec	19.4	7.56	g/L	tartaric acid	2.99	183	2
Aurore	United States	Arkansas	17.0–19.0	0.64–0.80	%	tartaric acid	3.68–3.85		9
Bronner	Switzerland	Wädenswill	19.0–22.5	7.3–9.6	g/L	n.a.	3.1		4
Cal 6-04	Switzerland	Bevaix	21.0–24.5	10.2–12.4	g/L	n.a.	2.9–3.0		3
Frontenac blanc	Canada	Québec	26.2	9.77	g/L	tartaric acid	3.27	372	2
Frontenac gris	Canada	Québec	26.8	9.91	g/L	tartaric acid	3.23	369	2
	United States	Minnesota	23.4–27.3	14.3–16.1	g/L	tartaric acid	2.93–3.08		16
Helios	Switzerland	Wädenswill	21.6	8.5	g/L	n.a.	3.2		4
Johanniter	Switzerland	Wädenswill	20.5	9	g/L	n.a.	3.2		4
La Crescent	Canada	Québec	22.8	14.2	g/L	tartaric acid	3	130	2
	United States	Minnesota	22.7–25.8	13.2–14.4	g/L	tartaric acid	2.88–2.99		16
	United States	Iowa	21.8	8.9	g/L	tartaric acid	3.36		15
Noah	China	Beijing	19.9	6.9	g/L	H_2SO_4			5
Osceola Muscat	Canada	Québec	23.5	8.72	g/L	tartaric acid	3.08	163	2
Seyval	Canada	Québec	17.7–22.4	8.77–12.3	g/L	tartaric acid	2.86–3.16	94–180	22
	United States	Arkansas	16.9–17.6	0.60–0.89	%	tartaric acid	3.69–3.91		9
Solaris	Switzerland	Stäfa	26.2–26.9	5.7–7.3	g/L	n.a.	3.2–3.5		3
	Switzerland	Wädenswill	24.9–30.4	5.8–9.5	g/L	n.a.	3.3		4
Soleil blanc	Switzerland	Wädenswill	22.9	8.73	g/L	n.a.	3.43		18
St. Pepin	United States	Minnesota	22.0–23.8	8.8–9.8	g/L	tartaric acid	2.94–3.25		16
Traminette	United States	New York	20.7	7.9	g/L	tartaric acid	3.18	95	20
Vandal-Cliche	Canada	Québec	17.3–19.7	11.2–13.4	g/L	tartaric acid	2.85–2.92	99–162	22
Verdelet	United States	Arkansas	16.2–20.1	0.35–0.84	%	tartaric acid	3.63–4.32		9
Vidal blanc	United States	Michigan	18.8–20.2	0.65–1.02	%	tartaric acid	3.28–3.30		23
Villard blanc	China	Beijing	20.1	6.8	g/L	H_2SO_4			5

[a] (1) Ratnasooriya et al., 2011; (2) Provost et al., 2012a; (3) Siegfried and Temperli, 2008; (4) Tuchschmid et al., 2006; (5) Zhu et al., 2012; (6) Miller et al., 1996; (7) Dami et al., 2006; (8) Reynolds et al., 1995; (9) Morris et al., 1984b; (10) Manns et al., 2013; (11) Sun et al., 2012; (12) Slegers et al., 2015; (13) Pedneault et al., 2013b; (14) Pedneault et al., 2013a); (15) Vos, 2014; (16) Haggerty, 2013; (17) Bavougian et al., 2012; (18) Striby, 2006; (19) Sun et al., 2011b; (20) Nisbet et al., 2014; (21) Eibach and Töpfer, 2003; (22) Barthe et al., 2012; (23) Wolpert et al., 1983.

Table 4

Anthocyanin profile and total anthocyanin concentration in berries (skin, whole berry) and wines of fungus-resistant grape varieties.

Variety	Origin	Dp-3-O-glucoside*	Cy-3-O-glucoside	Pt-3-O-glucoside	Pn-3-O-glucoside	Mv-3-O-glucoside	Pl-3-O-glucoside	Dp-3,5-O-diglucoside	Cy-3,5-O-diglucoside	Pn-3,5-O-diglucoside	Mv-3,5-O-diglucoside	Pl-3,5-O-diglucoside	Pt-3,5-O-diglucoside
skin													
Corot noir	NY, USA												
Maréchal Foch	NY, USA												
berry													
Baco Noir	NS, Canada	190	40	150		190							
Cabernet cortis	Italy	66.6	2.93	30.1	4.84	79	nd	–	3.11	21.7	1.95	0.04	–
Léon Millot	NS, Canada	130	21	100		96							
Lucy Khulman	NS, Canada	200	55	200		220							
Maréchal Foch	NS, Canada	250	42	130		110							
Regent	Germany	408	30	87	57	234	0.72	–	9.84	59.7	0.61	0.22	–
	Italy	221	24.4	71.3	41.5	203	0.32	–	4.7	60.1	1.3	0.17	–
wine													
Chambourcin	China				4.1	7.3					50.6		6.1
	OH, USA												
Corot noir	NY, USA												
	NY, USA	14.5–18.0	1.00–1.54	12.0–16.7	0.77–1.05	12.2–17.0		34.0–49.0	15.7–19.8	25.6–29.5	148–163		44.9–62.3
Maréchal Foch	NY, USA												
	NY, USA	12.6–56.3	1.14–2.21	16.1–49.0	1.62–3.39	45.1–89.6		2.88–7.39	1.98–2.39	6.12–7.01	50.5–56.9		4.71–6.66
Marquette	NY, USA	6.72–14.9	0.78–0.84	9.38–16.6	0.87–1.39	28.9–31.1		12.2–15.0	3.47–3.60	15.3–17.8	128–153		22.4–23.8

Variety	Origin	*Pn*-3-(6″-acetyl)-O-glucoside	Mv-3-(6″-acetyl)-O-glucoside	Dp-3-(6′-*p*-coumaroyl)-O-glucoside	Cy-3-(6″-*p*-coumaroyl)-O-glucoside	Pt-3-(6″-*p*-coumaroyl)-O-glucoside	Pn-3-(6″-*p*-coumaroyl)-O-glucoside	Mv-3-(6″-*p*-coumaroyl)-O-glucoside	Total anthocyanin	Units	Method	Ref.
skin												
Corot noir	NY, USA								0.994–1.26	mg/g FW[a]	a[d]	1[e]
Maréchal Foch	NY, USA								4.64–8.34	mg/g FW[a]	a	2
berry												
Baco Noir	NS, Canada									mg/100 g DW	b	3
Cabernet cortis	Italy	1.5	72.2	40.9	7.15	31.5	4.44	128		mg/kg FW	c	4
Léon Millot	NS, Canada									mg/100 g DW	b	3
Lucy Khulman	NS, Canada									mg/100 g DW	b	3
Maréchal Foch	NS, Canada									mg/100 g DW	b	3
Regent	Germany	2.87	15.6	76	60	36	34	91		mg/kg FW	c	4
	Italy	3.12	29.9	164	49.9	69	36.4	313		mg/kg FW	c	4
wine												
Chambourcin	China								84.6	mg/L[a]	b	5
	OH, USA								224–1138	mg/L[b]	d	6
Corot noir	NY, USA								671–897	mg/L[a]	a	1
	NY, USA									mg/L[c]	e	7
Maréchal Foch	NY, USA								479–919	mg/L[a]	a	2
	NY, USA									mg/L[c]	e	7
Marquette	NY, USA									mg/L[c]	e	7

*Dp: Delphinidin; Cy: Cyanidin; Pt: Petunidin; Pn: Peonidin; Mv: Malvidin; Pl: Pelargonidin.

[a] Quantified in malvidin-3-glucoside eq.

[b] Quantified in malvidin-3,5-diglucoside eq.

[c] Monoglucosides are quantified in malvidin-3-glucoside eq.; diglucosides are quantified in malvidin-3,5-diglucoside eq.

[d] (a) Adams-Harbertson protein precipitation assay; b) LC–MS/MS; c) UPLC–MS/MS; d) Spectrophotometry UV–vis at λ_{520nm}; e) HPLC-DAD.

[e] (1) Sun et al., 2012; (2) Sun et al., 2011b; (3) Ratnasooriya et al., 2011 ; (4) Ehrhardt et al., 2014; (5) Zhu et al., 2012; (6) Prajitna et al., 2007; (7) Manns et al., 2013.

is slightly higher than *V. vinifera* wines (26–111 mg/L) but significantly lower than the recommended limits of OIV for both reds (≤400 mg/L) and whites (≤250 mg/L) (Lee et al., 1975; Organisation Internationale de la Vigne et du Vin, 2011).

3.3.2. *Biogenic amines*

Exogenous nitrogen sources are routinely used to ferment *V. vinifera* varieties. In FRG carrying high YAN levels (see Section 3.1.1), this enrichment may cause an unwanted rise in fermentation temperature and contribute to increase the level of fusel alcohols, undesirable biogenic amines (e.g., histamine) and carcinogenic

Table 5
Flavan-3-ols profile and total tannin concentration in berries (seed, skin, whole berry) and wines of fungus-resistant grape varieties. Data on *Vitis vinifera* (Pinot noir var.) are presented for comparison purposes (from Springer and Sacks, 2014).

Matrix	Variety	Origin	(+)-catechin	(−)-epicatechin	epigallocatechin	(−)-epicatechin 3-O-gallate
seed						
red	Baco noir	NY, USA				
		ON, Canada	98	106		
	Corot noir	NY, USA				
		NY, USA				
	DeChaunac	NY, USA				
		ON, Canada	135	78		
	Frontenac	QC, Canada				
	Léon Millot	NY, USA				
	Maréchal Foch	NY, USA				
		ON, Canada	46	42		
		QC, Canada				
	Marquette	QC, Canada				
	Noiret	NY, USA				
	Sabrevois	QC, Canada				
	St. Croix	QC, Canada				
	Vincent	ON, Canada	155	284		
	Pinot noir[*]	NY, USA				
white	Seyval	ON, Canada	21	23		
skin						
reds	Baco noir	NY, USA				
	Corot noir	NY, USA				
		NY, USA				
	DeChaunac	NY, USA				
	Frontenac	QC, Canada				
	Léon Millot	NY, USA				
	Maréchal Foch	NY, USA				
		QC, Canada				
	Marquette	QC Canada				
	Noiret	NY, USA				
	Sabrevois	QC Canada				
	St. Croix	QC Canada				
	Pinot noir[*]	NY, USA				
berry						
red	Baco Noir	NS, Canada	1700	1100	15	140
	Cabernet cortis	Italy	94.5	101		
	Léon Millot	NS, Canada	860	600	11	99
	Lucy Khulman	NS, Canada	1700	780	11	88
	Maréchal Foch	NS, Canada	2100	990	15	99
	Regent	Germany	176	148		57.4
		Italy	167	115		36.7
white	Johanniter	Italy	84.9	42.1		
	Phoenix	Germany	231	187		121.7
		Italy	64.2	16.5		
	Solaris	Italy	81	111		12.7
wine						
red	Baco noir	NY, USA				
	Chambourcin	China	1.23	1.23	3.28	
		GA, USA	4.1–9.3	2.6–14.8		
	Corot noir	NY, USA				
		NY, USA	19.3–36.8	16.4–32.8		
		NY, USA				
	Frontenac	QC Canada				
	Maréchal Foch	NY, USA				
		NY, USA	36–337	11.5–62.1		
		QC, Canada				
	Marquette	NY, USA	13.9–30.0	5.55–14.4		
		QC, Canada				
	Sabrevois	QC, Canada				
	St. Croix	QC, Canada				
	Noiret	NY, USA				
	Pinot noir[*]	NY, USA				

Table 5 (*Continued*)

Matrix	epigallocatechin gallate	procyanidin B1	procyanidin B2	procyanidin B3	procyanidin B4	procyanidin C1	total tannins	Units	Method	*Ref.*
seed										
red							0.454	mg/g berry CE	a[b]	*1*[c]
		33	91	41	127	10		mg/100 g seed CE or B2E[a]	b	*2*
							0.33–0.53	mg/g berry CE	a	*3*
							0.917	mg/g berry CE	a	*1*
							0.264	mg/g berry CE	a	*1*
		4	22	2	12	tr		mg/100 g seed CE or B2E	b	*2*
							0.200	mg/g epicatechin eq.	c	*4*
							0.594	mg/g berry CE	a	*1*
							0.763	mg/g berry CE	a	*1*
		14	43	23	61	4		mg/100 g seed CE or B2E	b	*2*
							0.377	mg/g epicatechin eq.	c	*4*
							0.259	mg/g epicatechin eq.	c	*4*
							0.208	mg/g berry CE	a	*1*
							0.069	mg/g epicatechin eq.	c	*4*
							0.170	mg/g epicatechin eq.	c	*4*
		60	106	27	45	tr		mg/100 g seed CE or B2E	b	*2*
							1.19	mg/g berry CE	a	*1*
white		3	9	2		0		mg/100 g seed CE or B2E	b	*2*
skin										
reds							0.178	mg/g berry CE	a	*1*
							0.19–0.31	mg/berry CE	a	*3*
							0.34	mg/g berry CE	a	*1*
							0.178	mg/g berry CE	a	*1*
							0.051	mg/g epicatechin eq.	c	*4*
							0.221	mg/g berry CE	a	*1*
							0.248	mg/g berry CE	a	*1*
							0.030	mg/g epicatechin eq.	c	*4*
							0.055	mg/g epicatechin eq.	c	*4*
							0.785	mg/g berry CE	a	*1*
							0.076	mg/g epicatechin eq.	c	*4*
							0.192	mg/g epicatechin eq.	c	*4*
							0.559	mg/g berry CE	a	*1*
berry										
red	8.7							mg/kg DW	d	*5*
		43.8	106[#]	28.2	[#]			mg/kg FW berries	e	*6*
	7.5							mg/kg DW	d	*5*
	7							mg/kg DW	d	*5*
	8							mg/kg DW	d	*5*
		54.7	64.7[#]	30.9	[#]			mg/kg FW berries	e	*6*
		65.3	93.7[#]	45.5	[#]			mg/kg FW berries	e	*6*
white		37.8	50.2[#]	23	[#]			mg/kg FW berries	e	*6*
		66.8	59.3[#]	38.4	[#]			mg/kg FW berries	e	*6*
		19.3	22.6[#]	91.7	[#]			mg/kg FW berries	e	*6*
		3.6	113[#]	17.9	[#]			mg/kg FW berries	e	*6*
wine										
red							49	mg/L CE	a	*1*
								mg/L CE	d	*7*
				2.5–9.6				mg/L CE	f	*8*
							42.1–63.6	mg/L CE	a	*3*
								mg/L	f	*9*
							113	mg/L CE	a	*1*
							85.5	mg/L epicatechin eq.	c	*4*
							83	mg/L CE	a	*1*
								mg/L	f	*9*
							120	mg/L epicatechin eq.	c	*4*
								mg/L	f	*9*
							145	mg/L epicatechin eq.	c	*4*
							200	mg/L epicatechin eq.	c	*4*
							97.3	mg/L epicatechin eq.	c	*4*
							354	mg/L CE	a	*1*
							358	mg/L CE	a	*1*

[*] *Vitis vinifera.*

[#] Procyanidins B2 and B4 quantified together.

[a] Monomers are quantified as CE; dimers and trimers are quantified as B2E.

[b] Analytical method: (a) Adams-Harbertson protein precipitation assay; (b) HPLC-UV–vis; (c) HPLC-Fluorescence; (d) LC–MS/MS; (e) UPLC–MS/MS; (f) HPLC-DAD.

[c] (1) Springer and Sacks, 2014; (2) Fuleki and Ricardo da Silva, 1997; (3) Sun et al., 2012; (4) Pedneault et al., 2014; (5) Ratnasooriya et al., 2011; (6) Ehrhardt et al., 2014; (7) Zhu et al., 2012; 8) Auw et al., 1996; (9) Manns et al., 2013.

Table 6

Overview of the flavonol content in berries and wines of some red and white fungus-resistant grape varieties.

Matrix		Variety	Origin	kaempferol-3-o-glucoside	quercetin-3-o-glucoside	quercetin-3-o-glucuronide	isorhamnetin-3-o-rutinoside	quercetin	rutin	syringetin-3-glucoside	Units	Method	Ref.
berry	*red*	Baco Noir	NS, Canada		20						mg/kg DW	a[b]	1[c]
		Cabernet cortis	Italy	3.18	34.1	20.9	50.9				mg/kg FW	b	2
		Leon Millot	NS, Canada		16						mg/kg DW	a	1
		Lucy Khulman	NS, Canada		35						mg/kg DW	a	1
		Marechal Foch	NS, Canada		8						mg/kg DW	a	1
		Regent	Germany	4.04	45.6	60	87.2				mg/kg FW	b	2
			Italy	nd	8.1	18.9	163.1				mg/kg FW	b	2
	white	Johanniter	Italy	5.38	20.2	10.3	nd				mg/kg FW	b	2
		Phoenix	Germany	4.42	17.2	24.7	nd				mg/kg FW	b	2
			Italy	nd	16	6.44	nd				mg/kg FW	b	2
		Solaris	Italy	3.65	32.7	10.9	nd				mg/kg FW	b	2
wine	*red*	Chambourcin	China		6.84			5.63		5.69	mg/L[a]	a	3
		Corot noir	NY, USA					ND-0.70	0.65–7.72		mg/L	c	4
		Maréchal Foch	NY, USA					0.54–1.29	0.82–2.97		mg/L	c	4
		Marquette	NY, USA					ND-0.16	2.07–4.68		mg/L	c	4
	white	Noah	China		1.49			2.37		3.1	mg/L[a]	a	3
		Villard blanc	China		ND			3.31		0.2	mg/L[a]	a	3

[a] Quantified in mg/L quercetin eq. (QE).

[b] (a) LC–MS/MS; b) UPLC–MS/MS; c) HPLC-DAD.

[c] (1) Ratnasooriya et al., 2011; (2) Ehrhardt et al., 2014; (3) Zhu et al., 2012; (3) Auw et al., 1996; (4) Manns et al., 2013.

Table 7

Overview of the hydroxycinnamic and benzoic acids derivatives content in berries and wines of some red and white fungus-resistant grape varieties.

Matrix	Variety	Origin	Hydroxycinnamic acid and derivatives										Benzoic acid derivatives				Units	Method	Ref.
			caffeic acid	caftaric acid	cinnamic acid	coumaric acid	coutaric acid	caffeic acid ethyl ester	coumaric acid ethyl ester	ellagic acid	fertaric acid	GRP	dihydroxybenzoic acid	gallic acid	protocatechuic acid	ethyl gallate			
berry	*red*																		
	Cabernet cortis	Italy		54.6			25.7			2.97	3.96		ND				mg/kg FW	a[c]	1[d]
	Regent	Germany		36			30			4.78	1.75		0.02				mg/kg FW	a	1
		Italy		12.7			8.72			1.81	2.12		ND				mg/kg FW	a	1
	white																		
	Johanniter	Italy		17.9			6.44			2.59	4.93		ND				mg/kg FW	a	1
	Phoenix	Germany		26.3			6.49			2.28	1.79		0.03				mg/kg FW	a	1
		Italy		1.02			0.9			1.54	1.57		ND				mg/kg FW	a	1
	Solaris	Italy		15.5			6.93			2.44	1.79		ND				mg/kg FW	a	1
wine	*red*																		
	Chambourcin	China	2.2				5.76				1.09			7.79	1.63	4.81	mg/L[a]	b	2
		GA, USA		0.7–15.3			nd-9.3							2.9–17.0			mg/L[b]	c	3
	Corot noir	NY, USA	4.40–11.50	7.67–30.4	ND-0.25	1.36–14.2	2.09–13.5	0.05–1.17	0.07–2.02		0.54–1.76	0.61–3.68	0.60–1.61	4.64–10.7	0.93–1.30		mg/L	c	4
	Maréchal Foch	NY, USA	2.79–4.02	8.52–44.1	ND-0.37	3.54–4.82	1.18–10.6	ND-0.61	ND-0.71		1.48–2.65	2.37–3.84	ND-2.09	6.19–12.6	1.41–1.68		mg/L	c	4
	Marquette	NY, USA	2.98–6.64	26.7–58.8	ND	0.43–2.25	4.79–7.24	0.01–1.17	ND-0.37		1.23–1.33	3.09–6.64	ND-1.47	4.45–8.00	0.57–0.82		mg/L	c	4

[a] Hydroxycinamic derivatives are quantified in mg/L caffeic acid eq. (CAE); benzoic acid derivatives are quantified in mg/L gallic acid eq. (GAE).

[b] Quantified in mg/L gallic acid eq. (GAE).

[c] (a) UPLC–MS/MS; (b) HPLC-ESI–MS/MS; (c) HPLC-DAD.

[d] (1) Ehrhardt et al., 2014; (2) Zhu et al., 2012; (3) Auw et al., 1996; (4) Manns et al., 2013.

Table 8

Overview of the stilbene content in berries and wines of fungus-resistant grape varieties. Data on *Vitis vinifera* wines, from Naugler et al. (2007), are shown for comparison purposes.

Matrix	Variety	Origin	*trans*-resveratrol	*cis*-resveratrol	*trans*-resveratrol glucoside	*trans*-piceic	*cis*-piceid	total piceid	pallidol	astringin	Units	Method	Ref.
whole berry	*red*												
	Baco Noir	NS, Canada	4.5		9.8						mg/kg DW	a[b]	1[c]
	Cabernet cortis	Italy	nd	0.01		0.23	0.41		0.22	0.26	mg/kg FW	b	2
	Leon Millot	NS, Canada	4.3		9.0						mg/kg DW	a	1
	Lucy Khulman	NS, Canada	4.3		8.5						mg/kg DW	a	1
	Maréchal Foch	NS, Canada	4.7		7.8						mg/kg DW	a	1
	Regent	Germany	1.94	0.17		7.05	11.3		5.62	4.01	mg/kg FW	b	2
		Italy	nd	0.01		0.21	0.44		0.48	0.28	mg/kg FW	b	2
	white												
	Johanniter	Italy	nd	0.01		0.08	0.18		0.16	0.13	mg/kg FW	b	2
	Phoenix	Germany	nd	0.02		0.31	0.57		nd	0.15	mg/kg FW	b	2
		Italy	nd	nd		0.08	0.16		1.94	0.18	mg/kg FW	b	2
	Solaris	Italy	nd	nd		0.09	nd		0.26	0.13	mg/kg FW	b	2
wine	*red*												
	Baco noir	NS, Canada	0.86	3.68				3.57	0.26	0.16	mg/L RE[a]	c	3
		NS, Canada	0.90	0.80				3.95	0.14	0.18	mg/L RE	c	3
	Chambourcin	China				tr	nd				mg/L RE	a	4
		OH, USA	1.4–6.4	0.5–1.9		9.3–29.6					mg/L	d	5
	de Chaunac	NS, Canada	0.65	0.41				7.02	0.36	0.30	mg/L RE	c	3
	Leon Millot	NS, Canada	0.49	0.37				0.96	0.09	0.10	mg/L RE	c	3
		NS, Canada	0.75	0.38				1.13	0.40	0.17	mg/L RE	c	3
	Leon Millot/Lucie Kuhlman	NS, Canada	1.17	0.80				2.84	0.28	0.22	mg/L RE	c	3
		NS, Canada	1.92	0.95				2.36	0.38	0.10	mg/L RE	c	3
	Lucie Kuhlman	NS, Canada	0.93	0.68				1.64	0.16	0.16	mg/L RE	c	3
	Maréchal Foch	NS, Canada	0.15	0.74				0.64	0.06	0.04	mg/L RE	c	3
		NS, Canada	4.55	1.76				2.81	0.315	0.35	mg/L RE	c	3
		NS, Canada	0.99	0.65				1.34	0.25	0.13	mg/L RE	c	3
		NS, Canada	1.10	1.0				2.88	0.25	0.30	mg/L RE	c	3
	white												
	Noah	China				0.16	nd				mg/L RE	a	4
	Villard blanc	China				0.5	nd				mg/L RE	a	4
	V. vinifera reds												
	Zweigelt/Cabernet	NS, Canada	0.56	0.44				1.29	0.11	0.04	mg/L RE	c	3
	Pinot noir/Cabernet	NS, Canada	0.56	0.45				1.56	0.24	0.12	mg/L RE	c	3
	Pinot noir	NS, Canada	0.62	0.58				1.72	0.19	0.06	mg/L RE	c	3

[a] Quantified in mg/L resveratrol eq. (RE).

[b] (a) HPLC–MS/MS; (b) UPLC–MS/MS; (c) HPLC-DAD.

[c] (1) Ratnasooriya et al., 2011 ;(2) Ehrhardt et al., 2014; (3) Naugler et al., 2007; (4) Zhu et al., 2012; (5) Prajitna et al., 2007.

Table 9
Impact of cultural practices on grapevine, berries, juices and wine from red varieties.

treatment	variety	# year	main effects observed on			ref.
			grapevine	berry/juice	wine	
cluster thinning	Chambourcin	2–4	yield increased with crop level; thinning favored lignification and reduced bud cold injury	thinning increased TSS, TA, and pH		1[a]
	Chambourcin	5	thinning reduced yield, increased cluster and berry weight	thinning increased TSS, and pH		2
	DeChaunac	3	same yield and berry weight	no impact on TA, TSS, and pH		3
	DeChaunac	2		thinning increased TSS and total phenols		4
	Marquette	nd	thinning reduced yield	thinning increased TSS and pH		5
cluster thinning, pruning	Baco noir	3	pruning reduced yield, cluster weight	pruning increased pH and TSS		6
cluster thinning, shoot thinning	Chancellor	3	thinning increase cluster and berry weight	thinning increased TSS, pH, and red color		7
shoot thinning	Concord	nd	thinning increase cluster weight	thinning increased TSS		8
	Frontenac	1	similar cluster weight, reduced berry weight			9
	Frontenac	1	6 shoot/ft had highest cluster number and yield	no impact on TA, TSS, and pH		10
	Maréchal Foch	2	thinning reduced yield, increased berry weight	thinning increased TSS in juice, and berry anthocyanins	thinning decreased the level of C_6 alcohols (*cis*-3-hexenol, *trans*-2-hexenol, 1-hexanol) in wines but impact on wine sensory perception were minor; no impact on wine anthocyanin	11
training system	Chancellor	5	GDC[b] and YT increased yield, reduced cluster weight and showed optimal level of pruning weight when compared to HRU, 6AK, MWC	When significant, GDC showed TSS, TA and pH in the lowest range, and level of anthocyanin in the highest range		12
	Chancellor	4	GDC and 6AK had highest yields; 6AK and YT had highest cluster weight	6AK and YT had the lowest TSS and the highest pH	6AK wines had lowest% ethanol, TA and pH; GDC wines had the highest berry flavour and YT the lowest; HRU wines had the highest color intensity and the lowest intensity in earthy notes no impact on wine anthocyanins	13
	Frontenac	2	GCD increased yield	GDC had higher pH and TSS, and lower TA		14
	Frontenac	nd		VSP had higher total phenol concentration than SD		15
	Marquette	nd	UK increased yield, cluster weight, and clusters/vine	VSP increased TSS and pH; UK had lowest TSS and pH, and higher TA		16
training system and cluster thinning	Marquette	2	TWC had higher yield and cluster weight	TWC had lower TSS; cluster thinning increased TSS in TWC and VSP 18"		17
	St. Croix	2	TWC increased yield and cluster weight; cluster thinning reduced yield	TWC had higher TSS; cluster thinning increased TSS		17

[a] (1) Dami et al., 2005b; (2) Dami et al., 2006; (3) Morris et al., 1987; (4) Wood and Looney, 1977; (5) Emling and Sabbatini, 2013; (6) Byrne and Howell, 1978; (7) Morris et al., 2004; (8) Zabadal et al., 2002; (9) Rolfes et al., 2012; (10) Rolfes, 2014; (11) Sun et al., 2011b; (12) Reynolds et al., 1995; (13) Reynolds et al., 2004; (14) Bavougian et al., 2012; (15) Bavougian et al., 2013; (16) Martinson and Particka, 2013; (17) Provost et al., 2012b.

[b] 6AK: 6-arm Kniffin; GDC: Geneva double curtain; HRU: Hudson River Umbrella; SD: Smart-Dyson; TWC: Top Wire Cordon; UK: Umbrella Kniffin; VSP: Vertical Shoot Positioning; YT: Y-trellis.

Table 10
Impact of cultural practices on grapevine, berries, juices and wine from white fungus-resistant grape varieties.

treatment	variety	# years	main effects observed on			ref.
			grapevine	berry/juice	wine	
cluster thinning	Seyval	4	yield was similar between treatments; thinning increased berry weight	no impact on TA, TSS, pH		1[a]
	Seyval	1	thinning increased cluster weight, reduced yield	thinning increased TSS		2
	Vandal-Cliche	2	thinning reduced yield	no impact on TA, TSS, pH		2
	Vidal	2	thinning increased cluster weight	thinning increased TSS/TA ratio		3
leaf removal	Frontenac gris	nd	no impact on berry size	no impact on TSS, TA, pH		4
leaf removal, cluster thinning	La Crescent	nd	no impact on berry size	leaf removal + no thinning increased TSS		4
cluster exposition vs shading	Seyval	2	higher occurrence of bunch rot in shaded clusters	higher TSS and lower TA in exposed clusters	non significant differences between intensity of aroma, perceived acidity and quality of wines, but authors stated that wines from exposed clusters were “superiors”	5
	Traminette	3		full shaded clusters had lower TSS and PVT^{3} in juice; fully exposed berries had higher PVT	fruit exposure increased wine color and sensory ratings for linalool, rose and spice aromas no impact on wine taste, aftertaste and mouthfeel	6
shoot and cluster thinning	Seyval	2	shoot and cluster thinning reduced yield	little impact on TSS, TA, pH	wines issued from the cluster thinning treatment were preferred by the sensory panel only in the cooler year; under “normal” conditions, panelists rated the wines similarly	7
shoot thinning	La Crescent	1	similar cluster weight, reduced berry weight			8
training system	Kunleàny	nd	single curtain reduced winter frosts			9
	Seyval	4	GDC[b], 6-AK and YT had highest yields and lowest cluster weight	GDC and YT had lowest TSS and pH	GDC wines had lowest% ethanol and TA; GDC wines had higher intensity on melon notes, had low earthy and vegetal character, and had the lowest astringency	10
	Traminette	5	SH had highest yield compared to HC	SH and HC had higher TA, no impact on FVT[c] and PVT		11
	Traminette	2	GDC had highest berry weight compared to SH, SD and HC	VSP, SH and SD had the lowest TA; VSP had the highest juice pH; VSP and HC increased the level of FVT in juice		12
training system and cluster thinning	Louise Swenson	2	cluster thinning significantly reduced yield	TWC had higher TSS compared to VSP; cluster thinning increased TSS level in must		13

[a] (1) Morris et al., 1987; (2) Barthe et al., 2012; (3) Wolpert et al., 1983; (4) Portz et al., 2010; (5) Reynolds et al., 1986 (6) Skinkis et al., 2010; (7) Berkey et al., 2011; (8) Rolfes et al., 2012; (9) Balogh, 1989; (10) Reynolds et al., 2004; (11) Bordelon et al., 2008; (12) Ji and Dami, 2008; (13) Provost et al., 2012b.

[b] 6AK: 6-arms Kniffin; GDC: Geneva double curtain; HC: High cordon; SD: Smart-Dyson; SH: Scott Henry; TWC: Topwire Cordon; YT: Y-trellis.

[c] FVT: free volatile terpenes; PVT: potentially-volatile terpenes.

ethyl carbamate in wine (Vincenzini et al., 2009). Studies comparing the level of biogenic amine in FRG and *V. vinifera* wines showed contradictory results (Baucom et al., 1986; Soleas et al., 1999), suggesting that large differences exist between varieties. Similarly, studies showed higher level of biogenic amines in organic compared to conventional wine (reviewed by Provost and Pedneault, 2016).

3.3.3. Tannins and color

In contrast with *V. vinifera*, FRG wines contain high levels of diglycosylated and acetylated anthocyanins and high levels of delphinidin-3-*O*-glucoside and petunidin-3-*O*-glucoside that may provide their wines with purple-blue colors (Table 4) (Manns and Mansfield, 2012; Manns et al., 2013). This trait varies largely among FRG varieties.

Color instability and lack of mouthfeel are major issues in red FRG wines (Manns et al., 2013; Springer and Sacks, 2015). FRG wines generally carry low tannin levels (≤200 mg/L CE eq.) and high anthocyanin levels (200–1200 mg/L M3G eq.) (Tables 4 and 5). In comparison, red *V. vinifera* wines contain between 150 and 600 mg/L CE eq. of tannins and between 200 and 400 mg/L of anthocyanin, depending on the variety and winemaking process (Casassa and Harbertson, 2014; Kilmister et al., 2014; Pedneault et al., 2014; Springer and Sacks, 2014). Indeed, studies have demonstrated that the majority of traditional extraction processes for FRG winemaking lead to high amounts of anthocyanin rather than tannins, and yield very dark wines with little mouthfeel (Table 11, Auw et al., 1996; Manns et al., 2013; Pickering and Pour Nikfardjam, 2007; Pour Nikfardjam and Pickering, 2008).

Poor tannin extractability as well as poor retention of exogenous tannins in FRG wine was recently related to high protein concentration that may contribute to precipitate tannins during winemaking (Mansfield, 2015b; Springer and Sacks, 2014). Recently, pathogenesis-related proteins have been found to interfere with tannin retention in FRG wines (Springer et al., 2016). PR-proteins expressed in reaction to biotic stresses are the major proteins in *V. vinifera* wines; they are resistant to proteases and to low pH values, making them difficult to remove or denature (Ferreira et al., 2004).

The level of PR-proteins in wine is partly related to the disease pressure in the vineyard. For instance, organic *V. vinifera* wines were found to contain higher levels of PR-proteins compared to non-organic ones, which was attributed to their higher exposure to fungi in the field (Sauvage, 2011). The impact of disease pressure and its possible modulation of PR-protein concentration in FRG varieties grown under organic management have not been studied yet.

The solution currently proposed to resolve the tannin retention issue in FRG wine is to treat the juice or the wine with bentonite in order to precipitate the proteins and then add exogenous tannins (Springer et al., 2016).

3.3.4. Aroma

The majority of studies on the aroma of FRG wines focused on the well-known “foxy compounds” that provide the “hybrid character” to *V. labrusca*-based FRG wines. Recent GC-Olfactometry/MS analyses demonstrated that most foxy compounds such as *o*-aminophenone and methyl anthranilate are not very abundant in *V. riparia* based FRG wines (Sun et al., 2011a). Similarly, no foxy compounds were reported from GC-O/MS analyses of Frontenac wines from Minnesota (Mansfield and Vickers, 2009; Table 12).

Many red FRG wines are known for their fruitiness but herbaceous notes are also reported in certain varieties such as Cabernet cortis, Prior, Regent and Frontenac, among others (Table 12; Mansfield and Vickers, 2009; Rousseau et al., 2013). Herbaceousness could relate to the presence of methoxypyrazine and/or C_6 compounds such as hexanol and *cis*-3-hexenol in wine (Mansfield and Vickers, 2009; Pedneault et al., 2013a). The level of methoxypyrazines has been showed to decrease significantly in Frontenac berries during berry ripening (Pedneault et al., 2013a). The C_9 aldehydes nonanal and *trans*,*cis*-2,6-nonadienal have been shown to reach above-threshold concentrations in red FRG wines from Eastern Canada, suggesting that they could contribute to the green notes found in certain FRG wines (Slegers et al., 2015). The concentration of *trans*,*cis*-2,6-nonadienal has also been showed to increase in Frontenac and Marquette berries during ripening (Pedneault et al., 2013a).

3.4. Improving FRG wine quality

Historically, assays carried out to improve the quality of FRG wine were primarily meant to reduce the occurrence of foxy flavors with the use of different winemaking processes. In 1974, carbonic maceration was found to efficiently reduce foxy flavors in red Concord (*V. labrusca*) wines (Fuleki, 1974; Table 11). Carbonic maceration (CM) was initially developed to reduce oxidation reactions occurring spontaneously in grapes in order to preserve fruit flavors (Paul, 1996b). In organic wine production, restricting contact between berries and air using CM may be of particular interest because organic grapes have been shown to carry twice as much polyphenol oxidase activity compared to conventional ones (Núñez-Delicado et al., 2006).

White FRG wines such as Chardonnel, Solaris and La Crescent generally present desirable flowery notes that may be related to compounds such as C_{13}-norisoprenoids (e.g., β-damascenone) and monoterpenes (e.g., linalool) located in berry skin (Table 12; Cadwallader et al., 2009; Savits, 2014; Liu et al., 2015). In fact, extended skin maceration (24 h cold-soak and 30 h on-skin fermentation) significantly improved the intensity of floral notes in Solaris wines, but also increased green vegetable notes (Zhang et al., 2015). Conversely, short cold-soaks (3–8 h) did not improve the aroma intensity of Traminette wine (Skinkis et al., 2010).

A recent study reported for the first time the presence of 3-mercaptohexanol in the FRG variety Cayuga, at a concentration of 195 ng/L (Musumeci et al., 2015). This compound is a highly odor potent thiol (odor perception threshold: 60 ng/L) that produces a grapefruit aroma in white wine (Musumeci et al., 2015). Cayuga white is an offspring of Seyval blanc (Seyve-Villard 5–276), a variety that has often been used during the breeding of recent FRG varieties. This suggests that 3-mercaptohexanol could be present in other FRG varieties, although its presence has not yet been investigated. Based on this finding, viticulture (e.g., nitrogen status, disease control) and winemaking practices (e.g., oxidation control) that either enhance thiol production in berries, protect thiol during winemaking, or lead to thiol expression in wine could contribute to increase the occurrence of tropical aroma in FRG wines (Musumeci et al., 2015).

Blending is one of the most efficient ways to optimize the aroma of FRG wines. Indeed, most FRG varieties present a very large and rich flavor range, and many of them have complementary flavor profiles (Slegers et al., 2015). Blending may also significantly improve wine balance, especially acidity, reduce bitterness and improve wine’s overall bouquet. Such richness makes FRG varieties suitable to a large range of styles that have a high potential to appeal to consumers.

4. Conclusion

The well-documented susceptibility of *V. vinifera* cultivars to major diseases such as powdery mildew, downy mildew and botrytis is a significant challenge in organic viticulture. Increasing the

Table 11
Overview of the impact of several winemaking processes on the chemistry and the sensory perception of wines made from fungus-resistant grape varieties.

Treatments	Variety	Yeast strain	Impacts on wine			ref.
			Basic chemistry	Phenolic and volatile compounds	Sensory perception	
Extraction and alcoholic fermentation processes						
3 vs 8 h cold-soak at 12 °C	Traminette	Lalvin K1-V1116			no perceptible impact on wine aroma intensity	*1*[a]
– direct press after crushing – whole cluster press – 6 h cold soak – 24 h cold soak – 6 or 24 h cold soak + 30 h skin fermentation *chemical deacidification used on all treatments	Solaris	Lalvin DV10TM		24 h cold soak with or without skin fermentation increased total polyphenols; extended skin contact (24 h cold soak + 30 h skin fermentation) increased the concentration of linalool, hotrienol, α-terpineol, β-damascenone and S-methyl thioacetate in wine.	extended skin contact (24 h cold soak + 30 h skin fermentation) increased the intensity of floral (Rose, Elderflower) and green vegetable descriptors.	*2*
- cold-soak – enzyme addition at crush *- tannins addition at crush* *- hot press compared to skin fermentation (7 days)*	Maréchal Foch	GRE		hot press increased the level of non anthonyanin phenolic (including caftaric acid, coutaric acid, catechin, epicatechin, catechin, rutin), and the level of monoglucoside and diglucoside anthocyanins; tannin addition and hot press increased tannin concentration but had no impact on their mean degree of polymerization.		*3*
	Corot noir	GRE		*tannin addition increased tannin concentration whereas hot press decreased it, both did not impact the mean degree of polymerization.*		*3*
- hot press *- skin fermentation (7 days)*	Marquette	GRE		hot press increased anthocyanin monoglucosides and tannin concentrations.		*3*
- immediate press for juice *- immediate press for wine* *- hot press for juice* *- hot press for wine* *- skin fermentation (7, 13, and 21 days)*	Chambourcin	Prise de mousse		hot press (juice and wine) increased color intensity (A520 nm); 13d and 21d skin fermentation decrease color intensity compared to 7d treatment; immediat press (juice & wine) increased browning (Hue); extended on-skin fermentation decreased the level of caftaric acid, coutaric acid, and procyanidin B3, and increased the level of gallic acid; hot press increased total phenol concentration.		*4*
-carbonic maceration (CM) at 15 or 27 °C, for 1 or 2 weeks *- skin fermentation* *- hot press*	Concord	no starter in CM; unknown starter used in other trials		carbonic maceration reduced the occurrence of bluish tones, the concentration in total phenols and decreased the concentration in methyl anthranilate.	carbonic maceration decreased the intensity of *V. labrusca* typical flavor.	*5*

Table 11 (*Continued*)

Treatments	Variety	Yeast strain	Impacts on wine			ref.
			Basic chemistry	Phenolic and volatile compounds	Sensory perception	
two experiments: 1) *Standard fermentation with varying percentage of whole berries;* 2) *CM with whole clusters (2, 4, 8 days)*	Maréchal Foch	Epernay II	the use of 100% whole berries or whole clusters decreased the level of residual sugars; 8d CM decreased TA and alcohol percentage, and increased pH	100% whole berries and whole clusters decreased total phenols and color; extended CM (8d) increased total phenols.		*6*
addition of OptiRed® (inactivated yeast derivative) at the beginning of skin fermentation (19 days)	Baco noir	EC1118		OptiRed® increased the concentration of dimers procyanidins; OptiRed® increased the concentration of tyrosol and quercetin, and decreased the concentration of caffeic acid, grape reaction product, and delphinidin.	OptiRed® had no perceptible impact on wine mouthfeel.	*7,8*
	Maréchal Foch	EC1118		OptiRed® increased the concentration of dimer and trimers procyanidins; OptiRed® increased the concentration of caffeic acid and decreased the concentration of caftaric acid, *p*-coumaric acid, and quercetin.	OptiRed® had no perceptible impact on wine mouthfeel.	
malolactic fermentation (MLF): *non inoculated control compared to inoculation with the Leuconostoc oenos strains ML-34, PSU-1, and LS-5A*	Chancellor, DeChaunac, Maréchal Foch	Montrachet	Non-inoculated control did not completed MLF; PSU-1 and LS-5A strains completed MLF faster than ML-34; MLF increased wine pH in Chancellor (strain LS-5A only) and Maréchal Foch, decreased TA, and increased volatile acidity in all wines.		wines fermented with PSU-1 and LS-5A were preferred over ML-34 wines; all inoculated wines were preferred to the non inoculated control.	*9*
Post-fermentation processes and aging						
French (Nevers; Limousin) and American oak barrels aging compared to unoaked control	Seyval	n.d.		american oak increased gallic acid content of wine at a slightly higher rate than French oak; the concentration of other non-flavonoid compounds (photocatechuic, vanillic, caffeic, syringic and *p*-coumaric acids) were no affected.	perceptible changes in sensory attributes of wines compared to unoaked control were perceptible after 7 weeks of aging; by the 12th week, wines were distinguishable according to the oak type used for aging.	*10*

[a] (1) Skinkis et al., 2010; (2) Zhang et al., 2015; (3) Manns et al., 2013; (4) Auw et al., 1996; (5) Fuleki, 1974; (6) Miller and Howell, 1989; (7) Pour Nikfardjam and Pickering, 2008; (8) Pickering and Pour Nikfardjam, 2007; (9) Giannakopoulos et al., 1984; (10) Jindra and Gallander, 1987.

use of FRG varieties would allow significant benefits for organic and conventional growers, including reducing the number of treatments per season, increasing grape yield and reducing labor costs. In addition, FRG would allow significant reduction in the use of copper-based fungicide, therefore contributing to decrease copper accumulation in vineyard soils, especially in areas under high disease pressure.

Consumer surveys have showed that wines made from FRG varieties are at least equivalent and frequently rated as superior to *V. vinifera* wines in terms of quality. Trials conducted over the last 30 years have showed that canopy management and winemaking practices can contribute to improved FRG wine quality. Further research on these topics are needed to provide a more comprehensive understanding of the optimal cultural and winemaking practices for FRG varieties, with an emphasis on the potential side-effects from disease resistance that could interfere with the development of high quality wines (e.g., PR-proteins).

The commercialization of organic FRG wines faces a double challenge of growing grape varieties that are generally unknown to consumers and doing it under organic management. Both FRG and organic wines previously suffered from the production of bad wines that contributed to negative opinions among consumers

Table 12
Overview of volatile compounds, impact odorants and sensory descriptors in wines from 20 fungus-resistant grape varieties.

Variety[*]	Method	Analytical		Sensory	Ref.
		Volatile compounds[1]	Concentration (μg/L)	Aroma and flavors descriptors	
reds					
Cabernet Cortis	sensory analysis using similar descriptors for all varieties evaluated			foxy, herbaceous, bell pepper, jammy, spicy	1[a]
Chancellor	descriptive analysis			berry, currant, earthy, vegetal	2
Frontenac	descriptive analysis & G C-O/MS	ethyl isobutyrate[**]	0.1–0.5 mg/L	cherry, black currant, vegetal, earthy	3
		ethyl lactate	0.2–1.5 mg/L		
		ethyl 2-methylbutanoate	30–200		
		ethyl 3-methylbutanoate	40–720		
		1-hexanol	0-0.8 mg/L		
		ethyl hexanoate	1.2–3.6		
		phenethyl alcohol	0.8–2.1 mg/L		
		diethyl succinate	1.4–4.4		
		octanoic acid	0.8–5.4		
		ethyl decanoate	1.1–3.7		
Frontenac	GC–MS & odor activity values	nonanal	40		4
		trans,cis-2,6-nonadienal	1.26		
		β-damascenone	3.99		
		ethyl 2-methylpropanoate	281		
		ethyl hexanoate	450		
		ethyl octanoate	1128		
Maréchal Foch	GC–MS & odor activity values	nonanal	34.8		4
		trans,cis-2,6-nonadienal	1.44		
		β-damascenone	2.25		
		ethyl 2-methylpropanoate	281		
		ethyl hexanoate	227		
		ethyl octanoate	781		
Marquette	GC–MS & odor activity values	nonanal	52.2		4
		trans,cis-2,6-nonadienal	1.15		
		β-damascenone	2.47		
		linalool	36.2		
		ethyl 2-methylpropanoate	254		
		ethyl butanoate	327		
		ethyl hexanoate	803		
		ethyl octanoate	2383		
Othello	GC–MS & odor activity values	methyl anthranilate			5
		trans-2-hexenal			
		hexanol			
		ethyl 3-methylbutanoate			
		nonanal			
		2-phenylethanol			
		ethyl decanoate			
Prior	Sensory analysis using similar descriptors for all varieties evaluated			foxy, fusel alcohol, herbaceous, fresh fruit, jammy	1
Regent	Sensory analysis using similar descriptors for all varieties evaluated			foxy, animal, herbaceous, spicy	1
Sabrevois	GC–MS & odor activity values	nonanal	33.4		4
		trans,cis-2,6-nonadienal	1.13		
		eugenol	23.1		
		ethyl 2-methylpropanoate	283		
		ethyl octanoate	643		
St. Croix	GC–MS & odor activity values	nonanal	30		4
		trans,cis-2,6-nonadienal	1.19		
		eugenol	3.38		
		ethyl 2-methylpropanoate	265		
		ethyl octanoate	768		
whites					
Cayuga white	GC-O/MS (Charm)	2-phenylethanol			6
		β-damascenone			
		C_3 and C_4 fatty acids			
		ethyl butyrate			
		linalool			

Table 12 (*Continued*)

Variety*	Method	Analytical		Sensory	Ref.
		Volatile compounds[1]	Concentration (μg/L)	Aroma and flavors descriptors	
	GC–MS	3-mercaptohexanol	195 ng/L		7
Cabernet blanc	Sensory analysis using similar descriptors for all varieties evaluated			herbaceous, citrus fruit, tropical fruit	1
Chardonnel	descriptive analysis, GC-O. GC–MS, and OAVs	ethyl butanoate	147–422	fruit, floral, spicy	8
		ethyl 3-methylbutanoate	ND-25.1		
		ethyl hexanoate	721–999		
		3-methyl-1-butanol	37.5–170 ppm		
		2-phenylethanol	8.94–23.4 ppm		
		β-damascenone	1.4–3.2		
		sotolon	detected in GC-O; not quantified		
Johanniter	sensory analysis using similar descriptors for all varieties evaluated			sulfur, white fruit in syrup, dry fruit, apricot	1
La Crescent	descriptive analysis			apricot, grapefruit, lychee, pineapple, rose	9
Muscaris	sensory analysis using similar descriptors for all varieties evaluated			sulfur, fusel alcohol, citrus fruit, tropical fruit, white fruit in syrup	1
Seyval	descriptive analysis			floral, apple, earthy, melon, vegetal	2
	descriptive analysis			fruity, vegetal, caramelized, pungent	10
	GC-O/MS (Charm)	β-damascenone 2-phenylethanol methyl anthranilate ethyl 2-methylbutanoate vanillin			6
Solaris	descriptive analysis, GC–MS	ethyl butyrate		peach/apricot, Muscat, melon, banana, strawberry	11
		propyl acetate butyl acetate 3-methylbutyl acetate hexyl acetate *trans*-3-hexenyl-acetate 2-phenylethyl acetate			
	descriptive analysis			fruity, citrus, tropical fruit, flowery, elderflower	12
Vidal	GC-O/MS & OAVs	ethyl 2-methylbyturate***	14.2		13
		β-damascenone	11.3		
		decanal	13.7		
		geranyl acetone	0.26		
		ethyl hexanoate	878		
		1-octanol	9.34		
		nerol oxide	6.98		
		4-vinylguaiacol	111		
	descriptive analysis			young wines: apple, tropical fruit, citrus aged wines: cooked vegetables, straw, oxidized, pungent	14
	GC-O/MS (Charm)	β-damascenone 2-phenylethanol linalool			6

* 3 to 9 wines per varieties.

** Compounds with frequency of detection higher than 75%.

*** Nose-perceptible odorants.

[a] (1) Rousseau et al., 2013; (2) Reynolds et al., 2004; (3) Mansfield and Vickers, 2009; (4) Slegers et al., 2015; (5) Radulović et al., 2010; (6) Chisholm et al., 1994; (7) Musumeci et al., 2015 (8) Cadwallader et al., 2009; (9) Savits, 2014; (10) Andrews et al., 1990; (11) Liu et al., 2015; (12) Linden, 2014; (13) Bowen and Reynolds, 2012; (14) Chisholm et al., 1995.

concerning these products. Therefore, significant efforts are necessary to demonstrate and improve the quality of organic FRG wines, and have them accepted by consumers. According to the Web of Science database, the number of scientific publications involving FRG varieties increased by 86% between 2011 and 2016, when compared to the 2005–2010 period (search restricted to “fungus resistant grape or varieties” and “interspecific hybrid grape or varieties”). Such rise in the interest for FRG opens the door to great expectations regarding the future of these varieties, in both organic and conventional viticulture.

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