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Review

Minerality in Wine: Towards the Reality behind the Myths

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Abstract: Tasting minerality in wine is highly fashionable, but it is unclear what this involves. The present review outlines published work concerning how minerality in wine is perceived and conceptualised by wine professionals and consumers. Studies investigating physico-chemical sources of perceived minerality in wine are reviewed also. Unusually, for a wine sensory descriptor, the term frequently is taken to imply a genesis: the sensation is the taste of minerals in the wine that were transported through the vine from the vineyard rocks and soils. Recent studies exploring tasters' definitions of minerality in wine support this notion. However, there are reasons why this cannot be. First, minerals in wine are nutrient elements that are related distantly only to vineyard geological minerals. Second, mineral nutrients in wine normally have minuscule concentrations and generally lack flavour. Results of reviewed studies overall demonstrate marked variability in both wine professionals' and wine consumers' definitions and sensory-based judgments of minerality in wine, although there is some consensus in terms of the other wine attributes that associate with the term mineral. The main wine composition predictors of perceived minerality involve a complex combination of organic compounds dependent on grape ripeness and/or derived from wine fermentations and redox status.

Keywords: minerality; wine; sensory; chemistry; language

1. General Introduction

In the last decade or so, use of the word minerality in wine descriptions has increased markedly in frequency. Prior to this, certain wines were described as being "lean", "racy", "austere" and the like, but recently, it has become preferable to talk of the wines as being mineral, minerally or showing minerality. Apparently such m-words are now the most often used wine descriptors of all, even outstripping fruity, acid, oaky, and so forth [1]. Clearly, to many, the idea of minerality in wine is both welcome and useful.

However, the concept remains enigmatic and controversial in a number of ways, several of which are discussed in the present paper. The review begins by considering how minerality is conceptualised, including linguistic aspects associated with using the word as a geological metaphor, and how use of the term varies with tasters' expertise in wine. Of significance, unlike virtually all other sensory descriptors, the word mineral is often taken to have a literal origin; that is, that tasters are actually tasting minerals in the wine, transmitted through the vine from the rocks and soils in the vineyard. To address this notion, the article then summarises reasons why this cannot be, in any literal way, leading to the conundrum of what it is that tasters are perceiving in a wine that they report as mineral. This introduces analysis of sensory investigations aimed at deconstructing the concept of minerality, along with cross-cultural considerations and wine-variety differences. Finally, the review considers chemical constituents of wine that have been identified as potential drivers of perceived minerality.

2. Conceptual and Linguistic Aspects of Perceived Minerality in Wine

Currently, there appears to be no accepted definition of minerality in wine, no consensus on the characteristics that are associated with it, nor even whether it is perceived primarily as a smell, a taste or a mouthfeel sensation. Therefore, the first step in order to understand perceived minerality is exploration of the cerebral representation associated with this concept for different kinds of tasters and social groups. A number of strategies have been employed to achieve this purpose, and these are reviewed below.

2.1. Definition Tasks

The early studies on wine minerality adopted simple definition tasks using panels of wine professionals and occasionally wine consumers. For example, Ballester and colleagues [2] asked 34 wine professionals from the Chablis region in France to provide a short definition of wine minerality and to indicate which sensory modality they used when assessing minerality (i.e., nose, palate or both). The results of the questionnaire indicated that 63% of the wine professionals declared that they assessed minerality combining orthonasal (nose) and other flavour information (e.g., retronasal aroma; palate), while 20% only declared assessing minerality solely on the palate and 16% only by nose. Concerning the definition task, wine professionals elicited a large diversity of words and expressions to define minerality, suggesting that experts' definitions are far from consensual. The definitions reported referred to odours, tastes and textural sensations, confirming that minerality cannot be univocally associated with a single sensory modality. Moreover, some metaphoric and contradictory definitions were given by the respondents.

The words most frequently associated with wine minerality were categorised within several semantic categories. The most important of them was the stone-related category which comprised largely olfactory sensations and included gunflint, flint, wet or hot stone and chalky. A second important semantic category comprised mostly palate sensations that were related to acidity/freshness, but also included tension and vivacity. The third category in importance was composed of seashore-related terms such as iodine, saltiness, algae and shellfish.

The authors' results [2] were supported by a larger-scale study [3] that included not only a substantial number of wine professionals (N = 1411), but also wine consumers (N = 1339). In this study, the main semantic categories found for wine professionals were also stone-related and acidity/freshness-related terms, as well as many citations of saltiness and iodine. Additionally, the wine professionals evoked the idea that minerality was mainly associated with dry white wines. As expected, their corpus was richer than that of wine consumers. The stone-related semantic category was also quite important for consumers, although there were interesting difference between their data and that of the wine professionals: occurrences concerning the acidity/freshness category were rather low, and there was virtually no mention of saltiness or iodine by consumers. From this result, the authors interpreted that, unlike wine professionals, novices interpreted the word minerality in a very evocative way without associating any particular sensory dimensions. Whatever the group of respondents considered the word terroir to mean, it was amongst the most cited words.

The consumer corpus from Le Fur and Gautier's study [3] reported above was complemented with Swiss respondents in order to compare French and Swiss conceptions of minerality. These results showed that minerality represented different things to Swiss and French consumers. Swiss consumers had a richer vocabulary and higher declared wine knowledge than French [4], and the data concerning the definition of minerality showed that both groups cited mainly terroir and stone related terms. However, Swiss consumers cited many terms related to palate sensations that were virtually absent from the French corpus (saltiness; fizziness), while the proportion of respondents that declared not knowing anything about wine minerality was much higher in the French group.

In a later article, [5] the researchers proposed an innovative and rapid method to analyse free text data collected by open-ended questions using the previously mentioned wine professionals' data on minerality [3]. The results showed five main word clusters corresponding to different semantic fields. Besides the expected "soil link" cluster, an interesting "exemplification" cluster indicated that when the respondents had difficulties finding a definition, they tended to find examples of wine styles (e.g., white, dry), varieties (e.g., Sauvignon) or regions (e.g., Loire). Moreover, a small cluster of respondents introduced the idea of elegance and finesse associated with wine minerality. The remaining two clusters produced more ambiguous topics, mixing aroma, taste and mouthfeel sensations (e.g., freshness, saltiness, sourness).

A similar statistical approach was used by Deneulin and colleagues [6] on the consumer corpus. In this study, the authors tried to relate the socio-economic characteristics of the respondents to their conceptualisation of wine minerality. Results showed that the respondents could be grouped into ten clusters. Amongst them, some interesting trends emerged; the most inexperienced respondents declared to have never heard about minerality in wine. Young women, also inexperienced, mainly associated minerality with mineral ions as in bottled water. Older consumers related wine minerality with the idea of terroir as in all the previous studies. Finally, the most experienced consumers referred to sensory perceptions such as gunflint or acidity, which are two of the main semantic categories found in previous studies for wine professionals. The conceptual changes evidenced as a function of wine knowledge, from the more- to the less-experienced consumers, was interpreted by the authors as a conceptual transfer from wine professionals towards the wine connoisseurs. The respondents with lower expertise levels appeared to base their definitions on evocations and associations, but not on actual wine knowledge.

The researchers [6] also looked at the use of the term minerality in the Google corpus of French books. They noticed that the use of the term minerality reached a first maximum around 1994 at the same time the use of the term terroir started to decline. The authors hypothesised that the term minerality may have been employed in the last decade as a substitute for the term terroir, possibly related to overuse of the word terroir for other agricultural products.

2.2. Social and/or Cerebral Representation Methodology

Another approach to investigate the minerality concept was employed by Rodrigues and colleagues [7]. The authors used the theoretical framework of social representation [8], in particular the prototypical structural approach [9,10], to investigate wine professionals' and wine novices' minerality cerebral representations. This approach reveals not only the content (different elements or ideas) of the representation but also how these elements are structured [11]. By means of a free word-association task, the authors explored the minerality representation of a group of winemakers and a group of wine consumers, all of them from Burgundy. In addition, participants had to judge the importance and the valence of each elicited word. The combination of the average importance and the frequency of citation of each word gave an idea of its centrality in the representational structure. Results showed quite different representations for winemakers and wine consumers. Hence, the results are reported here in some detail.

The central core (elements with high citation and high importance) of the winemakers' representation included six elements, three of them with the highest frequency and importance being Chablis, terroir and geology related to origin and soil (see Figure 1). The remaining words of the central core were chalky, freshness and shellfish. While chalky is quite ambiguous (i.e., can be related to soil composition or to a sensory dimension), the other two are sensory properties of the wines that seem central to winemakers. By comparison, the central core for wine consumers was remarkably poor with only a single element: terroir.

The first periphery (i.e., elements with high citation, but low importance) of the winemakers' representation was also quite different from that of consumers. While winemakers had one element related to soil (stone) and three related to sensory properties (acidity, gunflint and salty), consumers had only one word, namely stone. The contrasting elements' zone (low frequency and high importance elements) also revealed different representations as a function of group; for winemakers, this zone evoked sensory attributes of iodine, tenseness and sensation, along with elements related to wine quality (quality and finesse). For consumers, sensory properties only were found in this zone (taste, chalky, freshness, salty, gunflint and colour). The final result to report concerns the second periphery, which represents idiosyncratic elements. This was the most numerous in terms of elements in the consumers' representation (18 elements), while only five elements were present in the wine professionals' representation.

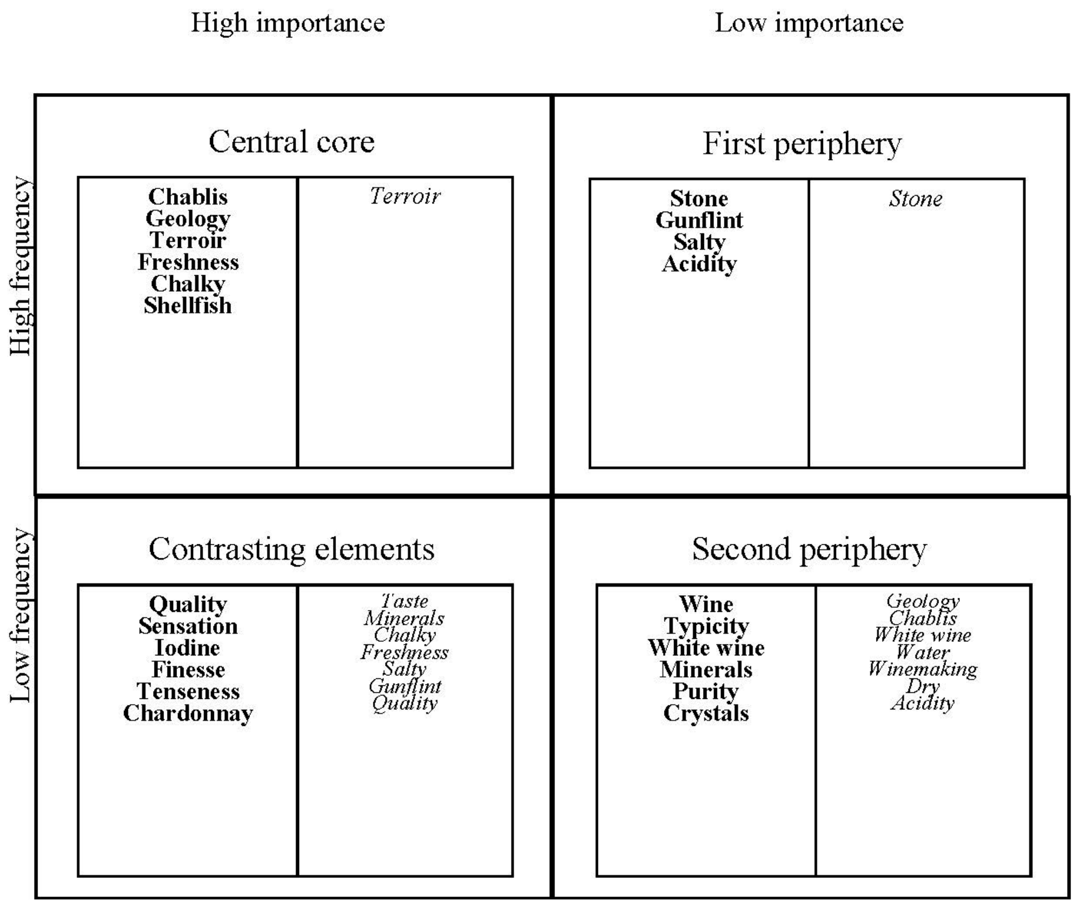

Figure 1. Diagram to exemplify the structure of a social representation according to Abric (1987), with the representational content from Rodrigues et al. (2015): wine producers in bold letters; wine consumers in italics.

Overall, the results of Rodrigues and colleagues [7] suggest that while many conceptualised elements concerning minerality in wine are common to winemakers and consumers, the structure of their respective representations is quite different. Winemakers showed a stable and well-structured representation based on a sense of place and the soil where the vines are grown. Their representation was completed by sensory dimensions related to minerality that were in agreement with previous studies employing alternate methodologies, and included complex concepts linked with wine quality. In contrast, the consumers' representation was relatively poor with only one element in the central core and many idiosyncratic elements in the second periphery of the concept's structure. Moreover, according to their valence scores, winemakers always associated a positive connotation to minerality, while some consumers expressed neutral or even negative connotations. In agreement with Deneulin and colleagues [6], the authors suggested that wine professionals' minerality representations emerged from their social practice and that such discourse is adopted by consumers afterwards.

2.3. Synthesis and Summary

Despite the different methodological approaches used to delineate the concept, minerality in wine seems to be a multimodal concept combining olfaction, gustation and mouthfeel sensations. The main olfactory dimensions reported were stone/flint related attributes, iodine and sea-related terms (e.g., shellfish). In terms of taste, the main dimensions reported were sourness and saltiness. Finally, for many study respondents, the concept of minerality appears to have a strong link with the notion of terroir, suggesting a causal relationship in the minds of participants.

3. Geological Considerations

Because of this cerebral association of minerality with soils, stones and terroir, this review now considers such geological matters, in particular the extent to which the conceptualised links have a tangible geological basis.

3.1. The Geological Mineral: Nutrient Mineral Confusion

It is well known that the vineyard ground is made of minerals, that plants need minerals to grow and that foodstuffs such as wine contain minerals. Hence, especially in view of the long-treasured connection between wine and the land, it is easy to see the temptation to give wine minerality a literal meaning: i.e., that tasters are simply tasting minerals in the wine that were transmitted there through the vine from the vineyard. It is a simple and attractive picture; the reality, however, is different, and geologist Alex Maltman detailed the arguments in a prior publication [12]. They are summarised here.

First, there is the confusion that surrounds the word mineral. The physical framework of a vineyard soil is indeed made of minerals, but these are solid, inorganic, chemical compounds and usually complex ones involving a range of chemical constituents intimately bonded together. They are minerals in the geological sense. On the other hand, the minerals essential for vine growth and present in wine are almost all single elements, mostly metals, and they have to be dissolved in water as cations in order for the vine roots to be able to use them. These are minerals in the nutrient sense.

Consider what is probably the most common geological mineral in the world's vineyards, feldspar; it contains potassium and other elements that are potential nutrients, but they are all inter-locked, sharing electrons in a crystalline lattice that gives a grain of the mineral strength and rigidity. To be accessible to vine roots in order for these elements to become potential nutrients, they have to become loosened and abstracted from this lattice and somehow taken into solution. This can utilise mycorrhizae and other microbiota [13] (although these function mainly in rich, fertile soils that are usually not taken to produce wines with perceived minerality), or it may involve a whole series of variable physico-chemical processes summed up by the term "weathering". These degrade the feldspar into a clay mineral such as kaolinite, which is able to exchange ions with the adjacent soil pore-water [14].

3.2. Mineral Nutrients in the Vine

Weathering processes, however, are simply too slow for the vineyard geology to be able to provide each year a new set of nutrient minerals. Hence, as in all agriculture, the nutrient minerals come largely not from the vineyard geology, but from the soil's organic component, humus [15]. Humus recycles and replenishes the supply, and it has a greater ion exchange capacity than clays. Moreover, it is the only means of providing at least two of the essential nutrients, nitrogen and phosphorus, as these are lacking in normal geological minerals.

Another matter often overlooked is that even if nutrients are available in the soil pore-water, they are not necessarily absorbed by the roots [16]. Various mechanisms within the vine, involving transporter proteins, lipid bilayers in membranes, hydrophobic deposits in cell walls, and so forth, determine which ions are loaded into the xylem and which are rejected. There is some passive uptake of ions, and the selectivity mechanisms are far from infallible, which can lead to nutrient imbalances; but these are routinely checked for by a conscientious grower and corrected as necessary.

Roots take up essential nutrients because they are needed in the growth processes, but although it may seem a truism to say so, the actual source of the nutrients is irrelevant [17]. The vine does not differentiate whether a particular nutrient mineral originated in this or that geological mineral, in humus or in fertiliser. An element is the same, irrespective of source, and does the same job.

3.3. Mineral Nutrients in Wine

The proportions of the different nutrients undergo further complex changes as vinification proceeds, through fermentation, possible filtering and fining and maturation [18–20]. Thus, the nutrient proportions in the eventual wine have only an indirect and complicated relationship with those in the vineyard ground, one reason why no way has been found to use these elements to identify regional identity and combat wine fraud [21,22]. This disconnect between the nutrient minerals in the wine and the vineyard's geological minerals differs substantially from the simple picture of the vine hoovering up whatever minerals are in the vineyard geology and then acting as a conduit to transport them through to the wine. There is however an even more serious difficulty with the idea: the actual amounts of the minerals in wine are minuscule, and they are virtually tasteless.

Although wines are popularly described as "mineral crammed", "mineral laden", "brimming with mineral" and the like [23], the inorganic content of wine is typically only around 0.15–0.20%, and 0.4% at the most [24], and most of that is potassium [25]. Occasionally, wines can have higher concentrations, but this is usually due to contamination from winery plumbing, traffic pollution or agrochemicals [26]. Significantly, this can present problems for the winemaker such as stuck fermentations and hazes.

There have been attempts to establish human detection thresholds for these dissolved inorganic elements in drinking water. The values are subjective and debatable [27], but they are generally higher than the concentrations found in wine. Moreover, in water, there are few competing flavour compounds, so that in wine, with its aromatic molecules detectable and recognisable at exceedingly low values [28], the thresholds must be vastly higher. Further, water tasters report that as the presence of metal ions becomes increasingly detectable, the water becomes more and more disagreeable [29]. In short, this hardly sounds like a desirable minerality. The presence of mineral nutrients in wine is certainly important in that they are known to affect a range of chemical reactions [30] and to influence our taste perceptions [31], but these are complex and circuitous effects; tasters are not actually tasting the minerals.

Worth noting is that the situation with groundwater is different. It can have a detectable flavour, as in some bottled waters, because substantial amounts of inorganic salts can be dissolved directly from the walls of the host aquifer [32]. The solubility of some of the elements is low, but then there is plenty of time: in the U.K., the average residence time of groundwater in an aquifer is over a century. Unlike with vine roots, there is no selectivity, so groundwater can contain all sorts of different elements. This includes sodium and chloride, which are normally rejected by vines [33], together with such things as bicarbonate, sulphate and halide. These are relatively insignificant in wine composition [34], but in groundwater, they can have a distinctive, measurable taste.

3.4. Rocks and Minerals Have No Flavour

There is a further problem with the idea that minerality has a literal, geological meaning. Because geological materials neither dissolve easily nor vaporise, they basically lack taste and smell: licking a freshly broken surface of a mineral or rock surface merely gives a tactile sensation. The only significant exception is the mineral halite (sodium chloride), which aggregates to make rock salt. It rapidly dissolves and, of course, gives the sensation of saltiness on the tongue. In general, growers avoid salt in vineyard soils, and as mentioned above, grapevines try to prevent its uptake. Hence, wine normally contains little salt, less than the minimum of several hundred parts per million that most people require to be present in water in order to recognise it [35]. The organic compounds that evoke the tastes of sweetness, bitterness and umami are not present in geological minerals or rocks.

Therefore, while it may be useful to conjure what rocks and minerals ought to taste like, thereby subliminally reinforcing a vineyard, ground-flavour connection, there is no tangible basis. Tasters are drawing on cognitive phenomena such as recollecting some cue that associates a taste or smell experience with something geological, but which is not itself involved in wine. The following are some examples of geological recollections used in this way.

3.5. Geological Terms as Metaphors

A number of "geological" smells arise from highly aromatic compounds that are common in the air and that become deposited on exposed earthy surfaces. For example, an earthy smell results from compounds common in vineyards and wineries such as 2-methylisoborneol derived from algae and a terpene known as geosmin (*trans*-1,10-dimethyltrans-9-decalol) due to bacteria and moulds [36]. Both these compounds have aromas that can be smelled when the earth is being tilled.

Similarly, an aroma of wet stone may be due to the release of the organic oils mentioned above together with what has been called petrichor [37]. This includes lipids, terpenes, carotenoids and, according to Bear and Kranzs [38], various fatty acids in the air, arising from the decomposition of animal and vegetable matter [39]. An exposed geological surface, on warming, wetting or when the relative humidity of the atmosphere approaches saturation, readily releases its film of these highly volatile compounds to give the familiar wet or hot stone odour. The metallic smell associated with handling coins and metal implements arises from the rapid reaction between the metal and skin chemicals to give highly volatile aromatic compounds. For example, Glindemann and colleagues [40] found that an odour described as metallic in vapours next to skin touching iron was due to the ketone 1-octen-3-one, detectable by humans even at very low concentrations.

In Section 2, it was reported that the perception of minerality is sometimes related to seashells [2], and Section 5 mentions possible organic sources of this aroma. The shells themselves, being composed very largely of the geological minerals calcite and aragonite, have no taste or smell. More often though, the connection is made with their fossilised ancestors, which happen to be conspicuous in the bedrock of a number of the world's vineyard regions (e.g., Chablis in France). However, equally, such fossilised shells have no flavour, being replicas preserved in durable geological minerals (most commonly calcite and quartz), which are wholly flavourless, as discussed earlier. Seeing fossil seashells in vineyard soils may prompt us to think of seafood and things maritime, but for the vines fossils are indistinguishable from any other piece of stone.

Section 2 also mentioned a flinty taste in wine. Geologically, flint is an ultra-fine-grained variety of silicon dioxide (the compound that also makes quartz), which in all its forms is tough, insoluble and virtually inert. This is why silicon dioxide is used as the basis of glass. Consequently, flint lacks any taste or odour and is unavailable to vine roots. To many, the epitome of flintiness lies in the wines from Chablis, but the vineyard soils there lack flint. The perception is probably a recollection of the distinctive smell produced by vigorously striking lumps of flint together, the chemical cause of which is discussed below in Section 5.

The frequently mentioned allusion to the aroma of gun-flint, or the smell of a struck flint or match, may also have the chemical origin reported in Section 5, but there is another effect at work. Capone and colleagues [41] suggested this may also involve benzyl mercaptan. If certain substances are struck in the presence of oxygen, they expel tiny fragments that burn, that is they spark [42]. The elements sodium, potassium and calcium, for example, do it spontaneously. The phosphorus used in match heads needs the addition of a little heat, such as from the friction of striking a match, while a few metals, including iron, spark if they are hit forcibly enough [42]. This is the basis of the "flint" in firearms and lighters, although in modern times, the iron or steel hits a synthetic alloy of cerium and iron. The true smell of gun-flint comes from the flintlock mechanism of early firearms, which few will have experienced, but significantly, the odour comes not from the flint, which is acting purely as an anvil, but from the burning particles of iron.

To summarise this section: clearly many people find it useful to conceptualise some wine sensations in terms of rocks and minerals. Tasters presumably draw on their associative memories to help convey what it is that they are experiencing, and this provides useful comparators for minerality. However, the scientific evidence is at odds with this by showing that the origin of these comparisons is not the vineyard ground. Minerality cannot be the taste of minerals, geological or nutrient, in any direct, literal way.

4. Sensory Characteristics of Minerality in Wine

Given the arguments summarised above, the question that arises naturally is: What are people tasting that they want to describe as mineral? This section reviews attempts at deconstructing the sensorial experience of minerality in wine; that is, at trying to understand just what it is that tasters are tasting.

The relatively few published studies have focused primarily on two aspects, namely (i) perceptual structure of the abstract terms mineral and/or minerality, identifying the wine attributes that tend to associate statistically with the umbrella term mineral and (ii) how consensual amongst tasters use of the term mineral is, both qualitatively and quantitatively. In terms of consensus amongst tasters, both cross-cultural effects [43] and type of domain-specific expertise [44] have been considered as important variables.

4.1. Empirical Investigations

Several early studies employing mineral as a wine attribute explored the distinctiveness of Sauvignon blanc wines as a function of wine origin [45–48]. Despite the lack of a clear definition of minerality for study participants, non-random results were reported. Parr and colleagues [45] and Green and colleagues [48] both reported that Sauvignon blanc wines from France (St Bris; Loire) were judged as more mineral than New Zealand (NZ) wines and in the case of the latter study [48], that French wines were also considered more mineral than Austrian wines. In Lund and colleagues' study [46], perceived minerality allowed differentiation of French and South-African wines from NZ wines.

Two other studies in which mineral character was judged by tasters involved the wine variety Riesling. An early study [49] showed a significant effect of judgments to the aroma descriptor mineral/flint in Canadian Rieslings. A second study, also employing Riesling [50], showed that the attribute mineral explained part of the difference between wines made in slate and sandstone bedrocks from those made in other bedrocks such as limestone, sandstone or basalt. Interestingly, two only of the sensory studies reported above used a physical reference for minerality for pre-experimental training purposes [46,47]. These research teams both employed a benzenemethanethiol (BMT) solution as a minerality reference, while the other studies relied on participants' internal, idiosyncratic representations [45,48,49], allowing for flexibility in definition of this attribute.

One of the first scientific investigations aimed specifically at understanding the sensorial nature of mineral character in wine was reported by Ballester and colleagues [2]. The study included both a conceptual and linguistic component (already described in Section 2.1 above), as well as a perceptual (sensory) component. Using Burgundy Chardonnays as wine stimuli for the sensory component, researchers asked wine professionals to rate intensity of mineral character orthonasally (nose only) and subsequently by palate only in a tasting condition where the tasters wore nose clips to minimise retronasal olfaction effects. Wine professionals reported experiencing minerality in both conditions, i.e., orthonasally and by palate only. However, there were substantial between-panellist differences amongst the wine professionals in terms of which wines were judged as most and least mineral in both conditions. To determine the wine sensory characteristics associating with perceived minerality, the wine professionals' minerality intensity ratings were associated statistically with sensory characterisation of the Chardonnay wines that had been undertaken by trained panellists.

Results showed the wine professionals to clump into three groups in each condition (smell only; palate only) based on the sensory characteristics they associated with minerality. Of particular interest in terms of supporting anecdotal evidence, lack of fruit, gunflint and reductive aromas were correlated with minerality judgments for two of the three groups of tasters in the smell-only condition, while in the palate-only condition, perceived acidity and bitterness were important to minerality judgments for two of the three groups of tasters.

Not much later, Heymann and colleagues [51] published work on the topic. These authors also employed wine professionals and trained panellists to investigate the concept of minerality, this time in a range of white wines (Chardonnay; Riesling; Pinot gris; Sauvignon blanc). The participant groups undertook different sensory tasks, with projective mapping of the wines undertaken by wine professionals, whilst the trained panellists undertook a standard, descriptive analysis task. Several results are noteworthy.

First, wine variety was a factor in judgments of mineral character with the Riesling, Pinot gris and Sauvignon blanc wines on average reported as more mineral than the Chardonnay wines, the latter judged as exhibiting qualities suggestive of oak and malo-lactic fermentation (MLF) influences, these associating negatively with the term mineral. This is an interesting, somewhat unexpected, result given that two of the four Chardonnay wines were Burgundian with the wine from Chablis associating more with notes of butter than with mineral character in the experts' data ([51]: figure 1, p. 7). Second, taking into account the data from both participant groups, several descriptors associated positively and others negatively with perceived mineral character. For wine professionals, minerality associated positively with citrus, fresh, wet stones and acid terms, while for trained panellists mineral associated positively with chalky, reduced, grassy aromas and bitter taste. Negative associations for both groups involved the characters associated with oak influence and MLF (e.g., butter; creamy). In addition, fruity and sweet notes were negatively associated with mineral for the trained panellists. Finally, the lack of consensus in judgments of mineral intensity in the wines reported by Ballester and colleagues [2] was supported by Heymann and colleagues' [51] data, which showed major between-panellist, group differences in ranking of mineral character to several of the aromatic varietal wines (Sauvignon blanc; Riesling; Pinot gris). The authors interpreted these between-group differences as reflecting perception-mode differences; their wine professionals utilised both smell and taste and were driven by acid taste in their mineral judgments, whereas the data suggested that the trained panellists' mineral judgments involved aroma only and not taste.

In a more cognitively-oriented study, [43] researchers asked whether minerality in wine is a sensorial reality or primarily a mental construct. That is, they asked whether their 63 experienced tasters (wine professionals) were perceiving something in wine via data-driven perception, evoking memories of soils, earthy notes, stones, and so forth, or whether their judgments of mineral character in the wines were primarily based on information already stored in the taster's head, the latter known as top-down information processing [52]. Arguing that consensus across tasters from different cultures in their qualitative, perceived minerality judgments would most likely indicate data-driven cognitive processing (i.e., judgments based on actual tasting of the wines, rather than on top-down cognitive processing), Parr and colleagues [43] asked French and NZ wine professionals to judge intensity of a range of wine attributes including minerality. The wines employed in the study were a selection of French and NZ Sauvignon blanc wines, some of which had received wine-industry judgments as expressing mineral character. This study extended prior work [2,51] by investigating cross-cultural phenomena and by employing a within-subject, procedural component where each participant from both cultures (France; NZ) undertook each task (sorting and descriptive rating). Descriptive ratings to the wines occurred under three, separate perception-mode conditions for each taster: orthonasal (nose only); palate only (taste; trigeminal stimulation); global perception (orthonasal, retronasal, taste, trigeminal).

Parr and colleagues [43] also tested several hypotheses with their bases either in anecdotal reports of potential sources of perceived minerality [53], or in prior research findings [2,51]. The hypotheses implicated the roles of perceived acidity, reductive phenomena, perceived stony/soil notes and relative absence of fruity notes in driving judgments of mineral character in Sauvignon blanc wines. Results demonstrated that both French and NZ wine professionals reported minerality via each perception mode; that is, orthonasally, retronasally and on the palate (taste and trigeminal stimulation). An interesting cross-cultural, cross-modal effect occurred with respect to minerality intensity judgments with olfaction contributing more to the judgments of French participants than NZ participants, the latter employing palate phenomena and olfaction more equally. Sorting task data demonstrated a remarkable consistency across cultures, with both French and NZ tasters largely separating the French wines from the NZ wines. Overall, the descriptive rating results also showed more similarities than differences indicating substantial cross-cultural consensus in terms of how minerality was perceived qualitatively in the French and NZ Sauvignon blanc wines. There was more cross-cultural consistency in perception modes of orthonasal and palate only than when retronasal judgments were made. Parr and colleagues [43] interpreted the substantial degree of cross-cultural consistency as providing evidence of data-driven cognitive processing and suggestive of a shared cognitive structure amongst wine professionals concerning the concept of minerality in Sauvignon blanc wine, with domain-specific expertise over-shadowing any culture-specific differences that could result from France and NZ having very different wine-production histories [54].

To summarise the wine description data [43], and taking all perception modes into account, the important positive predictors of minerality in the wines were attributes of citrus, fresh/zingy, bitter, flinty/smoky, chalky/calcareous and liking. Important negative predictors were fruity (passionfruit; green character), sweetness and most interestingly the taste of sourness (acid). Counter to the authors' hypothesis, reductive notes did not associate statistically with mineral in this study. These descriptive rating data show many similarities to, but also some important differences from, those of Heymann and colleagues [51] in terms of wine characteristics associating with the concept of mineral. Consistent across the studies were citrus, fresh/zingy, chalky and bitter taste associating positively with mineral, while fruity notes and sweetness negatively associated with mineral character. There were however some differences, with Heymann and colleagues [51] reporting reduced as positively associated with mineral by their trained panellists, while reductive notes (e.g., sulphide) were not significantly associated with perceived minerality in the wine professionals' data reported by Parr and colleagues [43]. Other important differences concern acidity where acid taste was a positive predictor of mineral character for Heymann and colleagues' tasters [51], whereas Parr and colleagues [43] report sourness/acid taste as a negative predictor of minerality for both French and NZ wine professionals. Clearly, further research involving various wine varieties is needed to clarify the attributes important to the internal structure of the abstract notion of perceived minerality in wine.

Zaldivar-Santamaria [44] recently extended others' work [43,51] to investigation of several white (Godello, Riesling, Sauvignon blanc, Treixadura, Ribolla and Grenache gris) and red varieties (Tempranillo, Blaufrankisch, Syrah, Poulsard and Grenache noir). The study also compared two panels of wine professionals with different types of domain-specific expertise (wine producers from La Rioja vs. wine merchants and sommeliers from Barcelona) in two conditions, nose only (orthonasal olfaction) and full tasting. The main results reported showed that both panels found significant differences between white wines in terms of their mineral intensity, but no significant effect was found for red wines. Interestingly, the minerality average score for red wines was significantly lower than that for white wines for the wine merchants/sommeliers' panel. Concerning the results for white wines, orthonasal minerality scores from both panels were significantly correlated with three Rieslings the most mineral wines of the sample set. Minerality differences in the full tasting condition were significant only for the wine producers. However, nose only and full tasting condition scores were not significantly correlated for wine producers. The same panellists carried out a sensory profile on the samples, the data used to predict minerality scores from the sensory attributes. The merchant/sommeliers' data did not produce any robust regression model on white wines. On the other hand, the wine producers' data yielded a robust regression model only for full tasting minerality scores. The negative predictors of minerality were tannin concentration (used here as a sensory descriptor) and balance, while the data concerning positive predictors showed unexpected results. More specifically, for the first time sweetness and alcohol were found to be positive predictors for minerality. More in keeping with prior research, acidity, palate weight and bitterness were also positive predictors [43,51].

Taking a somewhat different approach to investigating perceived minerality in white wine [55], Rodrigues and colleagues limited their study to the specific variant of Chardonnay table wine produced in the Burgundian region of Chablis and focused on influence of vineyard location. The wines of Chablis are often reported as flinty by wine producers and wine critics [56], with their terroir or origin implicated, in particular the vineyard soil types (e.g., Kimmeridgean marl), fossils and river bank (left or right side of the Serein River). Right-bank wines tend to be described as softer and fruitier, while left-bank wines exhibit a fresh, zingy note [57]. In their study, Rodrigues and colleagues [55] investigated sensory and chemical aspects of minerality in Chablis wines as a function of vineyard location (left vs. right river bank), finding that their orthonasal sensory data showed a significant effect of vineyard location with left-bank wines reported as more mineral than right-bank wines. No such effect was demonstrated in the full tasting condition.

4.2. Synthesis and Summary

In summarising this section concerning the sensorial nature of minerality in wine, several conclusions can be drawn from the limited research published to date. First, although rating intensity of mineral character in a wine appears somewhat idiosyncratic across both wine tasters and wines, there is some consensus in terms of the other wine attributes that associate with the term mineral. This was particularly pronounced when the wine to be judged was produced from the aromatic varieties of Sauvignon blanc [43], Pinot gris and Riesling [44,51], rather than Burgundy Chardonnay [2,51]. This may signal a variety-specific aspect to judgments of minerality in white wines, a notion deserving of further research. Second, wine professionals appear to perceive minerality orthonasally, retronasally and on the palate. The limited data published to date suggest perception-mode effects may be influenced by culture [43] and type of expertise [51], with French wine professionals in the former study and trained panellists in the latter study demonstrating orthonasal dominance in their minerality judgments. Related to this, domain-specific expertise may over-rule cultural differences when an abstract notion such as wine minerality is considered as suggested by the data of Parr and colleagues [43]. There, considerable consensus amongst wine professionals was demonstrated in terms of the perceptual structure of minerality in Sauvignon blanc despite wine-related, cultural differences between France and NZ [54].

5. Associated Chemical Compounds

Although wine-industry media reports of perceived mineral character in wine frequently implicate various aspects of wine composition, notably perceived acidity [58] and reductive phenomena [53], as possible sources of the flinty, earthy, seashell and smoky notes reported by tasters, scientific studies on the topic are sparse. Several researchers have reported investigations into mineral content of a range of wine varieties [19,59,60]. Despite this, only a handful of published studies has attempted to associate wine physico-chemical composition with sensory data concerning perception of mineral character in wine [44,51,55,61–63].

5.1. Investigations of Compounds and Flavours Assumed Related to Minerality

One of the first scientific studies to associate an aspect of wine chemical composition with a mineral note in wine was reported by Tominaga and colleagues [64]. Whilst investigating thiol compounds in Sauvignon blanc wines, the authors described an aroma compound that they associated with a smoky or flinty note when the compound was at relatively low concentration. This compound, BMT, subsequently was employed in Sauvignon blanc aroma research when a standard was sought to exemplify for tasters the nature of a flinty and/or smoky wine attribute [46,47].

At around the same time, a relevant issue was investigated [65] where chemical and sensory data were associated to investigate metallic taste. Metallic or chemical taste has been reported as related to perceived minerality [51]. The authors [65] recorded intensity ratings of oral metallic sensation as a function of oral stimulation with sulphate solutions of copper, iron and zinc to determine retronasal input to the reported sensations. Results showed that iron sulphate appeared to have a retronasal component in tasters' reports of metallic sensation, whereas the copper and zinc salts did not.

5.2. Studies Specifically Investigating Physico-Chemical Drivers of Perceived Minerality

As seen in Section 4 above, a range of sensory dimensions has been associated with perception of minerality in wine. These sensory results implicate the following as potential sources of perceived mineral character: types and amount of acidity; reductive phenomena; relative absence of compounds assumed to provide flavour or fruitiness in a wine (e.g., varietal thiol compounds in Sauvignon blanc wines [66]); compounds assumed associated with flinty, stony, earthy and smoky notes (e.g., BMT and other sulphur compounds [41,64]). These implicated compounds have come under empirical investigation recently by several research groups.

To our knowledge, the first published study to investigate aspects of wine composition assumed responsible for perceived minerality was reported by Baron and Fiala [61]. Employing white wines (Italian Riesling; Gruner Veltliner), the authors investigated selected cation and amino acid concentrations, concluding from a blind wine tasting that succinic acid in higher concentrations resulted in tasters reporting qualities that have been considered related to perceived minerality (salty; sapid; slightly bitter). However, few details are provided about the methodologies employed for this study, in particular for the blind wine tasting, and therefore, these data must be treated with caution.

In their study reviewed above, Heymann and colleagues [51] associated their sensory data on minerality with basic wine parameters of pH, titratable acidity (TA) and residual sugar, along with free and total sulphur dioxide (SO_2), dissolved carbon dioxide (CO_2) and organic acids (tartaric; malic; succinic; lactic; acetic). To determine the drivers of perceived mineral character in their selected white wines, the authors associated statistically the physico-chemical data with the sensory data gathered from the procedures undertaken by their (i) wine professionals and (ii) trained panellists. Wine professionals' judgments of mineral were positively associated with malic and tartaric acids, and to a lesser degree with free and total SO_2. Free SO_2 was also a positive predictor of mineral judgments by the trained panellists, recalling that the sensory data described above suggested that these participants were more aroma-driven than taste-driven when judging mineral character.

Parr and colleagues [62] also report an investigation in which wine composition and wine sensory data were statistically associated in an attempt at elucidating the key aspects of wine physico-chemical composition driving perception of minerality in Sauvignon blanc wines from France and NZ. The authors associated their global tasting-condition data (i.e., the data from the full tasting condition involving orthonasal, retronasal, taste, and trigeminal sensations) reported in their earlier study [43] with a comprehensive set of wine composition data. These latter data included measures of wine standard parameters including non-volatile organic acids, elemental composition (18 cations), 33 volatile aroma compounds including varietal thiols and volatile sulphur compounds associated with pungent aromas, isobutyl methoxypyrazine and volatile organic acids.

As well as absence of fruit/flavour and presence of stony/soil notes, the researchers were particularly interested in reductive phenomena and qualitative aspects of acidity, these often reported in wine-industry media as potential drivers of perceived minerality [53,67]. In terms of acidity, they investigated not only pH and TA, but employed an index to relate these two parameters. Results of the complex analyses involving both sensory and physico-chemical data showed that several aspects of wine composition associated positively with perception of mineral character, while others associated negatively. Of particular interest, cross-cultural differences were more pronounced when the chemical data were factored in than when Parr and colleagues' sensory data were considered alone [43].

The outcomes reported by Parr and colleagues [62] demonstrate both similarities and differences with respect to the data reported by the prior research [51]. Consistent with Heymann and colleagues [51], French wine professionals associated free SO_2 positively with minerality, and NZ tasters associated malic acid and bound SO_2 positively with perceived mineral character in the Sauvignon blanc wines. Other compounds not reported by prior researchers also associated positively with perceived minerality, namely isoamyl acetate by the French and hexanoic acid and Na by the NZ wine professionals. The negative associations of perceived minerality with wine composition data are in some cases at odds with previously reported data [51] and are more difficult to interpret. Parr and colleagues [62] report tartaric acid and titratable acidity associating negatively with minerality for French tasters and isoamyl alcohol, diethyl succinate and isobutanol associating negatively for NZ tasters. Of note in terms of the a priori hypotheses of the authors, reductive phenomena were not found to drive perception of mineral character. The authors [62] interpreted these results as indicating both the complex nature of the situation, but also the importance of free and total/bound SO_2 as potential drivers of perceived mineral characters in white wines.

An even more comprehensive wine composition analysis was undertaken [55] in the study relating sensory and chemical aspects of minerality in Chablis wines (Chardonnay) from two vineyard locations, the left and right banks of the Serein River, reported above in Section 4.1. Physico-chemical analyses in this study included wine standard parameters, non-volatile organic acids, 76 aroma compounds, phosphorus, as well as 10 metals.

The results demonstrated several relevant wine-composition differences as a function of vineyard location. Left bank wines on average showed higher concentrations of methanethiol, a compound implicated as a source of mineral character in wine [64] and linked to shellfish aroma [55]. This result is in keeping with Rodrigues and colleagues' orthonasal sensory data which showed left bank Chablis wines to be judged as more mineral than right bank wines. Right bank wines, which showed lower minerality scores, also showed higher levels of copper and norisoprenoids in the chemical analyses. Both compounds can have a negative impact on perceived minerality. On the one hand, copper is involved in the formation of an odourless complex with methanethiol, decreasing the intensity of shellfish aroma, decreasing perceived minerality. On the other hand, norisoprenoids are related either directly or indirectly to floral and fruity notes in wines [68,69], which according to the authors, are negatively correlated with minerality.

Another recent study [63] argued for the important role of sulphur compounds in perceived minerality, in particular polysulphanes that are usually associated to flinty, gunpowder and match odours (see Section 3 above). The authors first selected two Chasselas wines from Switzerland considered as highly mineral by a panel of 62 wine professionals, as well as two wines considered as having no minerality by the same panel. Chemical analyses showed significantly higher polysulphane concentrations in the Chasselas wines perceived as having high minerality. Starkenmann and colleagues [63] argued that the flinty smell detected in the two Chasselas wines involves the same unstable disulphane compounds that produce gun-flint notes from struck surfaces, the result of complex oxidation and reduction reactions. As mentioned in Section 3, other researchers [41,64] have suggested another sulphur compound, namely BMT, as a source of flinty notes in Chardonnay wines.

Finally in this section, Zaldivar-Santamaria [44] also attempted to link perceived minerality to the chemical composition of a number of white and red wines. The author analysed wine standard parameters, non-volatile organic acids, 75 aroma compounds, as well as 16 metals. Regarding white wines, a partial least squares (PLS) regression with sensory and chemical data showed that perceived minerality in the full tasting condition could be positively predicted by tartaric acid, glucose + fructose and Mg. The negative predictors were pH (which is consistent with the TA effect) and potassium.

5.3. Summary and Conclusions

It is clear from the limited data published to date and summarized in Table 1 that the physico-chemical drivers of perceived mineral character in wine do not have a simple explanation. Each study reviewed provides some hints, but as yet, no strong evidence about the specific roles of anecdotally-implicated phenomena. We have attempted to summarise the key findings to date concerning the roles of the most frequently implicated factors, namely acidity, reductive phenomena, compounds producing earthy/stony/smoky/seashell notes and absence of compounds related to fruitiness and/or wine flavour.

5.3.1. Acidity

Despite wine critics' reviews often linking the terms "mineral" and "acidity", evidence on the topic is unclear and equivocal. Baron and Fiala [61] suggested a positive association between succinic acid and wine attributes pertaining to mineral character, while others [51,62] reported that wine professionals' judgments of minerality were positively associated with malic acid. On the other hand, whereas Heymann and colleagues [51] and Zaldivar-Santamaria [44] reported tartaric acid also to be a positive predictor, Parr and colleagues [62] reported that tartaric acid and titratable acidity associated negatively with minerality for the French tasters in their study. Further, there was no significant effect of either pH or the acidity index employed in Parr et al.'s study, nor of any of the other organic acids measured. Clearly, further research is required in this area.

Table 1. Summary of the chemical compounds having a significant positive or negative impact on perceived minerality. § in brackets, the numbers of the references where the sensory dimension has associated significantly with perceived minerality. # in brackets, the numbers of the references where the chemical compound has associated significantly with perceived minerality.

Sensory Dimension §	Compound	Positive #	Negative #
Reductive/gunflint [2,3,7,43,51,55,63]	benzenemethanethiol	[41,64]	
	disulphane	[63]	
Reductive [2,43]	free SO_2	[51,62]	
	bound SO_2	[62]	
	Cu		[55]
Reductive/seashore [2,7]	methanethiol	[55]	
Lack of fruit [2,43,55]	damascenone		[55]
Citrus [43,51]	3-mercapto-1-hexanol	[62]	
Acidity/freshness [2,3,7,43,44,51]	titratable acidity	[51]	[62]
	pH		[44]
	tartaric acid	[44,51]	[62]
	malic acid	[51,62]	
	lactic acid		[51]
Saltiness [2,7]	Na	[62]	
Sweetness [44]	glucose + fructose	[44]	
No particular sensory dimension	isoamyl acetate	[62]	
	hexanoic acid	[62]	
	isoamyl alcohol		[62]
	diethyl succinate		[62]
	isobutanol		[62]
	glucose + fructose	[44]	
	Mg	[44]	
	K		[44]

5.3.2. Reductive Phenomena and SO_2

That low-level, reductive phenomena may be experienced by wine judges as perceived minerality has been alluded to by many wine critics/writers, not least because the increased use of inert bottle closures (e.g., screw-cap) has occurred concurrently with an increased use of the term mineral to describe wine. However, despite investigating a comprehensive list of implicated compounds, neither Parr and colleagues [62] nor Zaldivar-Santamaria [44] found a relationship between any of the volatile sulphur compounds associated with pungent aromas and perceived mineral intensity scores. However, Rodrigues and colleagues [55] found a significant link between methanethiol and the shellfish aroma, which was associated with minerality, in particular for left bank, Chablis wines.

On the other hand, two studies [51,62] reported positive relationships between perceived minerality and free, bound and total SO_2. These various forms of SO_2 in wine are therefore an important factor to consider in future research.

5.3.3. Compounds Producing/Stony/Smoky Notes

In line with the previous section, the few studies that have related flinty/smoky notes to sulphur compounds have produced data providing a complex overall picture. The seminal work of Tominaga and colleagues [64] with several white wine varieties argued that BMT was responsible for a flinty note. On the other hand, recent research [44,62] failed to find a significant link between BMT concentration and perceived mineral character. However, in their evaluation of the role of thiols in Australian Chardonnay wines [41], Capone and colleagues found a statistical link between BMT and the presence of flint and wet stone notes. As mentioned above [63], it has been argued that a flinty smell also involves unstable disulphanes released by striking surfaces of flint.

5.3.4. Compounds Producing Saltiness

Although wine normally contains little salt (sodium chloride), a salty taste appears to be associated with minerality in wine in every conceptual study reported to date [2,4,5,7]. In spite of this, none of the sensory studies aimed at understanding perception of minerality reported intensity judgments to saltiness in the wines. An exception is the study [61] that partially showed the sensory impact of (salty tasting) succinic acid on the perceived saltiness of white wine. On the other hand, Zaldivar-Santamaria [44] did not find any significant link between succinic acid and minerality, leaving the situation ambiguous. Concerning the role of cations, Parr and colleagues [62] showed for their NZ tasters a correlation between Na and mineral intensity judgments, together with a minor effect for Ca. An effect for Mg has been reported [44] and of Cu [55]. However, as mentioned in Section 3.3, given their rather low concentrations a direct sensory impact is unlikely.

5.3.5. Absence of Fruitiness and/or Wine Flavour

The hypothesis that a lack of wine flavour acts as a positive predictor of perceived minerality received some support [43] by Parr and colleagues' sensory data. However, when chemical and sensory data were associated [62], no significant relationship was found between concentration of key impact compounds of Sauvignon blanc wines (varietal thiols; isobutyl methoxypyrazine) and perceived minerality. Some indirect support for this hypothesis was found in that methanethiol, which was associated with higher perceived minerality levels, reported as exerting a masking effect on floral and fruity nuances [55].

To conclude this section, the wine-composition drivers of perceived mineral-like characters remain elusive. Further research employing methodologies that can associate large sets of wine-composition data with sensory data is needed. Chemical compounds implicated by the research reported to date, namely malic acid, sulphur dioxide (free and bound), BMT, copper and norisoprenoids, deserve further attention. In addition, several aspects of wine composition that have associated with the perception of mineral character in a single study only (e.g., fatty acids; isoamyl alcohol; succinic acid) and are difficult to interpret also deserve future investigation and replication to rule out their role as either spurious correlation or effect of interest.

6. Overall Conclusions

Some headway has been made over the last decade to delineate both sensorial and chemical drivers of perceived minerality in wine. Nonetheless, the topic in terms of sound empirical research is in its infancy and deserving of further investigation, not least because of the frequency with which the term is employed to describe wine. Perhaps the most obvious overall conclusion is that the perception of mineral character in wine is an extremely complex issue, this being evidenced in that virtually all the wine-industry, popularised hypotheses concerning the source(s) of mineral character in wine failed to gain consistent support in the experimental work published to date. The popular notion that we are simply tasting inorganic minerals in the wine transmitted from the vineyard ground is not scientifically plausible. The null results of the sensory and chemical experimental studies could have several origins, not least that those published to date have involved a range of wine varieties, geographical regions and dependent measures. To increase clarity in the field, we suggest that more consideration be given to wine variety in future studies, with potential for both sensorial and chemical aspects of minerality to differ as a function of wine variety and wine-production style. Chardonnay would appear a particularly complex wine variety to study given the variability internationally in oenological approach to this variety, whereas Riesling wines appear a particularly appropriate variety to consider in future research given anecdotal tasting reports of perceived minerality, along with relative consistency in wine-production methods (apart from sugar-acid balance aspects) geographically. Finally, it would be interesting to validate the potential drivers of minerality found in the different studies. Classical addition or omission studies using neutral or synthetic wines [68,70,71] could be an interesting sensory strategy to carry out this validation. In terms of a further novel direction, perception of saltiness and salinity in wine appear to be taking on a new significance in taste perceptions and could form the basis of interesting future research. This topic would seem particularly fruitful for future investigation, given the lack of sound empirical data on the issue despite anecdotal evidence supporting an association by some wine tasters of a salty taste with perceived mineral character.

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References

1. Van Casteren, C. Un terme très tendence. In Proceedings of the Lallemand tour 'Les Minéraux et le vin', Nîmes/Mâcon/Chinon/Bordeaux, France, 17–20 January 2012.
2. Ballester, J.; Mihnea, M.; Peyron, D.; Valentin, D. Exploring minerality of Burgundy Chardonnay wines: A sensory approach with wine experts and trained panellists. *Aust. J. Grape Wine Res.* **2013**, *19*, 140–152. [CrossRef]
3. Le Fur, Y.; Gautier, L. De la minéralité dans les rosés? *Revue Française d'Oenologie* **2013**, *260*, 40–43.
4. Deneulin, P.; Le Bras, G.; Le Fur, Y.; Gautier, L.; Bavaud, F. La minéralité des vins: Exploitation de sémantique cognitive d'une étude consommateurs. *La Revue des Œnologues* **2014**, *153*, 56–58.
5. Deneulin, P.; Bavaud, F. Analyses of open-ended questions by renormalized associativities and textual networks: A study of perception of minerality in wine. *Food Qual. Prefer.* **2016**, *47*, 34–44. [CrossRef]
6. Deneulin, P.; Le Fur, Y.; Bavaud, F. Study of the polysemic term of minerality in wine: Segmentation of consumers based on their textual responses to an open-ended survey. *Food Res. Int.* **2016**, *90*, 288–297. [CrossRef] [PubMed]
7. Rodrigues, H.; Ballester, J.; Saenz-Navajas, M.P.; Valentin, D. Structural approach of social representation: Application to the concept of wine minerality in experts and consumers. *Food Qual. Prefer.* **2015**, *46*, 166–172. [CrossRef]
8. Jodelet, D. *Les Representations Sociales*; Presses universitaires de France: Paris, France, 1989.
9. Abric, J.C. Jeux, Conflits et Representations Sociales. Ph.D. Thesis, Université de Provence, Marseille, France, 1976.

10. Vergès, P. L'evocation de l'argent: Une méthode pour la définition du noyau central d'une représentation. *Bull. Psychol.* **1992**, *45*, 203–209.
11. Lo Monaco, G.; Lheureux, F. Représentations sociales: Théorie du noyau central et méthodes d'étude. *Revue Electronique de Psychologie Sociale* **2007**, *1*, 55–64.
12. Maltman, A.J. Minerality in wine: A geological perspective. *J. Wine Res.* **2013**, *24*, 169–181. [CrossRef]
13. Schreiner, P. Mycorrhyzas and Mineral Acquisition in Grapevines. In *Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium*; Christensen, P., Smart, D.R., Eds.; ASEV: Davis, CA, USA, 2005; pp. 49–60.
14. Velde, B.; Meunier, A. *The Origin of Clay Minerals in Soils and Weathered Rocks*; Springer: Berlin, Germany, 2008.
15. Fageria, N.K.; Baligar, V.C.; Jones, C.A. *Growth and Mineral Nutrition of Field Crops*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2010.
16. Keller, M. *The Science of Grapevines: Anatomy and Physiology*; Academic Press: Burlington, MA, USA, 2010.
17. Savvas, D. Hydroponics: A modern technology supporting the application of integrated crop management in greenhouse. *Food Agric. Environ.* **2003**, *1*, 80–86.
18. Castiñera Gómez Mdel, M.; Brandt, R.; Jakubowski, N.; Anderson, J.T. Changes of the metal composition in German white wines through the winemaking process. A study of 63 elements by inductively coupled plasma-mass spectrometry. *J. Agric. Food Chem.* **2004**, *52*, 2953–2961. [CrossRef] [PubMed]
19. Pohl, P. What do metals tell us about wine? *TrAC Trends Anal. Chem.* **2007**, *26*, 941–949. [CrossRef]
20. Tatár, E.; Mihucz, V.G.; Virág, I.; Rácz, L.; Záray, G. Effect of four bentonite samples on the rare earth element concentrations of selected Hungarian wine samples. *Microchem. J.* **2007**, *85*, 132–135.
21. Aceto, M.; Bonello, F.; Musso, D.; Tsolakis, C.; Cassino, C.; Osella, D. Wine traceability with rare earth elements. *Beverages* **2018**, *4*, 23. [CrossRef]
22. Wilkes, E.; Day, M.; Herderich, M.; Johnson, D. In vino veritas—Investigating technologies to fight wine fraud. *Wine Vitic. J.* **2016**, *31*, 36–38.
23. Hommerberg, C.; Paradis, C. Constructing credibility through representations in the discourse of wine: Evidentiality, temporality and epistemic control. In *Subjectivity and Epistemicity. Corpus, Discourse, and Literary Approaches to Stance*; Glynn, D., Sjölin, M., Eds.; Lund University Press: Lund, Sweden, 2014; pp. 211–238.
24. Coombe, B.G.; Dry, P.R. (Eds.) *Viticulture: Volume 1—Resources*, 2nd ed.; Winetitles Pty Ltd.: Prospect East, Adelaide, Australia, 2004.
25. Jackisch, P. *Modern Winemaking*; Cornell University Press: Ithaca, NY, USA, 1985.
26. Komárek, M.; Cadková, E.; Chrastný, V.; Bordas, F.; Bollinger, J.C. Contamination of vineyard soils with fungicides: A review of environmental and toxicological aspects. *Environ. Int.* **2010**, *36*, 138–151. [CrossRef]
27. Epke, M.; Lawless, H.T. Retronasal smell and detection thresholds of iron and copper salts. *Physiol. Behav.* **2007**, *92*, 487–491. [CrossRef] [PubMed]
28. Burdock, G.A. *Fenaroli's Handbook of Flavor Ingredients*, 6th ed.; CRC Press: Boca Raton, FL, USA, 2009.
29. Bruce Goldstein, E. *Sensation and Perception*, 8th ed.; Wadsworth: Belmont, CA, USA, 2010; Chapter 15. Available online: http://zhenilo.narod.ru/main/students/Goldstein.pdf (accessed on 19 August 2018).
30. Kreitman, G.Y.; Danilewicz, J.C.; Jeffery, D.W.; Elias, R.J. Reaction mechanisms of metals with hydrogen sulfide and thiols in model wine. Part 2: Iron- and Copper-Catalyzed Oxidation. *J. Agric. Food Chem.* **2016**, *64*, 4105–4113. [CrossRef] [PubMed]
31. Wang, A.; Duncan, S.E.; Dietrich, M. Effect of iron on taste perception and emotional response of sweetened beverage under different water conditions. *Food Qual. Prefer.* **2016**, *54*, 58–66. [CrossRef]
32. Riemann, C.; Birke, M. (Eds.) *Geochemistry of European Bottled Water*; Borntraeger Science Publishers: Stuttgart, Germany, 2010.
33. Walker, R.R.; Blackmore, D.H.; Clingeleffer, P.C.; Correll, R.L. Rootstock effects on salt tolerance of irrigated field-grown grapevines (*Vitis vinifera* L. cv. Sultana) 2. Ion concentrations in leaves and juice. *Aust. J. Grape Wine Res.* **2004**, *10*, 90–99. [CrossRef]
34. Waterhouse, A.L.; Sacks, G.L.; Jeffery, D.W. *Understanding Wine Chemistry*; Wiley-Blackwell: Hoboken, NJ, USA, 2016.
35. Wiesenthal, K.E.; McGuire, M.J.; Suffet, I.H. Characteristics of salt taste and free chlorine or chloramine in drinking water. *Water Sci. Technol.* **2007**, *55*, 293–300. [CrossRef] [PubMed]
36. Fugelsang, K.C.; Edwards, C.G. *Wine Microbiology: Practical Applications and Procedures*, 2nd ed.; Springer: New York, NY, USA, 2007.
37. Bear, I.J.; Thomas, R.G. Genesis of petrichor. *Geochim. Cosmochim. Acta* **1966**, *30*, 869–879. [CrossRef]

38. Bear, I.J.; Kranzs, Z.H. Fatty acids from exposed rock surfaces. *Aust. J. Chem.* **1965**, *18*, 915. [CrossRef]
39. Bear, I.J.; Thomas, R.G. Nature of argillaceous odour. *Nature* **1964**, *201*, 993–995. [CrossRef]
40. Glindemann, D.; Dietrich, A.; Staerk, H.-J.; Kuschk, P. The two odors of iron when touched or pickled: (skin) carbonyl compounds and organophosphines. *Angew. Chem. Int. Ed.* **2006**, *45*, 7006–7009. [CrossRef] [PubMed]
41. Capone, D.L.; Barker, A.; Williamson, P.O.; Francis, I.L. The role of potent thiols in Chardonnay wine aroma. *Aust. J. Grape Wine Res.* **2017**, *24*, 38–50. [CrossRef]
42. Angelo, P.C.; Subramanian, R. *Powder Metallurgy: Science, Technology and Applications*; Prentice-Hall of India Pvt. Ltd.: New Delhi, India, 2008.
43. Parr, W.V.; Ballester, J.; Peyron, D.; Grose, C.; Valentin, D. Investigation of perceived minerality in Sauvignon wines: Influence of culture and mode of perception. *Food Qual. Prefer.* **2015**, *41*, 121–132. [CrossRef]
44. Zaldivar-Santamaria, E. Caracterizacion Quimico-Sensorial del Atributo « mineralidad » en Vinos Blancos y Tintos. Ph.D. Thesis, Universidad de La Rioja, Logroño, Spain, 30 June 2017.
45. Parr, W.V.; Green, J.A.; White, K.G.; Sherlock, R.R. The distinctive flavour of New Zealand Sauvignon blanc: Sensory characterisation by wine professionals. *Food Qual. Prefer.* **2007**, *18*, 849–861. [CrossRef]
46. Lund, C.M.; Thompson, M.; Benkwitz, F.; Wohler, M.W.; Triggs, C.M.; Gardner, R.; Heymann, H.; Nicolau, L. New Zealand Sauvignon blanc distinct flavor characteristics: Sensory, chemical, and consumer aspects. *Am. J. Enol. Vitic.* **2009**, *60*, 1–12.
47. Parr, W.V.; Valentin, D.; Green, J.A.; Dacremont, C. Evaluation of French and New Zealand Sauvignon wines by experienced French wine assessors. *Food Qual. Prefer.* **2010**, *21*, 56–64. [CrossRef]
48. Green, J.A.; Parr, W.V.; Breitmeyer, J.; Valentin, D.; Sherlock, R. Sensory and chemical characterisation of Sauvignon blanc wine: Influence of source of origin. *Food Res. Int.* **2011**, *44*, 2788–2797. [CrossRef]
49. Douglas, D.; Cliff, M.A.; Reynolds, A.G. Canadian terroir: Characterization of Riesling wines from the Niagara Peninsula. *Food Res. Int.* **2001**, *34*, 559–563. [CrossRef]
50. Bauer, A.; Fischer, U. Factors causing sensory variation in Riesling wines from different Terroirs in Germany. In Proceedings of the 9th International Symposium of Enology of Bordeaux, Bordeaux, France, 15–17 June 2011; pp. 1087–1091.
51. Heymann, H.; Hopfer, H.; Bershaw, D. An exploration of the perception of minerality in white wines by projective mapping and descriptive analysis. *J. Sens. Stud.* **2014**, *29*, 1–13. [CrossRef]
52. Dalton, P. Fragrance perception: From the nose to the brain. *J. Cosmet. Sci.* **2000**, *51*, 141–150.
53. Goode, J. Minerality in wine. *Sommel. J.* **2012**, 63–67.
54. Mouret, M.; Lo Monaco, G.; Urdapilleta, I.; Parr, W.V. Social representations of wine and culture: A comparison between France and New Zealand. *Food Qual. Prefer.* **2013**, *30*, 102–107. [CrossRef]
55. Rodrigues, H.; Saenz-Navajas, M.-P.; Franco-Luesma, E.; Valentin, D.; Fernando-Zurbano, P.; Ferreira, V.; De La Fuente Blanco, A.; Ballester, J. Sensory and chemical drivers of wine minerality aroma: An application to Chablis wines. *Food Chem.* **2017**, *230*, 553–562. [CrossRef] [PubMed]
56. Easton, S. Minerality. *Drinks Bus.* **2009**, 86–88.
57. Jefford, A. Jefford on Monday: The Chablis Difference. *Decanter*, 2 July 2018. Available online: https://www.decanter.com/wine-news/opinion/jefford-on-monday/chablis-and-burgundy-difference-396329/ (accessed on 4 July 2018).
58. Ross, J. Minerality: Rigorous or romantic? *Pract. Winery Vineyard J.* **2012**, *XXXIII*, 50–57.
59. Moreno, I.M.; Gutierrez, A.J.; Rubio, C.; Gonzalez, A.G.; Gonzalez-Weller, D.; Bencharki, N.; Hardisson, A.; Revert, C. Classification of Spanish red wines using neural networks with enological parameters and mineral content. *Am. J. Enol. Vitic.* **2018**, *69*, 167–175. [CrossRef]
60. Cabello-Pasini, A.; Macias-Carranza, V.; Siqueiros-Valencia, A.; Huerta-Diaz, M.A. Concentrations of calcium, magnesium, potassium and sodium in wines from Mexico. *Am. J. Enol. Vitic.* **2013**, *64*, 280–284. [CrossRef]
61. Baron, M.; Fiala, J. Chasing after minerality, relationship to yeast nutritional stress and succinic acid production. *Czech J. Food Sci.* **2012**, *30*, 188–193. [CrossRef]
62. Parr, W.V.; Valentin, D.; Breitmeyer, J.; Peyron, D.; Darriet, P.; Sherlock, R.R.; Robinson, B.; Grose, C.; Ballester, J. Perceived minerality in Sauvignon blanc wine: Chemical reality or cultural construct? *Food Res. Int.* **2016**, *87*, 168–179. [CrossRef] [PubMed]

63. Starkenmann, C.; Chappuis, C.J.-F.; Niclass, Y.; Deneulin, P. Identification of hydrogen disulfanes and hydrogen trisulfanes in H_2S bottle, in flint, and in dry mineral white wine. *J. Agric. Food Chem.* **2016**, *64*, 9033–9040. [CrossRef] [PubMed]
64. Tominaga, T.; Guimbertau, G.; Dubourdieu, D. Contribution of benzenemethanethiol to smoky aroma of certain *Vitis vinifera* L. wines. *J. Agric. Food Chem.* **2003**, *51*, 1373–1376. [CrossRef] [PubMed]
65. Lawless, H.T.; Schlake, S.; Smythe, J.; Lim, J.; Yang, H.; Chapman, K.; Bolton, B. Metallic taste and retronasal smell. *Chem. Sens.* **2004**, *29*, 25–33. [CrossRef]
66. Tominaga, T.; Baltenweck-Guyot, R.; Peyrot des Gachons, C.; Dubourdieu, D. Contribution of volatile thiols to the aromas of white wines made from several *Vitis vinifera* grape varieties. *Am. J. Enol. Vitic.* **2000**, *51*, 178–181.
67. Goode, J. *The Science of Wine: From Vine to Glass*; Octopus Publishing Group Ltd.: London, UK, 2005.
68. Ferreira, V.; Ortin, N.; Escudero, A.; Lopez, R.; Cacho, J. Chemical characterization of the aroma of Grenache Rose wines: Aroma extract dilution analysis, quantitative determination and sensory reconstitution studies. *J. Agric. Food Chem.* **2002**, *50*, 4048–4054. [CrossRef] [PubMed]
69. Pineau, B.; Barbe, J.-C.; Van Leeuwen, C.; Dubourdieu, D. Which Impact for β-Damascenone on Red Wines Aroma? *J. Agric. Food Chem.* **2007**, *55*, 4103–4108. [CrossRef] [PubMed]
70. Lorrain, B.; Ballester, J.; Thomas-Danguin, T.; Blanquet, J.; Meunier, J.-M.; Le Fur, Y. Selection of potential impact odorants and sensory validation of their importance in typical Chardonnay wines. *J. Agric. Food Chem.* **2006**, *54*, 3973–3981. [CrossRef] [PubMed]
71. Tomasino, E.; Harrison, R.; Breitmeyer, J.; Sedcole, R.; Sherlock, R.; Frost, A. Aroma composition of 2-year-old New Zealand pinot noir wine and its relationship to sensory characteristics using canonical correlation analysis and addition/omission tests. *Aust. J. Grape Wine Res.* **2015**, *21*, 376–388. [CrossRef]