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Review

Aroma of peas, its constituents and reduction strategies – Effects from breeding to processing

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ABSTRACT

Peas as an alternative protein source have attracted a great deal of interest from the food industry and consumers in recent years. However, pea proteins usually do not taste neutral and exhibit a distinct flavor, often characterized as "beany". This is usually contrasted by the food industry's desire for sensory neutral protein sources. In this review, we highlight the current state of knowledge about the aroma of peas and its changes along the pea value chain. Possible causes and origins, and approaches to reduce or eliminate the aroma constituents are presented. Fermentative methods were identified as interesting to mitigate undesirable off-flavors. Major potential has also been discussed for breeding, as there appears to be a considerable leverage at this point in the value chain: a reduction of plant-derived flavors, precursors, or substrates involved in off-flavor evolution could prevent the need for expensive removal later.

1. Introduction

The market for protein-rich plant-based products has grown strongly in the last years. Pea protein as protein source for meat alternatives has steadily gained importance in the last 15 years and is expected to become the most used protein source in the short and medium term (Bashi, McCullough, Ong, & Ramirez, 2019). Whereas early meat-alternative products were often based on soy and gluten, pea has increasingly attracted the interest of producers in the past years. From a consumer perspective, healthiness and taste are very important for consumer acceptance of alternative meat products (Onwezen et al., 2021). On the other hand, meat-eaters have low taste expectations for meat alternatives, as shown in a study of consumers from Germany, France, and the United Kingdom. They expected a pea and algae burger to be less tasty than a beef burger (Michel, Knaapila, Hartmann, & Siegrist, 2021). Similarly, a study of products made with pea flour demonstrated that the flavor (pea, green) can be disadvantageous for the acceptance of the products. The more pea flour the product contained, the less it was liked (Saint-Eve et al., 2019). Therefore, for long-term success of pea-protein-based products as meat alternatives, it is crucial to improve the sensory profile and match the average consumer's taste expectations.

The sensorial perception of plant-based products in general can be altered at several points along the value-chain, from (a) breeding via (b) down-streaming to get to protein concentrates/isolates, (c) formulation and processing to (d) masking, e.g., with seasonings. In the following sections, we review (i) general aspects of pea flavor and beany off-flavor, (ii) the molecular origins of the major aroma molecules, (iii) approaches to identify key aroma components of the pea flavor and (iv) the impact of various steps in the value chain of pea processing on pea/pea protein volatile profiles. While this review focuses on flavor, its constituents and off-flavor reduction strategies, readers are directed to other very recent reviews if they are interested in the functionality of peas (Zha et al., 2021b) and the chromatographic analysis of pulses (Viana & English, 2021).

2. General aspects of the pea flavor and its beany off-flavor

The terms flavor, aroma, and taste are often inconsistently used. For clarity, these expressions are used in line with literature (Roland et al., 2017) within this review. Shortly, aroma is composed of volatiles and is nasally perceived, while taste is caused by non-volatiles and perceived in the oral cavity by the tongue. Flavor is mainly composed of taste and aroma. Off-flavor is considered as the perception of an unpleasant taste, aroma and/or other effects such as astringency.

Since the second half of the 20th century, the off-flavors of peas have been examined (Whitfield & Shipton, 1966; Bengtsson & Bosund, 1964; Shipton et al., 1969; Rackis et al., 1979). The so-called beany flavor is a

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typical attribute also for many other pulses and can be seen as an important off-flavor. More details about off-flavors in pulses can be found in a review by Roland et al. (Roland et al., 2017). Several molecules that are considered to be responsible for a beany off-flavor have been identified. Among those are 3-methyl-1-butanol, 1-pentanol, 1-octen-3-ol, (*E,E*)-2,4-heptadienal, acetophenone,1-octen-3-one, and 3-isopropyl-2-methoxypyrazine (Bott & Chambers, 2006; Vara-Ubol et al., 2004). While early research focused intensively on molecules that are responsible for the beany flavor, it has become obvious later that the flavor cannot easily be explained by the presence of single molecules alone (Bott & Chambers, 2006). Accordingly, it has been realized to be difficult to align sensory analyses with single volatiles detected (Malcolmson et al., 2014). More research is needed to evaluate the flavor contribution of individual compounds in an aroma mixture (Mehle et al., 2020).

There are molecules with attributed beany flavor characteristics, but they can only partly explain off-flavor formation and its perception: as shown in Fig. 1, the beany aroma develops in some cases only at certain concentrations of the compounds (Vara-Ubol et al., 2004).

The finding that mixing non-beany with beany volatiles can result in an increase of beany perception underlines the currently unpredictable physiological responses to molecule mixtures. For example, hexanal can contribute to a possible off-flavor but has itself no beany odor; nevertheless, it can lead to an increased intensity of beany odor. Bott and Chambers identified various binary mixtures of molecules showing shifts of aroma perception at varying concentrations (Fig. 2) (Bott & Chambers, 2006). Similarly, Ang and Boatright showed that a mixture of combined odorants was perceived to possess more resemblance to the characteristic odor of protein isolates than any of the individual odorants. One component, 2-pentylfuran, was found to even suppress the perception of another molecule, dimethyltrisulfide (Ang & Boatright, 2003).

Concluding, concentrations, the ratios of odorants, and the complex impact on human flavor perception of molecule mixtures make it difficult to evaluate the roles of individual molecules and to identify targeted strategies for removal. The presence of an individual molecule alone typically does not explain the beany off-flavor.

3. The molecular origins of aroma molecules

Only a few molecular sources are known as the origin of odorants that are associated with the aroma of peas. A large quantity of the odorants derives from the degradation of the fatty acids linoleic acid and linolenic acid, either by enzymatic activity, oxidation or a combination of both (Table 1). The hydroperoxide formation with molecular oxygen via autoxidation (Wang et al., 2020a) and *via* lipoxygenases (Baysal & Demirdöven, 2007; Zhang et al., 2020) contributes to the degradation of these fatty acids (St. Angelo et al., 1980; Grosch et al., 1974). Additional activity of lipases facilitates oxidation, as free fatty acids are more prone to oxidation than those in triglycerides. Lipoxygenases typically catalyze the bi-oxygenation of polyunsaturated fatty acids containing a (*Z,Z*)-1,4-pentadiene unit (e.g., linoleic and linolenic acid) to form conjugated hydroperoxydienes. These can be further converted by enzymes, such as hydroperoxide lyases, hydroperoxide-dependent peroxygenases or epoxygenases and hydroperoxide isomerases. Several reviews discuss the oxidation pathways of fatty acids in more detail (Frankel, 1991; Baysal & Demirdöven, 2007; Wang et al., 2020a).

The decomposition routes of fatty acids by auto-oxidation or enzymatic degradation have been broadly examined, especially the formation of primary (hydroperoxides) and secondary oxidation products. Therefore, the origins of many odor molecules formed in peas seem to be rather well resolved; many alkanals, alkenals, alcohols originate from unsaturated fatty acids. It is indisputable that linolenic acid and linoleic acids are the major sources. As shown in Table 1, nonanal is one of the few compounds formed mostly by autooxidation of oleic acid; two other compounds, heptanal and octanal, can be formed from oleic acid but also linoleic acid (Murray et al., 1976; Wang et al., 2020a). γ-lactones might originate from oleic acid as well (Murray et al., 1976; Bader et al., 2009).

In case of hexanal, it seems that the amount of free linolenic acid correlates with its formation (Zhang et al., 2020). Comparison of hexanal formation in peas with soybeans supports this assumption, although, according to the authors, the quantities do not correlate linearly, as the enzymatic activity in peas and soybeans is different. In addition, even if enzymes such as lipoxygenases are deactivated, the formation of off-flavors can still occur (Murat et al., 2013). Odor-active molecules such as 1-pentanol, hexanal, 2-heptanone, 1-octen-3-ol, 2-pentylfuran, (*E*)-2-octenal, octanoic acid, (*E,E*)-2,4-nonadienal, (*E,E*)-2,4-decadienal, (*E,E*)-2,4-heptadienal, (*E,E*)-3,5-octadione and others not mentioned here are considered to be typically formed by the autooxidation of linoleic and linoleic acid.

Other very potent, non-fatty-acid-derived odorants like pyrazines also contribute to the aroma of peas, such as 3-alkyl-2-methoxypyrazines, which occur naturally in peas (Jakobsen et al., 1998; Murat et al., 2013). Even if they are present at very low concentrations, they are perceivable due to their low odor thresholds. They also can originate from Maillard reactions between amino acids and carbohydrates. Accordingly, several derivatives were found in roasted peas (Bi et al., 2020). 2-Isopropyl-3-methoxypyrazine and 2,5-dimethylpyrazine are reported to be used to train the attributes “pea-like” and “malty, nutty”, respectively, for sensory panelists (Arteaga et al., 2021).

Non-fatty-acid-derived odorants from pea extracts with concentrations above their odor thresholds also include 2-acetyl-1-pyrroline, methional and *p*-vinylguaiacol (Trikusuma et al., 2020). 2-Acetyl-1 pyrroline exhibits a roasty and methional a potato-like odor, and *p*-vinylguaiacol is described sensorially as “roasted peanut”. 2-Acetyl-1-pyrroline and methional are known as Maillard reaction products while *p*-vinylguaiacol can be formed by the decarboxylation of ferulic acid. Summarizing, most odor-active compounds are fatty acid-derived, a few potent odorants have another origin.

chemicals	odor characteristics at different concentration levels (ppm)						
	1	10	100	1'000	5'000	10'000	100'000
3-methyl-1-butanol	**beany**		sweaty, medicinal				
pentanol	**beany**	sweaty				barnyard/manure	
1-octen-3-ol	musty/earthy		**beany**		musty/earthy, green/dill, chemical-like, pungent		
2,4-heptadienal	**beany**			rancid oil, fishy, cinnamon			
acetophenone	**beany**		musty/earty, floral, sweet	cherry, bitter almond, sweet			mothball, cherry, bitter almond
1-octen-3-one	**beany**		green/dill, sour, sweet, musty/earthy	green/dill, sour, musty/earthy, green/weed, algae		spearmint, green/grass	
3-isopropyl-2-methoxypyrazine	**beany**		musty/earthy, green/weed, chemical-like, pungent				

Fig. 1. Odor characteristics of chemicals that exhibit beany characteristics at some concentrations (Vara-Ubol et al., 2004).

compound 1	concentration (ppm)	& compound 2	concentration of compound 2 (ppm) and perceived odor characteristics for combinations of compound 1 and 2 at various ratios			
			1	10	100	1000
beany		**non-beany**				
1-octen-3-one	10	hexanal	beany			
1-octen-3-one	10	(*E*)-2-octenal	beany			waxy, floral, green, chemical
1-octen-3-one	10	(*E*)-2-octenal	beany			musty/earthy, chemical
1-octen-3-one	10	(*E,E*)-2,4-nonadienal	beany			chemical, burnt
1-octen-3-one	10	(*E,E*)-2,4-decadienal	beany			
3-methyl-1-butanol	1	hexanal	beany			weedy, horseradish, green, nutty, peanuts
3-methyl-1-butanol	1	(*E*)-2-octenal	green	beany		scorched, green
3-methyl-1-butanol	1	(*E,E*)-2,4-nonadienal	beany			green, chemical, musty/dusty, woody, burnt
3-methyl-1-butanol	1	(*E,E*)-2,4-decadienal	beany			musty, chemical, floral, green
beany		**beany**				
1-octen-3-one	10	3-methyl-1-butanol	cardboard	beany		sour, chemical
1-octen-3-one	10	acetophenone	beany			lye, leather
1-octen-3-one	10	1-octen-3-ol	slight odor	beany		dill
3-methyl-1-butanol	1	1-octen-3-one	unidentified		beany	sour, dill, vegetation, green bean
3-methyl-1-butanol	1	acetophenone	lye	beany		hominy, lye
3-methyl-1-butanol	1	1-octen-3-ol	beany			musty/earty, musty/dusty, dill
acetophenone	10	1-octen-3-one	unidentified	beany		mushroom, green, sour
non-beany		**non-beany**				
hexanal	10	(*E*)-2-nonenal	beany			cucumber, green, leather
hexanal	10	(*E,E*)-2,4-nonadienal	beany			cucumber, musty/earthy, nutty
hexanal	10	(*E*)-2-hexenal	beany			nutty, cherry almond, sunflower seed, brown
(*E*)-2-octenal	10	(*E,E*)-2,4-decadienal	beany			vegetation, woody, green bean
(*E*)-2-octenal	10	(*E*)-2-hexenal	beany			green, sweet, almond, rancid nuts, floral
(*E*)-2-octenal	10	pentanal	beany			sour, musty, cheesy, green

Fig. 2. Odor characteristics for combinations of beany and non-beany chemicals at different concentrations (Bott & Chambers, 2006). The concentration and the identity of compound 1 is given on the left. The concentration of compound 2 is indicated on the top right. Binary combinations that are perceived as beany are highlighted in green. Other perceptions are shown in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Approaches to identify key aroma components of the pea flavor

Plenty of studies examine specific volatiles from raw peas, pea flour, protein isolates, etc., but only a few performed untargeted analyses followed by extensive, full quantifications of key-odor-active compounds (Table 2). In reductionistic approaches, the odorless molecules or molecules with high odor thresholds are usually excluded from further evaluation. Literature and olfactometric analyses can help to identify odor-active molecules.

If an absolute concentration of an odor-active molecule in the sample is determined, the relevance of the volatile on the overall odor can be judged by the calculation of OAVs or OAV rates (odor activity value = OAV $= \frac{\text{concentration}}{\text{odor threshold}}$). A list of thresholds (in water) was published by Leffingwell and associates (Leffingwell & Associates). Molecules with an OAV > 1 can be considered to be relevant for an aroma, meaning their concentration is greater than the minimal concentration at which they are perceived. This assessment strongly depends on threshold values in water, and of course pea flour is a quite different matrix compared to an aqueous solution. Therefore, the OAVs calculated based on thresholds determined in aqueous solutions and quantifications in pea products remain with an uncertain accuracy.

As seen in Table 2, 25 molecules were found to have concentrations in pea samples above a published odor threshold and therefore might be highly relevant for the aroma of pea products: based on their frequency of appearance, the odorants of high relevance seem to be hexanal, (*E*)-2-octenal, nonanal, 1-octen-3-ol, and 2-pentylfuran. El Youssef et al. and Zhang et al both focused on off-flavors (El Youssef et al., 2020; Zhang et al., 2020). Their findings help to choose molecular markers to follow potential off-flavor formations.

To evaluate the influence of single molecules in odor-active-molecule mixtures, Bi et al. established model mixtures with volatiles having OAVs > 1 in pea samples (Bi et al., 2020). Upon mixing these molecules at similar concentrations to the ones in peas, they started to systematically omit single components. The omission of hexanal, (*E*)-2-octenal, benzaldehyde, (*Z*)-2-penten-1-ol, benzyl alcohol and 3-methylbutanoic acid lead to noticeable differences in the aroma perception. Interestingly, the omission of 1-pentanol caused no significant difference even if it is perceived as beany at lower ppm concentrations (Bott & Chambers, 2006). The altered aroma perception due to the omission of hexanal and 3-methylbutanoic acid is in line with their considerable OAVs supporting their importance as aroma compounds. Zhang et al. also used OAVs (and OAV contribution frequency) to evaluate the importance of certain odor-active molecule for perceived off-flavors (Zhang et al., 2020). They found 11 molecules (OAV > 1) to be relevant for flavor formation: hexanal, 2-pentylfuran, 1-octen-3-ol, 1-hexanol, 2-octenal, decanal, (*E,E*)-2,4-nonadienal, (*E,E*)-2,4-decadienal, nonanal, 1-octanol, and 2-methoxy-3-isopropyl-(5 or 6)-methylpyrazine. The last three were considered to be unpleasant, while the others were perceived as neither positive nor negative. The component 2-methoxy-3-isopropyl-(5 or 6)-methylpyrazine was the most potent flavor compound according to the calculated contribution rate followed by hexanal, (*E,E*)-2,4-nonadienal, (*E,E*)-2,4-decadienal, 1-octen-3-ol, and 2-pentylfuran. 2-Pentylfuran has also been discussed elsewhere to be one of the molecules leading to an off-flavor in soy products (Min et al., 2005).

Beany, pasta and potato aromas were rated highest in sensorial

Table 1
Origin in model systems of aliphatic monocarbonyls identified in unblanched peas (Murray et al., 1976). The involved fatty acids are abbreviated as following: O = oleic, L = linoleic, Ln = linolenic, A = arachidonic.

	fatty acid involved		
compound	**lipoxygenation**	**autoxidation**	
acetaldehyde	Ln	Ln	
propanal	Ln	Ln	
pentanal	L	L, A	
(*Z*)-2-pentenal	Ln	Ln	
(*E*)-2-pentenal	Ln	Ln	
hexanal	L	L, Ln, A	
(*E*)-2-hexenal	Ln	Ln	
(*E,E*)-2,4-hexadienal	unknown		
heptanal		O, L	
(*E*)-2-heptenal	L	L, A	
(*E,Z*)-2,4-heptadienal	Ln	Ln	
(*E,E*)-2,4-heptadienal	Ln	Ln	
octanal		O, L	
(*E*)-2-octenal	L	L, A	
nonanal		O	
(*E*)-2-nonenal	L	L	
(*E,Z*)-2,4-nonadienal	unknown		
(*E,E*)-2,4-nonadienal	L	L	
(*E,Z*)-2,6-nonadienal		Ln	
(*E,Z*)-2,4-decadienal	L	L, A	
(*E,E*)-2,4-decadienal	L	L, A	
acetone			anaerobic respiration
1-penten-3-one		Ln	
1-octen-3-one		L	
(*E*)-3-octen-2-one		A	
(*E,Z*)-3,5-octadien-2-one	Ln	Ln	
(*E,E*)-3,5-octadien-2-one	Ln	Ln	

analyses performed on pea protein beverages (Trikusuma et al., 2020). Molecules with OAVs > 1 were considered as important aroma contributors. While the beany aroma might be related to the molecules also discussed by Bott and Chambers (Bott & Chambers, 2006), the potato aroma was thought to originate, but not solely, from methional. As mentioned before, other non-fatty acid derived molecules such as *p*-vinylguaiacol, 2-acetyl-1-pyrroline and 2-isobutyl-3-methoxypyrazine were also found to be probable contributors to the aroma of pea beverages.

Of course, there are also odorants with OAVs < 1. Some are often found in various untargeted analyses. These molecules include pentanal, (*E*)-2-hexenal, (*E*)-2-heptenal, 3-methyl-1-butanol, 1-penten-3-ol, 1-heptanol, and 1-nonanol. Their importance to pea aroma remains to be elucidated.

The current literature on pea and pea protein flavor mainly describes the use of physicochemical methods and/or sensory evaluations to identify odor-active molecules. To further unravel the flavor complexity including relevant flavor compounds, new approaches such as untargeted metabolomics can be used (Pavagadhi & Swarup, 2020). During the processing of peas, untargeted metabolomics helped to identify differences in aroma profiles. For example, the group of Bingcan Cheng reported relevant odor-active molecules that allow a differentiation of milling procedures, pH changes, cultivars, and spray-drying (Cui et al., 2020c; Cui et al., 2020b; Gu et al., 2021).

5. How to impact pea/pea protein volatile profiles along the value chain

Various studies have looked at how to influence the aroma of pea or related products along the pea value chain. The following sections present the current knowledge from breeding *via* protein concentrates/isolates processing to product applications.

Table 2
List of key-odorants found to be highly relevant for the aroma of pea preparations based on OAVs > 1. The green fields indicate that the molecule was found and quantified by the authors. The yellow and orange boxes (including the numbers) indicate the frequency (2x and 3-4x resp.) at which the molecules were found in the four indicated publications. El Youssed et al. and Zhang et al. explicitly focused on off-flavor related molecules. [a]only the compounds are listed that are considered as neutral or unpleasant contributors to off-flavor. [b]only odorants found in the non-UHT processed pea protein beverages are listed. [c]only odorants found detected above a dilution factor of 4 and perceived by 50% of the panelists were quantified. [d]off-flavor molecules were chosen based on literature reports and then quantified. [e]only odorants found in the uninoculated sample are listed. 2-Ethylfuran and (*E*)-2-methyl-2-butenal were not evaluated here, as no odor threshold was available either in the publication or in the values published by Leffingwell and associates.

Reference	(Bi et al., 2020)	(El Youssef et al., 2020)[d,e]	(Trikusuma et al., 2020)[b]	(Zhang et al., 2020)[a]	
Year of publication	2020	2020	2020	2020	
Odorant/Sample type	pea flour	pea protein solution	pea protein beverage	pea milk	number of quantifications
2-methylpropanal		■			1
butanal		■			1
hexanal	■	■	■	■	4
heptanal		■	■		2
octanal		■			1
(*E*)-2-octenal	■	■		■	3
nonanal	■	■	■	■	4
(*E,E*)-2,4-nonadienal			■	■	2
decanal		■		■	2
(*E,E*)-2,4-decadienal				■	1
methional			■		1
benzaldehyde	■				1
1-pentanol	■				1
(*Z*)-2-penten-1-ol	■				1
hexanol	■			■	2
1-octanol				■	1
1-octen-3-ol		■	■	■	3
benzyl alcohol	■				1
2-nonanone		■			1
2-pentylfuran		■	■	■	3
3-methyl-butanoic acid	■		■		2
2-methoxy-3-isopropyl-(5 or 6)-methyl pyrazine				■	1
2-isobutyl-3-methoxy pyrazine			■		1
2-acetyl-1-pyrroline			■		1
p-vinylguaiacol			■		1

5.1. Breeding and cultivation

The field pea is seen as the oldest grain legume domesticated 10′000 years ago. Therefore, it is not surprising that a large variety of germplasms and cultivars is available. Approximately 98′000 pea accessions are existing in various gene banks worldwide while 59′000 are unique. These variations could potentially be used as a foundation in breeding programs for development of new cultivars of field pea with high nutritional level, but also for cultivars with desired flavor properties (Parihar et al., 2020). In relation to this large number of accessions, only the volatiles composition of a tiny number of cultivars has been examined. The cultivars are difficult to compare as the amount of specific volatiles of a single cultivar varies among the crop from year to year and the sites of cultivation (Azarnia et al., 2011a; Azarnia et al., 2011b; Malcolmson et al., 2014). Very recently, studies that investigated the sensory difference of cultivars to select ideal ones for protein isolate processing were conducted (Arteaga et al., 2021). Few differences in taste were found, just the pea-like and bitter attributes were different. In another study, cultivars had a strong effect on protein isolates gained by protein precipitation: while the precipitation can be slightly tuned to improve the sensory profile, the cultivars strongly influenced the result (Cui et al., 2020c). Concerning specific molecules with a high relevance for the pea odor, Jakobsen showed that the genotype of peas can have a significant effect on 2/3-methyl-1-butanol, 2–pentylfuran and hexanal concentration (Jakobsen et al., 1998). Just as enzymes might be expressed differently in various cultivars, they could be responsible for quantity variations of odor-active molecules among the cultivars. Haydar et al. observed that the lipoxygenase activity in three different commercially available pea varieties was different (up to 70%), however, they did not study the effects on flavor development (Haydar & Hadziyev, 1973a). Guerdam et al. characterized a lipoxygenase of peas and speculated that the elevated expression of lipoxygenase could be part of a defending mechanism against pests and pathogens. Given that usually a low lipoxygenase activity is favorable to keep fat oxidation at a minimum, breeding to increase resistance to external stresses might be helpful to control enzyme activity (Guerdam et al., 1993). Furthermore, also Haydar et al. found that in mitochondria the highest concentrations of unsaturated lipids are found. As fat oxidation is increased with mitochondria swelling (which in turn could be a consequence of soaking of dry peas during processing) in the presence of selected divalent ions, they assumed that mitochondrial fat oxidation could contribute significantly to flavor formation although the concrete route (enzymatically or non-enzymatically) is not clear (Haydar & Hadziyev, 1974). The lipid composition in mitochondria in turn can be affected by the ability of a species to resist chilling temperature. Resistance against low temperatures could therefore be a direction of future breeding strategies. Concluding, the evidence suggests that breeding is a promising way to obtain peas with favorable flavors.

5.2. Harvest and pea morphology

Mechanically harvested peas can suffer tissue damage that stimulates the enzymatic production of volatiles (Murray et al., 1976; Bengtsson et al., 1967). To avoid these damages new methods for the harvest and shelling of peas were developed in the 1960s (Mitchell et al., 1969). Nevertheless, the former rough pea treatment led to an remarkable increase of volatiles in unblanched peas after harvest (Bengtsson & Bosund, 1964). Depending on temperature, a short delay after harvesting until further processing (1–2 h) did not seem to negatively affect the flavor, however larger delays produced off-flavors (Shipton & Last, 1968). Size also plays a role; smaller peas more readily develop an off-flavor than larger ones. A reason might be that small peas are typical more tender than the big ones and consequently are more easily damaged (Bengtsson et al., 1967). Another reason might be an uneven formation of off-flavor-molecules within the peas. Bengtson et al. showed that hexanal development mainly takes place in the testa (seed coat) and less in the cotyledons (See Fig. 3 for the pea morphology (Weitbrecht et al., 2011)). As the skin comprises a higher fraction of the total pea mass in smaller peas than in larger ones, hexanal formation had a bigger impact in smaller peas. This finding is in line with Azarnia showing a reduced total count of volatiles in dehulled peas (Azarnia et al., 2011b). Eriksson et al. found the highest concentration of extractable lipoxygenase in the outer parts of the cotyledons (Eriksson, 1967), which could further support Bengtsson's findings. However, another study could not confirm the compartmentalization of lipoxygenase in a specific fraction of the pea seedling (Haydar & Hadziyev, 1973a).

The volatiles of pea shells (pods) have been rarely examined, even though they account for 30–40% of mass as pea by-product during processing (Hanan et al., 2021). A detailed comparison of the volatiles present in pea shells with the ones present in unblanched peas revealed a major difference for the C6 and C7 alkanals and the C5 to C8 alkenals that were present in relatively higher concentrations in the shell. The difference indicates that dehydrogenase activity, relative to lipoxygenase activity, is lower in the shell. The authors suppose that the difference may also reflect an effect of the short heat treatment involved in the shelling operation (Murray et al., 1976). Interestingly, the concentration of 3-isopropyl-2-methoxypyrazine in the pea shells (pods) was found to be much higher than in the whole pea seeds (Murray & Whitfield, 1975). As the compound is typically perceived as pea-like, the difference could account for the enhancement of the flavor achieved by a former domestic practice of adding a few shells during cooking (Murray et al., 1976).

Summarizing, prevention of damage, dehulling and fast processing after harvest can help to reduce potential off-flavor formation.

5.3. Storage

Storage can have an impact on flavor, whereas the atmosphere, temperature, and humidity are key contributing factors for unwanted flavor formation. Higher temperatures and moisture levels typically accelerate the formation of unpleasant odor-active molecules (Pattee et al., 1982). The off-flavor formation can occur in all sample types such as whole peas, pea flours and pea protein isolates. Pea flours and pea isolates with a moisture content of about 13.5% stored at 30 °C for one year changed from a fresh pea odor to a fishy odor, while samples with a moisture content below 10% did not develop an unpleasant odor (Sumner et al., 1979). Similarly, Mehle et al. examined the influence of temperature and water content on the flavor profile of pea protein isolates where 11 well known odor-active molecules were monitored. Higher temperatures and a higher water content were responsible for the largest aroma profile shifts. Not all of the observed aroma-active molecules increased in concentration during storage. For example, the concentration of 2,4-nonadienal and 2,4-decadienal decreased at 37 °C and high water activity (Mehle et al., 2020). An analysis of volatiles originating from pea seeds stored at 4 °C revealed a lower total area (chromatogram signals) of volatiles than that of peas stored at 37 °C. All chemical families with the exception of aldehydes and sulfur compounds were present in higher amounts in samples stored at 4 °C, while the concentration of aldehydes was found to be massively increased at higher temperatures (Azarnia et al., 2011a). Hexanal, that is typically found in every GC analysis of pea volatiles, was correlated with the development of off-flavors in peas. The more hexanal was present, the less the peas were liked (Bengtsson et al., 1967). These results were questioned by latter research indicating that 3–methyl-propanal might have been co-measured (Murray et al., 1976). The quantification of hexanal as well as 1-hexanol was also used to evaluate the storage stability of untreated, pasteurized and fermented protein extracts. After 87 days at 37 °C only slight changes were observed for all samples (Schindler et al., 2012).

Many raw vegetables can be stored for only a short time, even at subzero temperatures, as several enzymes are still active and cause changes

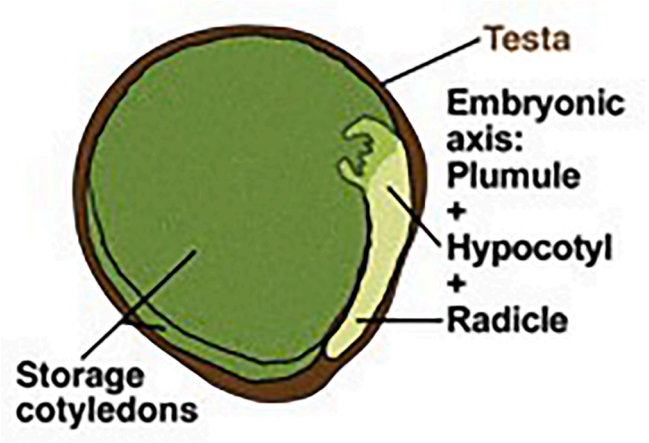

Fig. 3. Morphology of a pea seed (Pisum sativum). The pod is not illustrated. Reproduced from (Weitbrecht et al., 2011).

of the texture, color, flavor and nutritional quality. At 4 °C enzymes such as the lipoxygenases can still be active; nevertheless they lose activity (Liagre et al., 1996). During freezing of unblanched peas at –18 °C their lipoxygenase activity is reduced to about 80% and remains stable for at least a year. Also peroxidases seem to lose activity continuously during a year, down to about 50% (Gökmen et al., 2005). Despite the reduction of enzyme activities at –20 °C, freezing temperatures might not be enough to preserve the desired pea quality. Unblanched peas stored at –10 °C for 8 months were considered completely inedible and also freezing them at −26 °C for 1–2 months not fully inhibited the development of off-flavors (Bengtsson & Bosund, 1964). Destructive enzymes are still active and lipid hydrolysis occurs (Bengtsson & Bosund, 1966; Lee & Mattick, 1961). However, based on a few chromatographic signals, −30 °C seems to largely reduce the formation of volatiles (Bengtsson & Bosund, 1964). A heat pre-treatment prior to storage at –20 °C is mandatory for long-term off-odor reduction. While raw peas develop an off-odor, blanched and cooked peas preserved a “normal” odor (Rhee & Watts, 1966).

Summarizing, depending on pre-treatments such as blanching or cooking, low storage temperatures, and low water contents can help to mitigate off flavor formation in pea preparations during storage.

5.4. Germination

Upon germination, the metabolism in the pea is activated. Probably, the germination promotes the enzyme-assisted decomposition of lipids and proteins in accordance to an increased lipoxygenase activity and an increase of free radicals (Xu et al., 2020). To be able to extract useful information from the large number of molecules detected in a typical GC-MS-analysis, Xu et al. evaluated the influence on germination solely by focusing on 6 marker molecules (3–methyl-1-butanol, a molecule with a typical beany odor, and molecules typically associated with a beany aroma like 1–hexanol, hexanal, (*E,E*)-2,4-nonadienal, (*E,E*)-2,4-decadienal, 2-pentylfuran). Germination times longer than 1 day resulted in an increase of those beany-odor-related molecules as shown for pea flour, while no significant beany flavor formation was observed for shorter germination times. Remarkably, the concentration of pyrazines stayed constant during germination (Xu et al., 2019). For protein isolates, the situation was similar, a 1-day germination changed the volatile composition slightly, while longer germination times lead to an increase of the beany odor. The authors believe that controlled germination conditions, such as germination time, substrates, environmental stress, and the addition of antioxidants might be possible measures for lowering the population of free radicals and further mitigating beany-related odor in germinated pulse proteins (Xu et al., 2020). Similarly, pre-germination, an early seed germination during which no radicals yet emerge, was shown to reduce the intense flavor of peas in baked breads (Frohlich et al., 2019).

All in all, only few publications examined the influence of germination on pea flavor and their products. It seems possible to partially mitigate off-flavors formation by short germination times.

5.5. Thermal treatment

Just as heat promotes lipid and amino acid degradation reactions, processing steps that use elevated temperatures can lead to the formation of odor-active molecules (Murat et al., 2013). Such processing steps comprise roasting, cooking/blanching, UHT treatment and spray drying. Blanching of raw peas can help prevent unwanted changes of the flavor in combination with deep-freezing, and it can stabilize the flavor for several months. The heat impact during blanching is considered to deactivate enzymes that are involved in the decomposition of fatty acids (Williams et al., 1986; Jakobsen et al., 1998; Ma et al., 2016; Gökmen et al., 2005; Shi et al., 2020). However, Williams et al. also showed that in their samples at least two peroxidases and lipoxygenases have a high heat stability even during blanching at 60 °C. The authors also report that heat stability is considerably higher in whole compared to homogenized peas. To determine minimum blanching time and temperature, lipoxygenase and peroxidase activities were measured after various blanching conditions. A blanching temperature of 80 °C for 2 min was shown to be effective in eliminating lipoxygenase activity while peroxidase activity dropped to < 10% activity (Gökmen et al., 2005). Peroxidase was found to be one of the most stable among the examined enzymes. Blanching at 90–100 °C for 60 s reduced the peroxidase activity to <2%, while lipoxygenase activity was completely turned off (Rhee & Watts, 1966).

Ma et al. investigated not only the influence of precooking but also the influence of roasting and spray drying of seeds and flours. Based on the relative area percentage of the GC-MS-chromatogram, alcohols were reduced by pre-cooking while other molecules such as aromatics increased. The total area of volatiles showed a strong tendency to be reduced by cooking while roasting of seeds and flours had no strong effect (Ma et al., 2016). Cooking was also shown to reduce the amount of the odorant 1-octen-3-ol in milks prepared from precooked pea (Zhang et al., 2020). An increase in the number of volatiles was observed during roasting in another study, especially a large variety of pyrazines was generated. The authors state that roasting generally increased the variety of volatile compounds and provided peas with more nutty and caramel-like aroma active compounds and fewer beany and fatty notes (Bi et al., 2020). The flavor of roasted pea products was also examined elsewhere: whole yellow peas were roasted, micronized and milled to improve the flavor of tortillas and pitas made from the pea flour (Frohlich et al., 2021). While the authors only found minimal effects on beany and bitter flavor reduction for the tortillas and pita breads, they showed that micronization prior to milling reduced the strong aroma associated with peas (Frohlich et al., 2019).

During pasteurization of protein extracts, Schindler et al. observed an increase of hexanal serving as a lipid oxidation marker. This increase seemed to be compensated by evaporation during the final spray drying (Schindler et al., 2012). Similarly, pea protein beverages were sterilized by ultra-high temperature (UHT) processing that included temperatures up to 140 °C for a few seconds. As for pasteurization of protein extracts, UHT leads to a general increase of odor-active molecules; however, the beany note decreased during processing. The authors presume, that, as certain combinations of odor-active molecules and their ratios result in a specific aroma, the ratio changes might be responsible for the perceived decrease of a beany note (Trikusuma et al., 2020).

The way a pea meal is prepared can alter its flavor perception: heating pea pastes in an iron pot, compared to a clay pot, led to considerably higher concentration of typical fat oxidation products like hexanal or nonanal (Xing et al., 2018). Although the authors did not mention it explicitly, iron ions are known to promote fat oxidation. This is supported by findings from Haydar et al., who could show that

probably only a part of the fat oxidation potential goes back to active lipoxygenase but another to active haem-containing complexes (Haydar & Hadziyev, 1973a). The authors did not discuss potential implications in the protein extraction process, but residual haem complexes from enzymes or active porphyrin-systems could be of considerable relevance in flavor alterations during and after the protein extraction process.

In conclusion, blanching at high temperatures helps to stabilise the flavor although not all relevant enzymes can be fully inactivated. Roasting and other high temperature treatments typically alter the aroma profile.

5.6. Grinding/Milling

Milling is typically one of the first steps during flour production. As the friction during milling leads to increasing product temperatures, typical heat-induced degradation reactions can take place. Gwiazda et al. reported the formation of an unpleasant beany odor during dry milling (Gwiazda et al., 1979). Gu et al. examined possible odor alterations caused by various milling strategies (Gu et al., 2021). As the authors controlled the product temperature by vacuum drying air, they could postulate that no new aroma molecules are formed during milling. They attributed changes in the aroma profile to the release of aroma molecules of pea flour, originally inherent in the peas. Smaller particles are thought to release more easily the volatiles (Gu et al., 2021). Vatansever et al. supported this point of view by examining size fractionated flours gained by hammer milling and sieving. They concluded that larger particle sizes result in less-aroma compounds based on GC data while bitterness increased (Vatansever et al., 2021). To maintain the aroma profile and to obtain a desirable pasting performance of the milled yellow pea flour without producing other beany related volatiles, Gu et al. proposed an ultra-centrifugal milling configuration with a screen aperture size of 500 μm. An aperture of 500 μm size produced a particle size that avoided a stronger release of volatiles when compared to an aperture size of 250 μm.

The studies suggest that milling must be cautiously controlled to achieve a minimum level of undesirable volatiles.

5.7. Volatile extraction

Alcoholic extractions have shown to reduce the quantity of volatiles in pea flour. Wang et al. investigated the impact of alcohol washing of air-classified pea protein flour on the volatile profile (Wang et al., 2020b. They found that total volatile concentration can be reduced effectively with alcohol, preferentially at higher alcohol concentrations that enable the denaturation of lipoxygenase and prevent the new formation of volatiles during the following drying process. As a trade-off they found considerable denaturation of proteins, negatively impacting solubility and oil-holding capacity. The volatile extraction process with a combination of supercritical CO_2 and alcohols showed a reduction of trace aroma volatiles (Vatansever & Hall, 2020). Vatansever et al. focused on select marker molecules to evaluate the reduction of volatiles based on their total quantity. As CO_2 is considered to be a bad solvent for polar compounds, Vatansever showed that the combination with ethanol gave a better extraction compared to CO_2 alone.

Even if there are not yet many studies for peas, the hereby presented washings were shown to be very effective.

5.8. Protein extraction and dry fractionation

Various strategies for the extraction of proteins from pulse flours have been applied (Boukid et al., 2021). They typically comprise alkaline extraction/isoelectric precipitation, ultrafiltration, salt extraction/dialysis, and micellar precipitation (Stone et al., 2015; Boye et al., 2010; Fuhrmeister & Meuser, 2003; Karaca et al., 2011; Cui et al., 2020a). The extraction method influences the composition of the protein isolates (Stone et al., 2015) and it also modifies the profile of odor-active molecules, as shown by the following publications.

Xu et al. investigated the impact of an alkaline protein extraction process with isoelectric precipitation on the quantity and profile of volatiles (Xu et al., 2020). A large quantity of volatiles was removed by the extraction process, while new ones developed. The authors speculated that, on the one hand, water-soluble molecules are easily removed during the water-based extraction process, while others might bind to non-soluble carbohydrates in the dry matter and consequently are separated from the protein extract during processing. On the other hand, they assumed that new flavor-relevant molecules evolve due to a release from conjugates with protein or lipids, by alkaline hydrolysis for example, or are newly formed due to lipid oxidation during the protein extraction process. Similar results were also obtained elsewhere (Murat et al., 2013).

The pH of the protein solubilisation step also has a strong impact on some key components of a beany flavor sensation (i.e hexanal, 1-pentanol and 3-methyl-1-butanol) (Gao et al., 2020). The lowest beany flavor perception in the final product was found for an extraction-pH of 9 (compared with 8.5 and 9.5). The lipoxygenase-activity was also low at pH 9 during extraction; however, it was the lowest for the neutralized protein isolates. The latter is rather surprising as pea lipoxgenases work optimally between pH 5.5 to pH 7 (Szymanowska et al., 2009; Haydar & Hadziyev, 1973b; Siddiqi & Tappel, 1956; Dillard et al., 1960). Nevertheless, Gao et al. speculated about the impact of the process on flavor compound formation due to an activation of the enzymes like lipoxygenase upon water addition to the raw material. Cui et al. also investigated the impact of pH on flavor profile (for two different cultivars) and attributed their findings to different protein–flavor compound bindings as a function of pH (Cui et al., 2020c). In particular, they found increases of GC peak areas for most of their targeted compounds comparing spray-dried samples after alkaline extraction, after isoelectric point (IEP)-precipitation (increase) and neutralization (decrease again). Furthermore, they only found partial differences in the pattern between an extraction pH of 8.5 and 9.5. The authors concluded that the pH-dependent flavor-compound–protein interactions determine the quantity of each volatile in the samples rather than the initial extraction pH.

The pH of extracted pea globulin solutions was adjusted to a neutral and to an acidic pH in another study, in which off-flavour molecules should be transferred to a second phase that is rich in maltodextrin. At the acidic pH more volatiles were released. The denaturation of isolated pea globulins at low pH was linked to this release of volatiles into the headspace (Nguyen et al., 2014). A more refined model was proposed by Lynn Heng indicating that the retention of volatiles depends on their polarity. Polar compounds tend to be released from proteins at pH 8 and apolar compounds at pH 4 (Heng, 2005). Not only the pH influences the flavor retention. Some interactions of volatiles such as ketone–protein interactions also depend on the ionic strength and the type of ions (Wang & Arntfield, 2015). According to their findings, higher ionic strength promotes flavor retention while an increasing pH reduces flavor retention. All in all, Wang and Arntfield discovered that salt-extracted proteins exhibit higher flavor binding abilities than alkaline-extracted ones. This general conclusion was not valid for all odor-active molecules. Aldehydes, for example, bound more strongly to the pea protein when they were obtained by alkaline extraction in contrast to salt extraction (Wang & Arntfield, 2014). Again, these effects can be attributed to the polarity of the proteins: most flavor compounds are rather hydrophobic and are retained when the hydrophilic nature of proteins is either reduced by a reduction of the proteins' hydration layer above salting-in conditions or by approaching the IEP.

The occurring conformational changes of proteins caused by co-spraying agents are also speculated to modify the hydrophobicity of proteins and thereby the retention of potential volatiles (Cui et al., 2021). From another angle, the binding of aldehydes and ketones to proteins led to increased protein unfolding, resulting in reduced protein denaturation enthalpies (Wang & Arntfield, 2014).

The majority of the cited publications used inorganic acids to adjust

the pH for protein extraction but an acidifcation can also be provoked by fermentation. The employment of lactic acid bacteria showed an increase of solubility for the extracted proteins, but no information on the sensorial properties was given (Emkani et al., 2021).

Dry fractionation (milling followed by air classification) seems to be an attractive, more sustainable alternative to wet extraction as it consumes less energy and chemicals, but it produces protein concentrates of lower purity (Schutyser et al., 2015). When extrusion was tested with dry fractured pea protein as well as with pea protein isolates obtained by wet extraction, the odor and taste profile was more intense in the first case, indicating that the extraction process strongly impacts the flavor profile of pea protein (De Angelis et al., 2020). Schutyser et al. argued that a number of enzymes in dry fractionated protein concentrates are still active, among them lipoxygenase, leading to a beany flavor. The authors proposed a gentle heat treatment at 60 °C for inactivation (Schutyser et al., 2015).

In conclusion, pH and salt concentration must be carefully chosen to obtain the lowest degree of flavor retention. With typically applied extraction strategies, a complete removal of odor-active molecules does not seem feasible. Other methods such as air classification need further development to reduce undesired flavors.

5.9. Fermentation and enzymatic/chemical modifications

Enzymatic treatment and fermentation are possible methods to alter the sensory profiles of food samples. As explained below, lactic acid fermentation of pea protein preparations leads to a favorable alteration of the volatile profile due to a reduction of off-flavor molecules (Schindler et al., 2012). Pasteurized pea protein extracts were fermented for 48 h with lactic acid bacteria at a pH of 4.5 and were shown to possess a more pleasant sensory profile. The reason, i.e. degradation of unpleasant molecules or masking by formation of new flavor components, was not clear (Schindler et al., 2012). The same effect of lactic acid fermentation of protein isolates was shown by Shi et al., who reported a large decrease of aldehydes and ketones (up to 64%). A sensory descriptive analysis confirmed the reduction of overall aroma and flavor intensity (Shi, 2020; Shi et al., 2021). A co-fermentation with additional yeast has furthermore introduced esters to the matrix which has been equally appreciated (El Youssef et al., 2020). Arteaga et al. also observed alterations in the flavor profile during fermentation of protein isolates; however, the flavor changes were not considered to be beneficial. The authors believe that further research is required to find appropriate microorganisms to improve the aroma profile (Arteaga et al., 2020b). Li et al. also observed this dependency of flavor formation from the microbial strain during the fermentation of pea flour. They concluded that the aromatic compounds of the fermented yellow pea flours were highly reliant on the strains and the fermentation time. Longer fermentation time (48 h and 72 h) led to extremely different aromatic profiles among the different cultures compared to those with a shorter fermentation time (Li et al., 2021). Another study investigated the effect of fermentation and phytase treatment on the sensory profile of extruded meat products based on a pea/oat protein blend (Kaleda et al., 2020). The fermentation resulted in higher levels of carboxylic acids, alcohols, acetoin, and 2,4-decadienal, where the carboxylic acids accounted for a sour taste. The evolved 2,4-decandienal introduced a “medical”, “soapy“, and “citrus-like” taste. The typical legume taste was found to be significantly higher in the fermented sample, which might not be beneficial in meat analog products. The phytase treatment before extrusion did not affect the flavor profile at all (Kaleda et al., 2020).

Proteolytic enzymes were also tested to improve flavor. However, the treatment can lead to an increase in bitterness while the aroma does not change significantly (Arteaga, Guardia, Muranyi, Eisner, & Schweiggert-Weisz, 2020). The enzymatic hydrolysis of protein isolate with alcalase and the modification of reactive groups by acetylation and succinylation partially lead to a release of selected aroma volatiles (Wang & Arntfield, 2016). In detail, the gradual addition of acetic and succinic anhydride to the protein isolates provoked a subsequent release of an ester (hexyl acetate) and an aldehyde (octanal), while a ketone (2-octanone) and dibutyl disulfide were retained more strongly when the ratio of reactants to protein mass was kept low. The enzymatic hydrolysis released mainly the ketone and the ester molecules.

Instead of using peas as a main protein source, the hydrolysis of pea protein followed by the conjugation of carbohydrates was also applied, but hereby, to gain taste modifiers that enhanced saltiness, umami, and kokumi (Yan et al., 2021). The typical off-flavors related to pea products were not examined in this publication. In another publication, however, the conjugation of pea proteins with gum arabic due to a Maillard reaction reduced the quantity of beany odor marker molecules. The authors assumed that conformational changes and structural reorientations enabled the release of the molecules (Zha et al., 2019). A summary on Maillard-driven chemistry to tune the functionality of pea protein can be found in a review (Zha et al., 2021a).

In conclusion, fermentation seems to be a promising way to obtain a positively perceived aroma, even if there are few examples with unpleasant flavor formation.

5.10. Drying

Protein concentrates/isolates are usually dried for commercialization. Sumner observed that spray-drying of protein isolates was most effective in removing legume and other objectionable flavors, while freeze-drying led to a cereal flavor (Sumner et al., 1981). Ma et al. compared the effect of freeze and spray drying on precooked pea slurries. They observed a smaller total peak area of volatiles after spray drying of peas. However, a large peak area increase was observed for aldehydes during spray drying while the area for all other odor-active molecules decreased. The total area of volatiles of freeze-dried yellow pea did not differ significantly from that of raw yellow pea (Ma et al., 2016). This is in line with the general view that freeze drying leads to products that retained volatiles (Yen & Pratap-Singh, 2021). Schindler also observed that spray drying of protein extracts, at temperatures up to 180 °C for the inlet temperature, led to a decrease of the total content of volatiles. The authors believed that the majority of volatiles evaporated at elevated temperatures (Schindler et al., 2012).

Co-solid spray-drying of pea protein isolates was examined to enhance solubility and to mitigate off-flavors. For this purpose, gum arabic or maltodextrin was mixed with pea protein solutions at varying ratios prior to spray drying them. A 2-fold to 3-fold decrease of two beany markers, 1-pentanol and 1-octen-3-ol, attributed to a partial unfolding of secondary protein structures, was observed during spray drying; however, the concentration of hexanal did not change much (Lan et al., 2019). Similarly, co-spray-drying with emulsifying salts or disaccharides led to variations in the retained volatiles in the protein isolates. A clear tendency (decrease/increase) for all volatiles was not obvious for a specific type of co-spray-dried isolate, but for single molecules (Cui et al., 2021). In contrast to disaccharides, the use of cyclodextrins reduced the concentrations of molecules related to the beany off-flavor. The hydrophobic cavity of the cyclodextrin is thought to entrap and mask odor-active molecules (Cui et al., 2020b).

Microwave vacuum dehydration was classified as an alternative drying method of pea protein solutions. It strongly reduced the volatile concentration. The applied vacuum enabled drying at lower temperatures and, at the same time, with a low oxygen concentration. Therefore, decomposition reactions forming odor-active molecules were mitigated. As the initial high water content of the protein solution strongly lowered the solubility of the dried proteins, the drying had to be carried out with low moisture samples. (Yen & Pratap-Singh, 2021).

In summary, drying can help to reduce volatile concentration; however, it remains unclear how the reduction affects the sensory perception.

5.11. Extrusion/texturization

Little evidence is available so far for aroma changes occurring during pea protein texturization. Recent results compared the odor-active volatiles of pea protein isolates with the volatiles of the extrudates obtained by a dry/low moisture *versus* wet/high moisture texturization process (Ebert et al., 2021). Using GC-MS with olfactometric analysis, around 24 volatiles, which are also highly abundant in Table 2, were identified in pea protein isolates and extrudates. The number of signals in the chromatograms did not change much, but the peak height and the signal areas of most of these volatiles, especially of carbonyl compounds, were reduced in wet as well as in dry texturates. A decrease of the overall odor intensity of green and fatty odors was accordingly detected at the olfactory port. The beany odors were lower in the dry texturized samples. The authors assume that the heat applied during texturization might break down some of the molecules. Accordingly, a secondary Maillard reaction product 2-pentylpyridine increased during the processing and was sensed most intensely (Shahidi & Oh, 2020). Also, newly formed pyrazines appeared in the texturates. The authors conclude, that especially dry texturization might be successful in reducing off-flavors in pea proteins, while wet extrusions might even increase them. A reduction of alcohols, ketones, acids, esters, ethers was also described elsewhere for an extrusion process, while Maillard reactions products increased. The extrusion eliminated volatiles from the raw material and introduced new Maillard reaction products, including pyrazines, thiophenes, furans, and 1-pentanethiol (Kaleda et al., 2020; Guan et al., 2021). OAVs indicated for extruded pea flour that nonanal, 3-methylbutanal, hexanal, octanal, 1-octen-3-ol, heptanal, ethyl acetate, butyraldehyde, (*E*)-2-octenal, 2-pentylfuran, 2-ethylfuran and 1-hexanol were the characteristic aroma volatiles (Guan et al., 2021). The initial amino acid concentration is considered to be crucial for the formation of these Maillard products. Accordingly, an increase of free amino acids after fermentation correlated with the pyrazines concentration found in the extrudate (Kaleda et al., 2020).

So far it appears for the four publications, that certain extrusion strategies eliminated volatiles, also off-flavor-related ones, but introduced new Maillard reaction products.

6. Conclusion

The review shows that pea aroma is a product of complex interactions of a large number of volatiles. The volatiles are either already present natively in the pea or are formed during harvesting/processing, indicating that often aroma profile changes are essentially caused by fat oxidation products. A very limited quantity of literature sources tried to differentiate between the native aroma profile of a non-fat oxidized and the aroma profile of an additionally fat-oxidized pea. In this respect, it also remains widely unclear if, and at which point in the protein downstreaming, fat oxidation occurs and also to what extent processing even represents a part of the problem, e.g., by activation of lipoxygenases/lipases during harvesting due to mechanical damage, release/activation of degradation processes due to decompartmentalization during processing, access to oxygen, processing times and insufficient inactivation of enzymes. In addition, there are aroma components which do not arise from fat oxidation, some are naturally occurring in peas (e.g., pyrazines), others can be formed during processing (e.g., vinylguaiacol from ferulic acid).

The impact of harvest and post-harvest treatments on the pea aroma is not yet fully described in the literature. Concerning pea processing, alcohol/CO_2 extractions as well as additional fermentation seem to be promising to reduce the concentration of unwanted aroma molecules and/or to mask unwanted flavor with generated fermentation flavor.

For future research, it seems to be promising to differentiate between native aroma and induced aroma due to raw material treatment from harvesting to processing. It is necessary to fully understand the origin of new volatiles in the processing chain. Apart from this, breeding seems to be an opportunity to reduce the overall level of aroma-relevant components, including the quantity of polyunsaturated fatty acids, or precursors of volatiles activated during processing. It has to be clarified to what extent this is possible without other drawbacks, as the molecules also have a natural function, often with respect to protection of the plant tissue against pests or pathogens.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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