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Review

Beer Polyphenols—Bitterness, Astringency, and Off-Flavors

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Abstract: The acceptance of beer among consumers is most influenced by the taste and aroma. Polyphenols are widely responsible for both. Whereas polyphenols do not always result in a positive flavor and taste, they can surely impart certain off-flavors, which will be mentioned in this paper. However, the aftertaste is an important component of the beer-tasting experience and acceptance. The aftertaste, including astringency, may largely influence consumers' consumption preference and behavior. Bitterness is one of the main, desirable characteristics of beer, but to an untrained consumer, it can often be mistaken with astringency. This review aims to describe the differences between these two properties. Both attributes derive from the same beer components, polyphenols from barley and hop, but there is a distinctive difference between them. To understand the complexity of bitterness and astringency, polyphenols behavior, characteristics, and stability during the brewing process are also described in this review.

Keywords: bitterness; beer; aftertaste; off-flavor

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Citation: Habschied, K.; Košir, I.J.; Krstanović, V.; Kumrić, G.; Mastanjević, K. Beer Polyphenols—Bitterness, Astringency, and Off-Flavors. *Beverages* **2021**, *7*, 38. https://doi.org/10.3390/beverages7020038

Academic Editors: Luis F. Guido and Pavel Dostálek

Received: 5 May 2021
Accepted: 8 June 2021
Published: 11 June 2021

1. Introduction

Flavor stability is, besides colloidal stability, one of the most important indicators of beer quality. The two properties are narrowly connected since the colloidal stability purports the polyphenol removal, a big factor in flavor stability [1]. Some types of beer (i.e., Indian Pale Ale) are bound to contain strong hoppy notes and bitterness originating from polyphenols in hops or barley. In some types of beer, such as lagers, the manifestation of these properties is undesirable. However, the emergence of undesirable notes can be a result of a faulty lead brewing process, whether due to the over-dosage of hop (acids), low temperatures while dry hopping, polyphenols, or simply staling. The ongoing craft beer boom has aimed to present different types of beer to the broader public, and this includes hoppy and bitter beers (mostly ales) that differ from the industrial lagers by increased bitterness [2]. Other important beer characteristics, such as astringency, body, and fullness, are directly influenced by polyphenols [3].

As such, polyphenols can provide both bitterness and astringency, depending on their degree of isomerization [4]. The consumers' perception of bitterness depends on different factors and is very complex. The range of molecules that elicit bitter responses is very wide [5,6]; for example, the reactivity of flavanols with metal ions and molecular oxygen results in flavanol polymers.

Astringency, on the other hand, is much easier to explain. It is described as a mouthfeel characterized by a drying, puckering, or rough sensation across the oral cavity, especially on the tongue [7]. It occurs when large molecular weight polyphenols react with proline-rich proteins found in saliva. Upon their interaction, they precipitate onto the surface of the mouth, which leads to the feeling of a coating dryness [8].

Beer is comprised of several hundred compounds affecting its aroma and taste. The terminology for the determination of beer flavor is complex and includes dynamic interactions between the senses [9]. As reported in a review by Baert et al. [9], "flavor is the sum of perceptions resulting from stimulation of the sense ends that are grouped at the entrance of the alimentary and respiratory tracts" [10,11], and flavor is comprised of four different components: odor, aroma, taste, and mouthfeel. By definition, the odor is the perception of volatiles by the olfactory mucous membrane in the nasal cavity, after sniffing through the nose and entering the nasal passage. Aroma is also connected with volatile compounds, which volatilize by body heat after putting the beverage in the mouth. In both cases, volatile compounds end up in the nasal/retronasal cavity, where they are identified by the brain. Soluble substances in the mouth recognized by the receptors located on the surface of the tongue form the reception of taste [11–13]. Basic tastes can be described as sweet, sour, salty, bitter, umami, and fatty (which has still not been pinned to a particular place), as shown in Figure 1 [12].

Figure 1. Scheme of human tongue and taste receptors position.

Mouthfeel is a sensation of the haptic perception of the food product on the surface of the oral cavity (the sparkling of carbon dioxide, the oiliness of fats, and astringency) [12,14–16]. All of these components intertwine and sum up the perceived flavor as a result of complex reactions between the senses, as can be seen from Figure 2. A good example is when beers with higher CO_2 content taste more sour but less astringent.

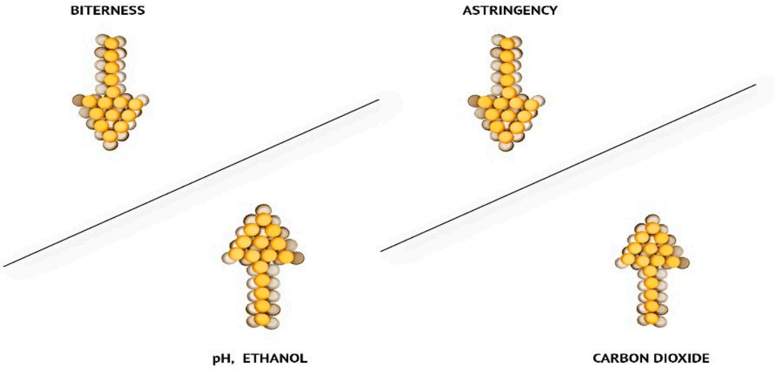

Figure 2. Changes in taste perception (higher levels of CO_2 in beer decrease astringency; higher C_2H_5OH concentration and higher beer pH increase the bitterness perception) [12].

2. Raw Materials and Polyphenols

2.1. Main Polyphenols in Raw Materials for Malting and Brewing

Even though beer is produced from four basic components, water, malt, hops, and yeast, phenolic compounds in beer commonly originate from hops (30%), malt (70%) [17], or can form during chemical transformations in the brewing process.

Phenolic acids are not as responsible for beer flavor, as they influence flavor precursors. Bottom-fermented light beers do not withstand heavy phenolic notes, which are, in this case, noted as off-flavor. Top-fermented beers, such as German Weizen or Belgian white beers, are designated by the volatile monophenols [18–20]. Much of the phenolic flavor precursors are a consequence of the malting and mashing processes. However, raw material also represents an important parameter [21].

According to [22,23], phenolic compounds quantified in beer are somewhat higher than in white wine and lower than in red wine. This inconsistency can be attributed to the varying quality of raw materials, yeast strains, and brewing process parameters [21].

Common phenolic compounds that can be found in barley (in free, esterified, or bound form) are benzoic and cinnamic acid derivatives, proanthocyanidins, quinines, flavonols, chalcones, flavones, flavanones, and amino phenolic compounds [24–33]. Ferulic and p-coumaric acid are the low-molecular weight (LMW) phenolic acids in barley grains. They can be detected in the husk, pericarp, testa, and aleurone, and even in the endosperm matrix. Phenolic acids such as vanillic, sinapinic, and p-hydroxybenzoic acids [26,31,34–37]; flavan-3-ols from monomers ((+)-catechin and (−)-epicatechin), dimers (prodelphinidin B3 and procyanidin B3), and trimers (procyanidin C2); and higher-molecular weight flavonoid-derived tannins are common in barley as well [26,38,39].

Polyphenols are secondary plant metabolites and play an important role as protective agents. There are many classes of polyphenols, but only prenylflavonoids are characteristically present in the hop plant. Bitter acids (multifidol glucosides) are also indigenous to hop plants [40]. The most common classes are presented in the following sections adapted from an extensive review by Knez Hrnčič et al. [40].

2.1.1. Prenylflavonoids

Prenylflavonoids represent a class of flavonoids with at least one prenyl or geranyl substituent in the ring [41]. It is presumed that the desmethylxanthohumol represents a precursor for the majority of flavonoids in hops [42]. Several other important prenylflavonoids are found in hops, such as the most potent phytoestrogens 8-prenylnaringenin and 6-prenylnaringenin, or the isomere of xanthohumol—isoxanthohumol. Xanthohumol is a well-known compound [40]. It has been studied as an anticancer agent, but poses many other positive properties against pathogenic fungi, malaria, and HIV-1 viruses [43]. It has chemopreventive, sedative, anti-inflammatory, and antimicrobial properties. Even though the isomer of xanthohumol—isoxanthohumol is proven to be a bit less potent than xanthohumol, it too has anti-mutagenic and antiangiogenic activity [43,44]. Another chemical compound with anticarcinogenic properties belonging to this group is 8-prenylnaringenin [45].

2.1.2. Catechins

Flavanol (+)-catechin is the third most abundant compound in hop cones possessing antioxidative and vasodilative features [43]. Flavanol(−)-epicatechin and (+)-gallocatechin can be found in hops as well [46]. Flavanols catechin and epicatechin show antioxidative and anti-inflammatory properties [47]. A mixture of hop proanthocyanidins shows more pronounced antioxidative properties than individual flavanols and proanthocyanidins [43].

2.1.3. Flavonols

Quercetin and kaempferol are the most mentioned antioxidant flavanols that can be found in fruits and vegetables, but also in hops [43,46]. Plants usually contain flavonols in the form of glycosides [48], which, in the case of quercetin, presents its bioavailable form, and the least bioavailable form of quercetin is rutin, the most common form of quercetin in hops [43,48]. It is widely recognized for its anti-aging properties [49]. Both, quercetin and kaempferol can inhibit the growth of various cancer cells [50].

2.1.4. Multifidol and Multifidol Glucosides

1-(2-methyl propanoyl)phloroglucinol-glucopyranoside, multifidol glucosides, 1-(3-methyl butyryl) phloroglucinol, and 5-(2 Methylpropanoyl) phloroglucinol are constituents of hops. Authors [51] have investigated the human recognition threshold concentrations and the lowest recognitions levels for 11 bitter tastants from the hop hard resin fraction, and the lowest concentration was determined for co-multifidol glucopyranoside (5 µmol/L) showing that minor hop compounds may act as significant taste-carriers [51].

Ferulic acid from hops is designated as a highly antioxidative polyphenolic compound that prevents lipid peroxidation, apoptotic cell death of healthy cells, and acts as a free radical scavenger [46,52]. It is important for the brewing industry because it retards the degradation of iso-α-acids and actively prevents beer spoilage [53]. Ferulic acid has many properties that enhance the toxicity of certain chemicals, carcinogenic agents, and ionizing radiation. It is a potent UV light absorber [52,54]. However, when coupled with certain enzymes, it may act as an anti-inflammatory, antiapoptotic, and anticarcinogenic agent [40]. Resveratrol is reportedly an anti-inflammatory and anticancer agent, and also acts preventively on cardiovascular diseases development [55,56]. Cosmetic industry acknowledges it as an anti-aging agent [49].

The malting process itself induces modifications in the composition of barley grain including the degradation of endogenous phenolic compounds [26,32,35,57–60]. According to several authors, the concentration of phenolic compounds in malt can be higher than in barley. However, the main groups remain the same, which indicates that the extraction of flavonoids and phenolic acids in malt is more pronounced [31,32,35]. Behavior of polyphenols after malting and brewing is described in the sections below.

2.2. Polyphenols during the Malting and Brewing Process

By definition, the common hop, *Humulus lupulus,* is a climbing herbaceous perennial vine that belongs to the family *Cannabaceae*. Its original name was given by the Romans, *Lupulus salictarius* [23]. For brewing, only the female plant flowers (pine-like cones) are used. Hops are used as a spice in the brewing process and only 200–600 g/hL of beer. Many hop varieties contribute to beer with two main characteristics: bitterness and aromas. However, some have more pronounced use for their bitterness and others for aromas [61]. Among many different compounds, resins and essential oils are the most important compounds for the brewing industry, but phenolic compounds, important for the flavor of the finished beer, are significant as well [61]. Hard resins appear as a result of oxidation and polymerization reactions of the soft resins substances. Humulones (α-acids) and lupulones (β-acids) belong to soft resins. They exhibit lower pH values because they contain a phenolic group that can release a hydrogen ion (H^+) [61]. The α-acids get extracted during wort boiling when they undergo oxidative isomerization to iso-α-acids (iso-humulones), also recognized as bitter compounds of beer (Figure 3). Circa 70% of beer bitterness is a result of isomerization [61].

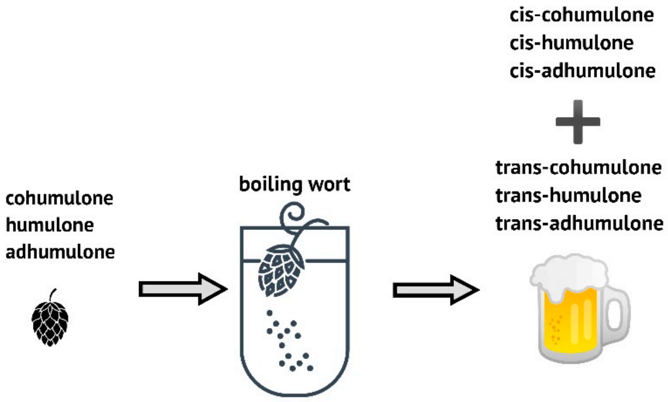

Figure 3. Scheme of α-acids isomerization to trans- and cis-forms.

Beer contains from 20–60 mg/L of iso-humulones, and oxidized β-acids sum up to the rest of the bitterness sensation. Besides resins, hops contain 0.5–3.0% of essential oils, which provide certain beer flavors. Phenolic compounds in beer are mostly tannins, flavonoids, and polyphenols. A significant portion of phenolic compounds are in the monomeric form (p-coumaric, ferulic, chlorogenic, caffeic acids, and gallic). Ferulic acid is commonly found in the endosperm cell wall of barley [62,63].

Humulones and linalool, the two-hop constituents, tend to prevent beer gushing [64] if added during wort boiling [65].

Polyphenolic molecules can be found in different stages during the brewing process and react with proteins: during wort boiling, they form the hot break; during cooling, they form the cold break; and during post-fermentation, they are involved in the formation of chill haze and permanent hazes and facilitate the removal of undesirable compounds with filtration. However, they tend to react with proteins in packaged beer and form undesirable haze after the expiration date [66].

As mentioned before, polyphenols can enter beer from hop and malt. Phenolic compounds—originating from malt—exhibit certain changes during the mashing stage. However, even before this stage, the polyphenolic content can show different values depending on which milling technique was used. Namely, wet milling, where the disintegration of the endosperm is optimal, leaves the husk intact, which leads to a decrease in ferulic acid and total phenolic content [67]. During mashing, different polyphenols, such as free cinnamic and ferulic acids, get solubilized into mash depending on the temperature [68–73]. Mashing-in time also plays an important factor in phenolic acid release, but viscosity and grist coarseness are important as well [68,70]. Total polyphenols concentrations depend on whether an infusion or decoction mashing regimes were applied. Decoction results with worts with higher total polyphenol content [74]. Wort separation from spent grain can be conducted via mash filter or lauter tun. Several authors [75] reported that using lauter tun can result in lower phenolic compounds levels in wort after separation. Research by [76] noted a significant increase of total polyphenols during lautering, probably due to their extraction from phenol-rich spelt material. The changes of dimers prodelphinidin B3 and procyanidin B3 levels originating from the raw materials to finished beer were also investigated [77]. The extraction of dimers prodelphinidin B3 and procyanidin B3 was incomplete, similar to catechin. Epicatechin was not detected in the raw materials, but later on, it was detected as a result of heating catechin in the boiling acidic wort [77]. Monomers, dimers, trimers, and polymers of flavanols from malt were extracted into sweet wort by 100%, 36%, 24%, and 23% [78]. Since boiling of wort implies the addition of hops, this completely changes the total polyphenols content and composition.

Polymerization reactions, protein–polyphenol interactions, and precipitation have a significant impact as well. It is predicted that during wort boiling, about 70% of polyphenols are extracted from hops [17,79], but according to their polarity and their tendency to form complexes with wort proteins, this number is variable [79]. Narziss and Bellmer [80] reported that protein precipitation greatly depends on the polyphenol polymerization index and that hop anthocyanogens exhibit higher reactivity than malt anthocyanogens. Besides, lower polymerization index or less oxidized polyphenols were more active in protein precipitation [80]. Hot trub contains 40–70% of proteins, 7–32% of bitter substances, 20–30% of organic substances, and 5% of ash [81]. Higher oligomeric phenolic compounds are prone to form complexes with proteins, and small phenolic molecules like phenolic acids easily get adsorbed to hot trub [82]. This leads to the conclusion that a significant share of higher oligomeric proanthocyanidins can be removed from wort with the settling of hot trub or get adsorbed to yeast cells during fermentation [82]. Proanthocyanidin tetramers and pentamers can be completely removed from worts after boiling and settling, and catechin and procyanidin B3 were found in the finished beer as reported by [83]. It has been reported that during whirlpool rest, phenolic compounds show a significant decrease, mostly because of their adsorption to hot trub. Catechin or dimeric proanthocyanidins are showing a significantly higher decrease than monophenolic compounds [76,77], with a noted decrease in antioxidant activity [84]. Leitao, however, declared no significant changes [85]. Following the process stages (fermentation, warm rest, and chill-lagering) contributes to the additional decreases in phenolic substances [75,84]. However, several phenolic acids and catechin, except for ferulic acid (35% decrease during warm rest), were not affected [76]. In another study, ferulic acid showed an increase during fermentation. This was attributed to yeast metabolic activity [72].

Hops-originating polyphenols, such as prenylflavanones and prenylchalcones, were also investigated. Prenylflavanones showed higher levels in beer than prenylchalcones, even though raw hops contain very low amounts of prenylflavanones [86–88]. Different research regarding xanthohumol and/or isoxanthohumol was conducted over the years. A study on early hopping of a lager beer showed that 98% of xanthohumol was detected as isoxanthohumol [87]. Xanthohumol losses commonly occur due to adsorption to hot trub, yeast, and cold trub. In the same research [87], it was reported that 13% of hop's xanthohumol can be found in the spent hops, and 12% adsorbs to hot trub. Further stages, such as fermentation, maturation, and lagering, result in a 17% reduction due to adsorption to cold trub (6%) and yeast (11%) [87]. Desmethylxanthohumol is one of the molecules that can be found in hop extracts [86,88,89]. It is usually modified to 6-prenylnaringenin and 8-prenylnaringenin during wort boiling [88]. Even though xanthohumol has a tendency to adsorb to hot trub proteins or yeast cells, and thus, get derived out of wort and consequently beer [87], it is interesting for the brewers (and consumers) due to its health benefits. Namely, certain efforts have been made in order to suppress its isomerization during brewing. Higher concentrations of xanthohumol (1–10 mg/L) were obtained in enriched beer by rapid cooling [90]. Xanthohumol isomerization assumedly occurs because xanthohumol binds to higher molecular weight (300 to 600 kDa) roasted substances [91–95], which can serve as xanthohumol carriers, and reduce its losses during fermentation, filtration, and stabilization process [95]. Beer stabilization can be ensured in different ways. Cold storage (the colder the better) for a short period reduces the potential haze-active material (protein-polyphenol complexes) in beer [96]. Utilization of adsorbents specific to proteins or polyphenols, proteolytic enzymes, and the addition of isinglass or tannic acid are common methods to achieve colloidal stability [83,97]. Polyvinylpolypyrrolidone (PVPP) shares structural similarity with polyproline and is often used as an adsorbent. According to research [98], 48% of total polyphenols were removed from beer treated with 100 g/hL PVPP. In other words, 78% of total flavanols, 90% of prodelphinidin B3, 96% of procyanidin B3, 79% of (+)-catechin, and 88% of (−)-epicatechin) bonded to PVPP. Lower levels of PVPP remove phenolic compounds with higher degrees of hydroxylation and oligomerization, and at higher levels, PVPP removes all polyphenols [99,100].

2.3. *Polyphenols Behavior during Beer Storage*

Storage time can significantly impact beer quality, such as colloidal stability and flavor. Beer aging decreases bitterness and aging off-flavors (sweet and cardboard-like notes) emerge [101]. Isomerized α-acids show significant reduction over five-month storage, where cis-isomers showed fewer changes than trans-isomers. However, this correlates with the storage conditions (light, temperature) of beer [102,103]. Changes in phenolic acids are also significant during storage. Authors [104] noted a total phenolic content decrease during a six-month storage time, while the most significant reduction was achieved in the first 3 months of storage. Correspondently, antioxidant activity also exhibited reduction. It is assumed that polyphenols undergo oxidative and acid-catalyzed polymerizations, which result in haze-active products [100]. In a study that followed changes during a six-month storage time, the concentrations of (+)-catechin, (−)-epicatechin, proanthocyanidin B3, and prodelphinidin showed a significant reduction [77], but monomeric flavanols showed increased stability over dimers during six months of storage [77,98]. A study on the influence of acetaldehyde from beer on haze formation and stability of beer phenolics reported that beer pH is influenced by acetaldehyde, which results in a reduction of catechin content and haze formation [105]. A year-long study by [106] showed a decrease in small flavonoid molecules (monomers to trimers), and it can be connected with the increase in color units. Compound 4-vinyl guaiacol also shows a decrease by 30% in 2 months at 6 °C [71]. Prenylated flavonoids exhibit stability during beer storage, resulting in almost no change in beer stored for 10 years at 20 °C in a brown glass bottle [103]. Xanthohumol concentration decreases during storage while isoxanthohumol levels show an increase [107].

2.4. Sensory Thresholds for Some Phenolic Acids

Phenolic acids show high sensory thresholds. For example, cinnamic acid has a threshold of 67 to 139 mg/L and benzoic acid derivatives are 206 to 315 mg/L for [108]; remaining decarboxylation products exhibit significant flavor activity [19]. The 4-vinyl guaiacol added to water has a flavor threshold of below 20 ppb [18]. Some volatile monophenols bring about the spicy, clove-like, sweet, and vanilla-like notes to a beer, but at higher concentrations, they become unpleasant [19]. Phenolic acids are precursors for volatile monophenols formed during wort boiling and fermentation. However, yeast strain and fermentation conditions influence and amplify the phenolic flavor of wheat beers more than temperature conditions [18,72].

3. Bitterness

Bitterness is an important property of beers and according to several authors, about 80% of bitterness originates from hops during boiling [109–111]. As mentioned before, the female hop cones and their soft resins rich in α-acids (cohumulone, humulone, adhumulone) and β-acids (colupulone, lupulone, adlupulone) are used in brewing. The major bitter compounds in beer are iso-α-acids [112]. The ratio of trans/cis stereoisomers for standard beers is close to 3:7 beers [113], or 68:32 in favor of the cis-compounds. The half-life of cis-compounds is approx. five years, and of trans-isomers is about a year. This makes cis-forms much more stable [114]. The isomerized α-acids are intensely bitter, and they represent the typically bitter beer taste. Their concentrations range from 15 (American lagers)–100 ppm (bitter English ales). However, bitter taste in beer is modified with residual sugars and results in pleasant bitterness for the consumer [114]. Isomerized α-acids have tensioactive properties, which stabilize the beer foam, and they act inhibitory to Gram-positive bacteria, while lactic acid bacteria in beer exhibit resistance to iso-α-acids.

Bittering procedures have evolved and have transferred the use of hops into almost all brewing stages, such as post-fermentation bittering, or dry hopping. Different hopping products are available as an aqueous extract or in pellet form. Such products have higher levels of cis-isomers relative to trans-isomers, and this results in a lower trans/cis ratio [115]. Chemically reduced derivatives of iso-α-acids (light stable tetrahydro-iso-humulones (tetra) and hexahydro-iso-humulones (hexa)) can ensure bitterness. The availability of the hop extends to different forms (cones, pellets, plugs) that can be added at different stages of the brewing process. Dry-hopping is a method of soaking hops in beer during fermentation or conditioning in order to add different aromas and flavors to the finished beer. This method grants oxidized α-acids, humulinones, to beer. Their concentrations in hop leaves and pellets range from 0.2–0.5% *w*/*w* [116–118]. Originating from hops, polyphenols contribute to bitterness as well [119]. Moreover, they are recognized as important acceptance factors in different beverages, including beer [120]. Flavan-3-ol monomers such as (+)-catechin and (−)-epicatechin can also impart bitterness to beer [7,121,122].

4. Astringency

As described in the introduction, astringency is a complex sensory property, characterized by drying, roughing, and puckering of the skin or mucosal surface in the mouth. Immediate perception is not always possible; however, it is usually recognized in the mouth after swallowing the content [123]. According to Siebert and Chassy [124], several compounds provide this sensation: salts of multivalent metallic cations (alum), dehydrating agents (ethanol or acetone), mineral and organic acids, and plant tannins (polyphenols). The reaction between saliva proteins that lubricate the mouth and polyphenols derived from foods results in an astringent sensation. Oxidation and lower pH enhances the astringency sensation [123,125].

Certain phenolic compounds (ferulic acid, p-coumaric acid, and protocatechuic acid) reportedly aid astringency [106]. On the other hand, flavanols, catechin, and epicatechin add bitterness [4,120].

As reported by several authors [111,122,126] flavonoid polyphenols induce the sensation of astringency. Research conducted by [127] investigated the addition of purified polyphenols and oxidized counterparts to water and beer. The conducted sensory analysis confirmed that the addition of polyphenols to beer induced harsh bitterness and increased astringency. A similar report was submitted by [7]. Sensory panelists graded beer with iso-α acids and 100 or 200 mg/L of polyphenols from spent hop as more bitter. Beers with added (+)-catechin, (−)-epicatechin, (−)-epigallocatechin, and (−)-epicatechin gallate has a notably longer bitterness with higher intensities for “harsh”, “medicinal”, and “metallic” as well. Table 1 presents the most common astringent/bitter compounds that are identified in beer.

Removal of acrospires from malt by polishing reduced the astringent components, resulting in smooth-tasting beer [128–130]. If subcritical water is applied to malt, from which beer was produced, such beer had reduced astringent components and aftertaste.

Lower pH values result in lesser polyphenols (tannins) that get extracted to beer, and this beer is then less astringent. Mg^{2+} in concentration over 15 mg/L can affect a sour or bitter astringency found in beer [61].

Table 1. Astringent/bitter compounds commonly found in beer adjusted from [61].

Compound	Concentration (mg/L)	Description
2-Methylpropanoic	0.1–2	Sweet, bitter, sour
Caffeic	1–10	Bitter, harsh, sour, diacetyl
Chlorogenic	1–10	Bitter, harsh, bitter-sweet, astringent
p-Courmaric	0.1–0.2	Sour, dry, bitter, astringent, medicinal
Gallic	1–5	Bitter, harsh, astringent, dry, sour, sweet
Hydroxybenzoic	0.13	Bitter, harsh, astringent, acidic, vinegar
Sinapic	1–10	Bitter, astringent, harsh, sour, dry
Syringic	1–10	Bitter, harsh, astringent, winey, malty
Vanillic	1–10	Harsh, bitter–sweet, sour, astringent, peppery, medicinal
Hexanal	0.003–0.07	Bitter, vinous
trans-2-Hexenal	0.005–0.01	Bitter, astringent
Heptanal	0.002	Aldehyde, bitter
Octanal	0.001–0.02	Orange peel, bitter
Nonanal	0.001–0.011	Astringent, bitter
Decanal	0.0–0.003	Bitter, orange peel
Tyrosol	3–40	Bitter, chemical

5. Polyphenols/Astringency-Related Off-Flavors

5.1. Skunky Flavor

Even though they contribute to beer stability, iso-α-acids are partly responsible for nascent off-flavors of aging (stale and cardboard flavors) [131]. Beer exposure to light causes a decomposition of different chemical compounds, which results in various off-flavors, with the skunky flavor being one of them. To avoid the formation of skunky flavor, due to the light transmission into the packaging, beer must be stored in opaque cans, or green/brown bottles. Iso-α-acids are especially sensitive to light, and its decomposition results in a skunky (or lightstruck) flavor, a 3-methylbut-2-ene-1-thiol [132]. The flavor threshold of this compound is very low (4 ng/L) but can irreversibly spoil beer quality [114,132].

To avoid this, brown bottles should be used as beer packaging and they should be stored away from the light. Sometimes, it only takes seconds for the reaction to occur and start instilling the undesirable skunk off-flavor. Light beers and beers hopped with more hops are more prone to obtain the skunky off-flavor. This only occurs in the finished beer and is always perceived as an off-flavor [132–134].

5.2. Other Off-Flavors

Medicinal/Phenolic-different phenols can cause a wide variety of off-flavors that can be described as a solvent, astringent, plastic, medicinal, bitter, spicy, herbal, drying, tea-like, clove-like, smoky, or band-aid. The threshold is between 0.05–0.55 mg/L. Medicinal off-flavors can usually be perceived during mashing and/or sparging. They are a result of an inappropriate pH level, water amounts, and applied temperatures. Inappropriate use of chlorinated tap water or sanitizers with chlorine or iodine can bring out chlorophenols. Yeast can also produce phenol, and a clove-like characteristic is desirable in some ales, especially wheat beers, but undesirable in bottom-fermenting beers [132–134]. The phenolic smell is caused by 4-vinyl guaiacol and can be perceived in concentrations as low as 0.05–0.55 mg/L.

Grainy/Husky reminds one of raw grain, fresh wheat, grainy, harsh, “green,” nutty flavors, which are comparable to astringency from tannins and/or oxidization. It can be perceived at 1–20 μg/L. The emergence of this off-flavor is mostly caused by the isobutyraldehyde in malt, but other aldehydes can impart the grainy character, and higher levels of these compounds are found in freshly made malt if it was not subjected to an appropriate rest phase before use. This off-flavor can also appear if malt has been crushed too finely, mashed for too long, sparged with water at too hot a temperature, or oversparged [132–134].

Catty (p-menthane-8-thiol-3-one) reminds one of tomcat urine, blackcurrant leaves, or tomato plants and is perceived at 15 ng/L. It is commonly considered as an off-flavor, but it can be desirable in some ales, especially IPAs, since p-menthane-8-thiol-3-one is associated with the flavor of certain hop varieties. However, if it is present because oxidation occurred, it is considered as an off-flavor [132].

Cheesy (isovaleric acid) is also designated as old cheese, rancidity, old hops, goaty, dirty socks, or sweaty. Its threshold is below 1 mg/L, and it is usually a result of oxidative processes of the alpha acids in hops. It may be confused with caprylic off-flavor. If associated with alpha acids, it is often accompanied by grassy notes, but it can also be caused by bacterial infection. To reduce this or completely avoid it, hops should be fresh or stored in an oxygen-deprived environment (vacuum bags in a freezer) [132].

Grassy reminds one of freshly cut grass or must, and can also be a result of inappropriate hops storage. To avoid this, fresh hops should be used or stored properly, as described above [133].

6. Conclusions

In order to brew a good beer, it is important to know the chemistry behind the bitterness and astringency of the hop. Even though the consumers enjoy a bitterer brew, they will surely dislike the astringent aftertaste, which can be a result of a faulty lead process. For that reason, it is important to pay attention to temperatures, the duration of hopping or dry hopping, and the quality of hops. Additional attention should be paid to post-packaging processes and conditions during transport and sales (UV light, temperature fluctuations, etc.). All stages of brewing affect and modify hop components, which as a result affects the overall sensory characteristics of the beer. Advanced hop products and techniques can help reduce the off-flavors and increase the flavor properties of beer. However, further research should be conducted in order to fully understand the complexity of polyphenolics in beer and chemical and biochemical reactions between other compounds and yeast, which affect the overall beer quality in general.

Author Contributions: conceptualization, K.H.; data curation, V.K. and K.M.; writing—original draft preparation, K.H.; writing—review and editing, I.J.K. and G.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aron, P.M.; Shellhammer, T.H. A discussion of polyphenols in beer physical and flavour stability. *J. Inst. Brew.* **2010**, *116*, 369–380. [CrossRef]
2. Mastanjević, K.; Krstanović, V.; Lukinac, J.; Jukić, M.; Lučan, M.; Mastanjević, K. Craft brewing—Is it really about the sensory revolution? *Kvasny prumysl* **2019**, *65*, 13–16. [CrossRef]
3. Dalgliesh, C.E. Flavour Stability. In *Proc. Eur. Brew. Conv. Congr., Amsterdam*; DSW: Dordrecht, The Netherlands, 1977; pp. 623–659.
4. Peleg, H.; Gacon, K.; Schlich, P.; Noble, A. Bitterness and astringency of flavan-3-ol monomers, dimers and trimers. *J. Sci. Food Agric.* **1999**, *79*, 1123–1128. [CrossRef]
5. Drewnowski, A. The science and complexity of bitter taste. *Nutr. Rev.* **2001**, *59*, 163–169. [CrossRef] [PubMed]
6. Walters, E.; Roy, G. Taste Interactions of Sweet and Bitter Compounds. In *Flavor-Food Interactions*; American Chemical Society: Washington, DC, USA, 1996; pp. 130–142.
7. McLaughlin, I.R.; Lederer, C.; Shellhammer, T.H. Bitterness-Modifying Properties of Hop Polyphenols Extracted from Spent Hop Material. *J. Am. Soc. Brew. Chem.* **2008**, *66*, 174–183. [CrossRef]
8. Luck, G.; Liao, H.; Murray, N.; Grimmer, H.; Warminski, E.; Williamson, M.; Lilley, T.; Haslam, E. Polyphenols, astringency and proline—Rich proteins. *Phytochemistry* **1994**, *37*, 357–371. [CrossRef]
9. Baert, J.J.; De Clippeleer, J.; Hughes, P.S.; De Cooman, L.; Aerts, G. On the origin of free and bound staling aldehydes in beer. *J. Agric. Food Chem.* **2012**, *60*, 11449–11472. [CrossRef] [PubMed]
10. Amerine, M.A.; Pangborn, R.M.; Roessler, E.B. *Principles of Sensory Evaluation of Food*; Academic Press: New York, NY, USA, 1965.
11. Meilgaard, M.; Civille, G.V.; Carr, B.T. *Sensory Evaluation Techniques*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2007.
12. Schmelzle, A. The beer aroma wheel. Updating beer flavor terminology according to sensory standards. *Brew. Sci.* **2009**, *62*, 26–32.
13. Saison, D.; De Schutter, D.P.; Uyttenhove, B.; Delvaux, F.; Delvaux, F.R. Contribution of staling compounds to the aged flavor of lager beer by studying their flavour thresholds. *Food Chem.* **2009**, *114*, 1206–1215. [CrossRef]
14. Langstaff, S.A.; Lewis, M.J. The mouthfeel of beer—A review. *J. Inst. Brew.* **1993**, *99*, 31–37. [CrossRef]
15. Meilgaard, M.C.; Dalgliesh, C.E.; Clapperton, J.F. Beer flavor terminology. *J. Am. Soc. Brew. Chem.* **1979**, *37*, 47–52. [CrossRef]
16. Langstaff, S.A.; Guinard, J.X.; Lewis, M.J. Sensory evaluation of the mouthfeel of beer. *J. Am. Soc. Brew. Chem.* **1991**, *49*, 54–59. [CrossRef]
17. Jerkovic, V.; Callemien, D.; Collin, S. Determination of stilbenes in hop pellets from different cultivars. *J. Agric. Food Chem.* **2005**, *53*, 4202–4206. [CrossRef] [PubMed]
18. Vanbeneden, N.; Gils, F.; Delvaux, F.; Delvaux, F.R. Formation of 4-vinyl and 4-ethyl derivatives from hydroxycinnamic acids: Occurrence of volatile phenolic flavour compounds in beer and distribution of pad1-activity among brewing yeasts. *Food Chem.* **2008**, *107*, 221–230. [CrossRef]
19. Sterckx, F.L.; Missiaen, J.; Saison, D.; Delvaux, F.R. Contribution of monophenols to beer flavour based on flavour thresholds, interactions and recombination experiments. *Food Chem.* **2011**, *126*, 1679–1685. [CrossRef] [PubMed]
20. Langos, D.; Granvogl, M.; Schieberle, P. Characterization of the key aroma compounds in two Bavarian wheat beers by means of the sensomics approach. *J. Agric. Food Chem.* **2013**, *61*, 11303–11311. [CrossRef] [PubMed]
21. Wannenmacher, J.; Gastl, M.; Becker, T. Phenolic Substances in Beer: Structural Diversity, Reactive Potential and Relevance for Brewing Process and Beer Quality. *Compr. Rev. Food Sci. Food Saf.* **2018**, *17*, 953–988. [CrossRef]
22. Neveu, V.; Perez-Jiménez, J.; Vos, F.; Crespy, V.; du Chaffaut, L.; Mennen, L. Phenol-Explorer: An online comprehensive database on polyphenol contents in foods. *Database* **2010**, *2010*, bap024. [CrossRef] [PubMed]
23. Bamforth, C.W. *Beer: Tapping into the Art and Science of Brewing*; Insight Books Plenum Publishing Corporation: New York, NY, USA; London, UK, 2003; pp. 60–65.
24. Bonoli, M.; Marconi, E.; Caboni, M.F. Free and bound phenolic compounds in barley (*Hordeum vulgare* L.) flours: Evaluation of the extraction capability of different solvent mixtures and pressurized liquid methods by micellar electrokinetic chromatography and spectrophotometry. *J. Chromatogr. A* **2004**, *1057*, 1–12. [CrossRef]
25. Bonoli, M.; Verardo, V.; Marconi, E.; Caboni, M.F. Antioxidant phenols in barley (*Hordeum vulgare* L.) flour: Comparative spectrophotometric study among extraction methods of free and bound phenolic compounds. *J. Agric. Food Chem.* **2004**, *52*, 5195–5200. [CrossRef]
26. Dvořáková, M.; Guido, L.F.; Dostálek, P.; Skulilová, Z.; Moreira, M.M.; Barros, A.A. Antioxidant properties of free, soluble ester and insoluble-bound phenolic compounds in different barley varieties and corresponding malts. *J. Inst. Brew.* **2008**, *114*, 27–33. [CrossRef]
27. Nardini, M.; Cirillo, E.; Natella, F.; Mencarelli, D.; Comisso, A.; Scaccini, C. Detection of bound phenolic acids: Prevention by ascorbic acid and ethylenediaminetetraacetic acid of degradation of phenolic acids during alkaline hydrolysis. *Food Chem.* **2002**, *79*, 119–124. [CrossRef]
28. Nardini, M.; Ghiselli, A. Determination of free and bound phenolic acids in beer. *Food Chem.* **2004**, *84*, 137–143. [CrossRef]
29. Nardini, M.; Natella, F.; Scaccini, C.; Ghiselli, A. Phenolic acids from beer are absorbed and extensively metabolized in humans. *J. Nutr. Biochem.* **2006**, *17*, 14–22. [CrossRef] [PubMed]

30. Gerhäuser, C. Beer constituents as potential cancer chemopreventive agents. *Eur. J. Cancer* **2005**, *41*, 1941–1954. [CrossRef] [PubMed]
31. Maillard, M.N.; Soum, M.H.; Boivin, P.; Berset, C. Antioxidant activity of barley and malt: Relationship with phenolic content. *LWT—Food Sci. Technol.* **1996**, *29*, 238–244. [CrossRef]
32. Lu, J.; Zhao, H.; Chen, J.; Fan, W.; Dong, J.; Kong, W.; Sun, J.; Cao, Y.; Cai, G. Evolution of phenolic compounds and antioxidant activity during malting. *J. Agric. Food Chem.* **2007**, *55*, 10994–11001. [CrossRef]
33. Carvalho, D.O.; Curto, A.F.; Guido, L.F. Determination of Phenolic Content in Different Barley Varieties and Corresponding Malts by Liquid Chromatography-diode Array Detection-Electrospray Ionization Tandem Mass Spectrometry. *Antioxidants* **2015**, *4*, 563–576. [CrossRef]
34. Whittle, N.; Eldridge, H.; Bartley, J.; Organ, G. Identification of the polyphenols in barley and beer by HPLC/MS and HPLC/electrochemical detection. *J. Inst. Brew.* **1999**, *105*, 89–99. [CrossRef]
35. Goupy, P.; Hugues, M.; Boivin, P.; Amiot, M.J. Antioxidant composition and activity of barley (*Hordeum vulgare*) and malt extracts and of isolated phenolic compounds. *J. Sci. Food Agric.* **1999**, *79*, 1625–1634. [CrossRef]
36. Liu, Q.; Yao, H. Antioxidant activities of barley seeds extracts. *Food Chem.* **2007**, *102*, 732–737. [CrossRef]
37. Kim, M.-J.; Hyun, J.-N.; Kim, J.-A.; Park, J.-C.; Kim, M.-Y.; Kim, J.-G.; Lee, S.-J.; Chun, S.-C.; Chung, I.-M. Relationship between phenolic compounds, anthocyanins content and antioxidant activity in colored barley germplasm. *J. Agric. Food Chem.* **2007**, *55*, 4802–4809. [CrossRef]
38. Holtekjølen, A.K.; Kinitz, C.; Knutsen, S.H. Flavanol and bound phenolic acid contents in different barley varieties. *J. Agric. Food Chem.* **2006**, *54*, 2253–2260. [CrossRef]
39. Dvorakova, M.; Moreira, M.M.; Dostalek, P.; Skulilova, Z.; Guido, L.F.; Barros, A.A. Characterization of monomeric and oligomeric flavan-3-ols from barley and malt by liquid chromatography-ultraviolet detection-electrospray ionization mass spectrometry. *J. Chromatogr. A* **2008**, *1189*, 398–405. [CrossRef]
40. Knez Hrnčič, M.; Španinger, E.; Košir, I.J.; Knez, Ž.; Bren, U. Hop Compounds: Extraction Techniques, Chemical Analyses, Antioxidative, Antimicrobial, and Anticarcinogenic Effects. *Nutrients* **2019**, *11*, 257. [CrossRef]
41. Plazar, J. Mechanism of Antigenotoxic Activity of Xanthohumol and Related Prenylflavonoids from Hops (*Humulus lupulus* L.). Ph.D. Thesis, Nacionalni Inštitut za Biologijo, Ljubljana, Slovenia, 2007.
42. Chadwick, L.R.; Pauli, G.F.; Farnsworth, N.R. The pharmacognosy of *Humulus lupulus* L. (hops) with an emphasis on estrogenic properties. *Phytomedicine* **2006**, *13*, 119–131. [CrossRef]
43. Biendl, M.; Pinzl, C. *Hops and Health Uses-Effects-History*, 2nd ed.; German Hop Museum Wonlzach: Wonlzach, Germany, 2013.
44. Ameh, S.J.; Ibekwe, N.N.; Ebeshi, B.U. Essential Oils in Ginger, Hops, Cloves, and Pepper Flavored Beverages–A Review. *J. Dietary Suppl.* **2015**, *12*, 241–260. [CrossRef] [PubMed]
45. Brunelli, E.; Minassi, A.; Appendino, G.; Moro, L. 8-Prenylnaringenin, inhibits estrogen receptor-alfa mediated cell growth and induces apoptosis in MCF-7 breast cancer cells. *J. Steroid Biochem. Mol. Biol.* **2007**, *107*, 140–148. [CrossRef]
46. Karabín, M.; Hudcová, T.; Jelínek, L.; Dostálek, P. Biologically Active Compounds from Hops and Prospects for Their Use. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 542–567. [CrossRef]
47. Fresco, P.; Borges, F.; Diniz, C.; Marques, M.P.M. New Insights on the Anticancer Properties of Dietary Polyphenols. *Med. Res. Rev.* **2006**, *26*, 747–766. [CrossRef]
48. Manach, C.; Scalbert, A.; Morand, C.; Rémésy, C.; Jiménez, L. Polyphenols: Food sources and bioavailability. *Am. J. Clin. Nutr.* **2004**, *79*, 727–747. [CrossRef] [PubMed]
49. Corrêa, R.C.G.; Peralta, R.M.; Haminiuk, C.W.I.; Maciel, G.M.; Bracht, A.; Ferreira, I.C.F.R. New phytochemicals as potential human anti-aging compounds: Reality, promise, and challenges. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 942–957. [CrossRef] [PubMed]
50. Dai, J.; Mumper, J.R. Plant Phenolics: Extraction, Analysis and Their Antioxidant and Anticancer Properties. *Molecules* **2010**, *15*, 7313–7352. [CrossRef] [PubMed]
51. Dresel, M.; Dunkel, A.; Hofmann, T. Sensomics Analysis of Key Bitter Compounds in the Hard Resin of Hops (*Humulus lupulus* L.) and Their Contribution to the Bitter Profile of Pilsner-Type Beer. *J. Agric. Food Chem.* **2015**, *63*, 3402–3418. [CrossRef]
52. Ghosh, S.; Basak, P.; Duttam, S.; Chowdhury, S.; Sil, P.C. New insights into the ameliorative effects of ferulic acid in pathophysiological conditions. *Food Chem. Toxicol.* **2017**, *103*, 41–55. [CrossRef]
53. Spreng, S.; Hofmann, T. Activity-Guided Identification of in Vitro Antioxidants in Beer. *J. Agric. Food Chem.* **2018**, *66*, 720–731. [CrossRef]
54. Bohr, G.; Gerhäuser, C.; Knauft, J.; Zapp, J.; Becker, H. Anti-inflammatory Acylphloroglucinol Derivatives from Hops (*Humulus lupulus*). *J. Nat. Prod.* **2005**, *68*, 1545–1548. [CrossRef]
55. Park, E.J.; Pezzuto, J.M. The pharmacology of resveratrol in animals and humans. *Biochim. Biophys. Acta* **2015**, *1852*, 1071–1113. [CrossRef]
56. Brglez Mojzer, E.; Knez-Hrnčič, M.; Škerget, M.; Knez, Ž.; Bren, U. Polyphenols: Extraction methods, antioxidative action, bioavailability and anticarcinogenic effects. *Molecules* **2016**, *21*, 901. [CrossRef] [PubMed]
57. Samaras, T.S.; Camburn, P.A.; Chandra, S.X.; Gordon, M.H.; Ames, J.M. Antioxidant properties of kilned and roasted malts. *J. Agric. Food Chem.* **2005**, *53*, 8068–8074. [CrossRef]
58. Leitao, C.; Marchioni, E.; Bergaentzlé, M.; Zhao, M.; Didierjean, L.; Miesch, L.; Holder, E.; Miesch, M.; Ennahar, S. Fate of polyphenols and antioxidant activity of barley throughout malting and brewing. *J. Cereal Sci.* **2012**, *55*, 318–322. [CrossRef]

59. Inns, E.L.; Buggey, L.A.; Booer, C.; Nursten, H.E.; Ames, J.M. Effect of modification of the kilning regimen on levels of free ferulic acid and antioxidant activity in malt. *J. Agric. Food Chem.* **2011**, *59*, 9335–9343. [CrossRef] [PubMed]
60. Inns, E.L.; Buggey, L.A.; Booer, C.; Nursten, H.E.; Ames, J.M. Effect of heat treatment on the antioxidant activity, color, and free phenolic acid profile of malt. *J. Agric. Food Chem.* **2007**, *55*, 6539–6546. [CrossRef] [PubMed]
61. Buiatti, S. Beer composition: An overview. In *Beer in Health and Disease Prevention*; Academic Press: London, UK, 2009; pp. 213–225.
62. Pollock, J.R.A. *Brewing Science*; Academic Press: London, UK, 1981; Volume 12, pp. 121–157.
63. Baxter, E.D.; Hughes, P.S. *Beer: Quality, Safety and Nutritional Aspects*; The Royal Society of Chemistry: Cambridge, UK, 2001; Volume 14, pp. 138–151.
64. Hanke, S.; Kern, M.; Herrmann, M.; Back, W.; Becker, T.; Krottenthaler, M. Suppression of gushing by hop constituents. *Mon. für Brauwiss.* **2009**, *62*, 181–186.
65. Srečec, S.; Zechner-Krpan, V.; Petravić-Tominac, V.; Košir, I.J.; Čerenak, A. Importance of Medical Effects of Xanthohumol, Hop (*Humulus lupulus* L.) Bioflavonoid in Restructuring of World Hop Industry. *Agric. Conspec. Sci.* **2012**, *77*, 61–67.
66. The Role of Polyphenols in Beer Haze Formation. Available online: https://draymans.com/the-role-of-polyphenols-in-beer-haze-formation/ (accessed on 1 May 2021).
67. Szwajgier, D. Dry and wet milling of malt. *A preliminary study comparing fermentable sugar, total protein, total phenolics and the ferulic acid content in non-hopped worts. J. Inst. Brew.* **2011**, *117*, 569–577.
68. Vanbeneden, N.; Van Roey, T.; Willems, F.; Delvaux, F.; Delvaux, F.R. Release of phenolic flavour precursors during wort production: Influence of process parameters and grist composition on ferulic acid release during brewing. *Food Chem.* **2008**, *111*, 83–91. [CrossRef]
69. Vanbeneden, N.; Gils, F.; Delvaux, F.; Delvaux, F.R. Variability in the release of free and bound hydroxycinnamic acids from diverse malted barley (*Hordeum vulgare* L.) cultivars during wort production. *J. Agri. Food Chem.* **2007**, *55*, 11002–11010. [CrossRef]
70. Schwarz, K.J.; Boitz, L.I.; Methner, F.-J. Release of phenolic acids and amino acids during mashing dependent on temperature, pH, time and raw materials. *J. Am. Soc. Brew. Chem.* **2012**, *70*, 290–295. [CrossRef]
71. McMurrough, I.; Madigan, D.; Donnelly, D.; Hurley, J.; Doyle, A.-M.; Hennigan, G.; McNulty, N. Control of ferulic acid and 4-vinyl guaiacol in brewing. *J. Inst. Brew.* **1996**, *102*, 327–332. [CrossRef]
72. Coghe, S.; Benoot, K.; Delvaux, F.; Vanderhaegen, B.; Delvaux, F.R. Ferulic acid release and 4-vinylguaiacol formation during brewing and fermentation: Indications for feruloyl esterase activity in *Saccharomyces cerevisiae*. *J. Agric. Food Chem.* **2004**, *52*, 602–608. [CrossRef]
73. Bartolom'e, B.; Garcia-Conesa, M.T.; Williamson, G. Release of the bioactive compound, ferulic acid, from malt extracts. *Biochem. Soc. Trans.* **1996**, *24*, 379S. [CrossRef] [PubMed]
74. Jurková, M.; Horák, T.; Hašková, D.; Čulík, J.; Čejka, P.; Kellner, V. Control of antioxidant beer activity by the mashing process. *J. Inst. Brew.* **2012**, *118*, 230–235. [CrossRef]
75. Fumi, M.D.; Galli, R.; Lambri, M.; Donadini, G.; De Faveri, D.M. Effect of full-scale brewing process on polyphenols in italian all-malt and maize adjunct lager beers. *J. Food Comp. Anal.* **2011**, *24*, 568–573. [CrossRef]
76. Pascoe, H.M.; Ames, J.M.; Sachin, C. Critical stages of the brewing process for changes in antioxidant activity and levels of phenolic compounds in ale. *J. Am. Soc. Brew. Chem.* **2003**, *61*, 203–209. [CrossRef]
77. Moll, M.; Fonknechten, G.; Carnielo, M.; Flayeux, R. Changes in polyphenols from raw materials to finished beer. *MBAA Tech. Q.* **1984**, *21*, 79–87.
78. McMurrough, I.; Hennigan, G.P.; Loughrey, M.J. Contents of simple, polymeric and complexed flavanols in worts and beers and their relationship to haze formation. *J. Inst. Brew.* **1983**, *89*, 15–23. [CrossRef]
79. Forster, A.; Gahr, A. On the fate of certain hop substances during dry hopping. *Brew. Sci.* **2013**, *66*, 93–103.
80. Narziss, L.; Bellmer, H.G. Ver¨anderungen der Polyphenole und ihres P. I. Während des Hopfenkochens in Wasser und Würze. *Brauwissenschaft* **1975**, *28*, 323–343.
81. Kühbeck, F.; Schütz, M.; Thiele, F.; Krottenthaler, M.; Back, W. Influence of lauter turbidity and hot trub on wort composition, fermentation, and beer quality. *J. Am. Soc. Brew. Chem.* **2006**, *64*, 16–28. [CrossRef]
82. Siebert, K.J.; Troukhanova, N.V.; Lynn, P.Y. Nature of polyphenol-protein interactions. *J. Agric. Food Chem.* **1996**, *44*, 80–85. [CrossRef]
83. Asano, K.; Ohtsu, K.; Shinagawa, K.; Hashimoto, N. Affinity of proanthocyanidins and their oxidation products for haze-forming proteins of beer and the formation of chill haze. *Agric. Biol. Chem.* **1984**, *48*, 1139–1146. [CrossRef]
84. Fantozzi, P.; Montanari, L.; Mancini, F.; Gasbarrini, A.; Addolorato, G.; Simoncini, M.; Scaccini, C. In vitro antioxidant capacity from wort to beer. *LWT—Food Sci. Technol.* **1998**, *31*, 221–227. [CrossRef]
85. Leitao, C.; Marchioni, E.; Bergaentzl'e, M.; Zhao, M.; Didierjean, L.; Taidi, B.; Ennahar, S. Effects of processing steps on the phenolic content and antioxidant activity of beer. *J. Agricul. Food Chem.* **2011**, *59*, 1249–1255. [CrossRef] [PubMed]
86. Stevens, J.F.; Page, J.E. Xanthohumol and related prenylflavonoids from hops and beer: To your good health! *Phytochemistry* **2004**, *65*, 1317–1330. [CrossRef]
87. Stevens, J.F.; Taylor, A.W.; Clawson, J.E.; Deinzer, M.L. Fate of xanthohumol and related prenylflavonoids from hops to beer. *J. Agric. Food Chem.* **1999**, *47*, 2421–2428. [CrossRef]
88. Venturelli, S.; Burkard, M.; Biendl, M.; Lauer, U.M.; Frank, J.; Busch, C. Prenylated chalcones and flavonoids for the prevention and treatment of cancer. *Nutrition* **2016**, *32*, 1171–1178. [CrossRef]

89. Stevens, J.F.; Ivancic, M.; Hsu, V.L.; Deinzer, M.L. Prenylflavonoids from *Humulus lupulus*. *Phytochemistry* **1997**, *44*, 1575–1585. [CrossRef]
90. Back, W.; Zürcher, A.; Wunderlich, S. Verfahren zur Herstellung eines xanthohumolhaltigen Getränkes aus Malz- und/oder Rohfruchtwürze sowie derart hergestelltes Getränk. *Dtschl. DE* **2004**, *102*, 166.
91. Magalháes, P.J.; Dostálek, P.; Cruz, J.M.; Guido, L.F.; Barros, A.A. The impact of a xanthohumol-enriched hop product on the behavior of xanthohumol and isoxanthohumol in pale and dark beers: A pilot scale approach. *J. Inst. Brew.* **2008**, *114*, 246–256. [CrossRef]
92. Magalhães, P.J.; Almeida, S.M.; Carvalho, A.M.; Goncalves, L.M.; Pacheco, J.G.; Cruz, J.M.; Barros, A.A. Influence of malt on the xanthohumol and isoxanthohumol behavior in pale and dark beers: A micro-scale approach. *Food Res. Int.* **2011**, *44*, 351–359. [CrossRef]
93. Wunderlich, S.; Zürcher, A.; Back, W. Enrichment of xanthohumol in the brewing process. *Mol. Nutr. Food Res.* **2005**, *49*, 874–881. [CrossRef]
94. Wunderlich, S.; Zürcher, A.; Back, W. Xanthohumol in brewing—Impact of malt, xanthohumol dosage, wort and storage temperature. *Mon. Brauwiss* **2012**, *65*, 7–15.
95. Wunderlich, S.; Wurzbacher, M.; Back, W. Roasting of malt and xanthohumol enrichment in beer. *Eur. Food Res. Technol.* **2013**, *237*, 137–148. [CrossRef]
96. Miedl, M.; Bamforth, C.W. The relative importance of temperature and time in the cold conditioning of beer. *J. Am. Soc. Brew. Chem.* **2004**, *62*, 75–78. [CrossRef]
97. Siebert, K.J.; Lynn, P.Y. Comparison of polyphenol interactions with polyvinylpolypyrrolidone and haze-active protein. *J. Am. Soc. Brew. Chem.* **1998**, *56*, 24–31. [CrossRef]
98. McMurrough, I.; Madigan, D.; Kelly, R.J. The role of flavonoid polyphenols in beer stability. *J. Am. Soc. Brew. Chem.* **1996**, *54*, 141–148.
99. McMurrough, I.; Madigan, D.; Smyth, M.R. Adsorption by polyvinylpyrrolidone of catechins and proanthocyanidins from beer. *J. Agric. Food Chem.* **1995**, *43*, 2687–2691. [CrossRef]
100. Gramshaw, J.W. Phenolic constituents of beer and brewing materials. II. The role of polyphenols in the formation of non-biological haze. *J. Inst. Brew.* **1967**, *73*, 455–472. [CrossRef]
101. Vanderhaegen, B.; Neven, H.; Verachtert, H.; Derdelinckx, G. The chemistry of beer aging—A critical review. *Food Chem.* **2006**, *95*, 357–381. [CrossRef]
102. Karabín, M.; Rýparová, A.; Jelínek, L.; Kunz, T.; Wietstock, P.; Methner, F.-J.; Dostálek, P. Relationship of iso-α-acid content and endogenous antioxidative potential during storage of lager beer. *J. Inst. Brew.* **2014**, *120*, 212–219. [CrossRef]
103. Intelmann, D.; Haseleu, G.; Dunkel, A.; Lagemann, A.; Stephan, A.; Hofmann, T. Comprehensive sensomics analysis of hop-derived bitter compounds during storage of beer. *J. Agric. Food Chem.* **2011**, *59*, 1939–1953. [CrossRef] [PubMed]
104. Li, H.; Zhao, M.; Cui, C.; Sun, W.; Zhao, H. Antioxidant activity and typical ageing compounds: Their evolutions and relationships during the storage of lager beers. *Int. J. Food Sci. Technol.* **2016**, *51*, 2026–2033. [CrossRef]
105. Delcour, J.A.; Dondeyne, P. The reactions between polyphenols and aldehydes and the influence of acetaldehyde on haze formation in beer. *J. Inst. Brew.* **1982**, *88*, 234–243. [CrossRef]
106. Callemien, D.; Collin, S. Structure, organoleptic properties, quantification methods, and stability of phenolic compounds in beer—A review. *Food Rev. Int.* **2009**, *26*, 1–84. [CrossRef]
107. Heuberger, A.L.; Broeckling, C.D.; Lewis, M.R.; Salazar, L.; Bouckaert, P.; Prenni, J.E. Metabolomic profiling of beer reveals effect of temperature on non-volatile small molecules during short-term storage. *Food Chem.* **2012**, *135*, 1284–1289. [CrossRef] [PubMed]
108. Hufnagel, J.C.; Hofmann, T. Orosensory-directed identification of astringent mouthfeel and bitter-tasting compounds in red wine *J. Agric. Food Chem.* **2008**, *56*, 1376–1386. [CrossRef] [PubMed]
109. Lesschaeve, I.; Noble, A.C. Polyphenols: Factors influencing their sensory properties and their effects on food and beverage preferences. *Am. J. Clin. Nutr.* **2005**, *81*, 330S–335S. [CrossRef]
110. Caballero, I.; Blanco, C.A.; Porras, M. Iso-a-acids, bitterness and loss of beer quality during storage. *Trends Food Sci. Tech.* **2012**, *26*, 21–30. [CrossRef]
111. Arrieta, Á.A.; Rodríguez-Méndez, M.L.; De Saja, J.A.; Blanco, C.A.; Nimubona, D. Prediction of bitterness and alcoholic strength in beer using an electronic tongue. *Food Chem.* **2010**, *123*, 642–646. [CrossRef]
112. Haseleu, G.; Lagemann, A.; Stephan, A.; Intelmann, D.; Dunkel, A.; Hofmann, T. Quantitative sensomics profiling of hopderived bitter compounds throughout a full-scale beer manufacturing process. *J. Agric. Food Chem.* **2010**, *58*, 7930–7939. [CrossRef] [PubMed]
113. Schönberger, C.; Kostelecky, T. 125th anniversary review: The role of hops in brewing. *J. Inst. Brew.* **2011**, *117*, 259–267. [CrossRef]
114. De Keukeleire, D. Fundamentals of beer and hop chemistry. *Quím. Nova* **2000**, *23*, 108–112. [CrossRef]
115. Schmidt, C.; Biendl, M.; Lagemann, A.; Stettner, G.; Vogt, C.; Dunkel, A.; Hofmann, T. Influence of different hop products on the cis/trans ratio of iso-a-acids in beer and changes in key aroma and bitter taste molecules during beer ageing. *J. Am. Soc. Brew. Chem*, **2014**, *72*, 116–125. [CrossRef]
116. Negri, G.; di Santi, D.; Tabach, R. Bitter acids from hydroethanolic extracts of *Humulus lupulus* L., *Cannabaceae*, used as anxiolytic. *Rev. Bras. Farmacogn.* **2010**, *20*, 850–859. [CrossRef]

117. Wolfe, P.H. A study of Factors Affecting the Extraction of Flavor When Dry Hopping Beer. Master's Thesis, Oregon State University, Corvallis, OR, USA, 2013. Available online: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/rx913t14h (accessed on 30 April 2021).
118. Cocuzza, S.; Mitter, W. Dry Hopping—A Study of Various Parameters Consequences of the Applied Dosing Method. *Brew. Beverage Ind. Int.* **2013**, *4*, 70–74.
119. Collin, S.; Jerkovic, V.; Bröhan, M.; Callemien, D. *Polyphenols and Beer Quality Natural Products*; Springer: Heidelberg, Germany, 2013; pp. 2333–2359.
120. Drewnowski, A.; Gomez-Carneros, C. Bitter taste, phytonutrients, and the consumer: A review. *Am. J. Clin. Nutr*, **2000**, *72*, 1424–1435. [CrossRef]
121. Kielhorn, S.; Thorngate, J.H. Oral sensations associated with the flavan-3-ols (+)-catechin and (-)-epicatechin. *Food Qual. Prefer.* **1999**, *10*, 109–116. [CrossRef]
122. Robichaud, J.L.; Noble, A.C. Astringency and bitterness of selected phenolics in wine. *J. Sci. Food Agric.* **1990**, *53*, 343–353. [CrossRef]
123. Guinard, J.-X.; Pangborn, R.-M.; Lewis, M.J. Preliminary studies on acidity-astringency interactions in model solutions and solutions. *J. Sci. Food Agric.* **1986**, *37*, 811–817. [CrossRef]
124. Siebert, K.J.; Chassy, A.W. An alternate mechanism for the astringent sensation of acids. *Food Qual. Prefer.* **2003**, *15*, 13–18. [CrossRef]
125. Noble, A.C. Astringency and Bitterness of Flavonoid Phenols. In *Chemistry of Taste: Mechanisms, Behavior and Mimics*; Given, P., Paredes, D., Eds.; ACS Symposium Series; ACS publisher: New York, NY, USA, 2002; pp. 192–201.
126. Delcour, J.A.; Vandenberghe, M.M.; Corten, P.F.; Dondeyne, P. Flavour thresholds of polyphenolics in water. *Am. J. Enol. Viticult.* **1984**, *35*, 134–136.
127. Dadic, M.; Belleau, G. Polyphenols and beer flavour. *Proc. Am. Soc. Brew. Chem.* **1973**, 107–114. [CrossRef]
128. Kageyama, N.; Tada, N.; Inui, T.; Komura, H.; Nakahara, K.; Oka, K.; Isoe, A. Studies on astringent substances in malt. *Proc. Congr. Eur. Brew. Conv.* **2007**, *31*, 185–196.
129. Tada, N.; Inui, T.; Kageyama, N.; Takaoka, S.; Kawasaki, Y. The influence of malt acrospires on beer taste and foam quality. *Tech. Q. Master Brew. Assoc. Am.* **2004**, *41*, 305–309.
130. Inui, T.; Tada, N.; Kageyama, N.; Takaoka, S.; Kawasaki, Y. The breakthrough technology in brewing: The capture and retention of fresh beer flavor. *Brauwelt* **2004**, *144*, 1488–1498.
131. Meilgaard, M. Hop analysis, Cohumulone Factor and the Bitterness of Beer: Review and Critical Evaluation. *J. Inst. Brew.* **1960**, *66*, 35–50. [CrossRef]
132. Carr, N. 18 Common "Off" Flavors In Beer (And How They Are Caused). Available online: https://learn.kegerator.com/off-flavors-in-beer/ (accessed on 1 May 2021).
133. "Off" Flavors In Beer Their Causes & How To Avoid Them. Available online: https://www.cicerone.org/sites/default/files/resources/off_flavor.pdf (accessed on 1 May 2021).
134. Common Homebrew Off-Flavors & How to Fix Them. Available online: https://www.homebrewery.com/image/data/Beer%20Information%20documents/Common%20Homebrew%20Off%20Flavors.pdf (accessed on 1 May 2021).