VOLATILE AND SENSORY PROFILING TO MINIMIZE OFF-FLAVORS IN PULSES

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ABSTRACT

Pulses are a nutrient-dense and sustainable protein source; however, only 17% of Americans consume them at or above the level recommended in dietary guidelines. Incorporating pulse flour into wheat-based products can promote consumption, but adoption remains limited due to undesirable flavors. Volatile organic compounds (VOCs) responsible for these off-flavors primarily include aldehydes, alcohols, ketones, acids, pyrazines, and sulfur compounds. Understanding the factors influencing VOC formation and their impact on sensory perception is critical for improving the quality of pulse-based products. To examine the effects of cultivar, processing (roasting and boiling), and harvest year on the volatile composition of eight pulse cultivars, headspace-solid phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS) was used. Processing trade-offs for mitigating undesirable flavors were assessed by pre-treating some of the pulses by roasting, followed by milling and cooking into model products (porridges), as well as soaking and boiling to evaluate changes in volatile concentrations. Additionally, cultivar differences were analyzed to identify variations in volatile profiles. The impact of crop year was assessed by comparing seven common bean (*Phaseolus vulgaris*) cultivars grown in Michigan in 2022 and 2023 to one commercially sourced chickpea (*Cicer arietinum*) grown in 2022. Roasted and non-roasted: flours and model product and boiled pulses prepared from each of the eight cultivars were analyzed by HS-SPME-GC-MS. Hierarchical clustering (HCA) and principal component analysis (PCA) revealed clustering based on harvest year and distinct volatile profiles among cultivars based on seed coat color. Roasting and boiling influenced VOC composition, with variations observed across different compound classes. To further investigate how variations in volatile profiles due to cultivar and processing treatments impact sensory perception, descriptive sensory analysis (DA) was conducted. Given the high cost of sensory panel testing, this study also evaluated the effectiveness of instrumental techniques such as GC-MS and electronic nose (e-nose) in predicting sensory attributes. PCA indicated that sensory variability among cultivars was driven by seed coat color which influenced both appearance and flavor, while HCA indicated that samples with shared sensory attributes clustered based on processing treatment. Pearson's correlation analysis revealed stronger correlations of e-nose discriminant ions with DA than GC-MS. By integrating sensory and instrumental analyses, this research supports efforts to improve consumer acceptance and increase pulse flour consumption in food products.

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Chapter 1: Introduction

Rationale and Significance

Pulses, including dry beans, peas, chickpeas, and lentils, are nutrient-dense crops with significant potential to enhance food security, sustainability, and dietary health (Calles, 2016; Mitchell et al., 2009). They are an inexpensive source of protein and provide complex carbohydrates, fiber, and essential vitamins and minerals, making them a valuable component of plant-based diets (J. I. Boye & Ma, 2012). Additionally, replacing 50% of animal-based protein with plant-based sources, including legumes, could reduce the agricultural and food production greenhouse gas emissions by approximately 30%, supporting environmental sustainability in food systems (Springmann et al., 2018). Although pulses offer numerous benefits, their consumption in the U.S. remains low. The 2025 Dietary Guidelines Advisory Committee reported that 83% of Americans consume pulses below the recommended intake of 2.5 cups per week (2025 Dietary Guidelines Advisory Committee, 2024; Garden-Robinson & West, 2023) primarily due to a lack of knowledge on cooking as well as an aversion to the taste and texture of pulses (Doma et al., 2019; Winham et al., 2020).

To increase consumption, expanding the use of pulse flour in convenience products offers a convenient, gluten-free alternative to wheat flour while reducing the lengthy cooking times required for dry pulses (Shevkani et al., 2022; Shukla et al., 2023). However, the undesirable flavor profile of pulses limits their widespread acceptance (Borsuk, 2011; Jeong et al., 2021; Kaya et al., 2018; Niva et al., 2017; Polat et al., 2020; Roland et al., 2017; Zare, 2011). Food flavor arises from the interaction of aroma, taste, and oral sensations, with volatile organic compounds (VOCs) primarily influencing aroma (Menis-Henrique et al., 2019). In pulses, off-flavors, often described as "beany," "green," or "earthy" are mainly associated with aldehydes, alcohols, and ketones, while bitterness and astringency result from sapid-glycosylated compounds such as saponins and phenolic compounds, including isoflavones, flavonols, and phenolic acids (Damodaran & Arora, 2013; MacLeod et al., 1988; Roland et al., 2017).

The abundance and composition of volatile compounds in pulses are influenced by multiple factors, including cultivar, growing location, crop year, and processing treatments (Azarnia et al., 2011; Ma et al., 2016; N. Singh, 2017). Additionally, storage conditions significantly impact volatile formation, with exposure to heat, light, and oxygen accelerating the production of off-flavored volatile compounds (Azarnia et al., 2011). As a result, off-flavors vary widely across

cultivars and processing methods, imparting distinct sensory experiences depending on the species and treatment (Bassett et al., 2021; Ma et al., 2013; Mcwatters & Heaton, 1979). Despite the widespread production and consumption of common beans *(Phaseolus vulgaris, L.)* (FAO, 2024; White et al., 2022) much of the existing research on pulse volatiles has focused on peas, chickpeas and faba beans (Roland et al., 2017; Saffarionpour, 2024). Studies on common beans primarily examine their volatile composition in boiled form, with limited investigation into how processing methods such as milling into flour influence their volatile profile and sensory attributes. Furthermore, the impact of final cooking steps on volatile compound changes and sensory perception remains underexplored in common beans. This gap highlights the need for research on cultivar selection and processing to mitigate off-flavors while preserving pulse quality.

Traditionally, sensory evaluation has been used to analyze taste and aroma attributes in food (Ashurst, 1999; Lopetcharat & McDaniel, 2005). However, sensory analysis is time-consuming, costly, and impractical for large-scale assessments. To address these challenges, analytical techniques such as gas chromatography-mass spectrometry (GC-MS) and Headspace-solid phase microextraction (HS-SPME) have been widely adopted for extracting volatiles, offering high sensitivity, robust identification capabilities and quantification (Jansen et al., 2011). While individual volatiles have distinct odors, overall aroma perception results from complex interactions within the volatilome, highlighting the need for more advanced profiling techniques.

Electronic nose (e-nose) instruments have gained attention for their ability to rapidly and objectively analyze volatile profiles, making them valuable for flavor monitoring and large-scale sample screening (Ciosek et al., 2004, 2006; Deisingh et al., 2004; Rodríguez Méndez et al., 2010). However, comparative studies between traditional VOC extraction techniques and novel analytical tools in pulse-based products remain limited. Further research is needed to assess the ability of instrumental techniques to accurately represent the overall flavor perception of pulses.

Objectives

Therefore, the objectives of this study were to:

1. Measure the effect of cultivar, processing (roasting, boiling), and crop year on the volatile composition of pulse samples using HS-SPME-GC-MS.
2. Characterize the effect of cultivar and processing on the sensory attributes of pulse samples through descriptive sensory analysis.
3. Identify chemical markers associated with off-flavors using instrumental techniques (HS-SPME-GC-MS and e-nose).

By examining the impact of cultivar variation and processing methods, this research seeks to identify cultivars with milder flavor profiles and assess the sensory trade-offs involved in processing strategies for reducing off-flavors. Additionally, comparative studies between analytical techniques aim to explore rapid screening that can enhance the sensory quality of pulse-based food products, ultimately increasing consumer acceptance and consumption.

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Chapter 2: Literature review

Pulses: classification and importance

Varieties of pulses

Legumes encompass edible parts such as leaves, stems, pods, and seeds of a broad group of plants within the Fabaceae or Leguminosae family. They are typically categorized into oilseed legumes, such as soybean, (Glycine *max* (L.) Merr.); groundnut, (*Arachis hypogaea* L.), and non-oilseed legumes. Non-oilseed legumes can be further divided into vegetable legumes, like green peas (*Pisum sativum* L.) and green beans (*Phaseolus vulgaris* L.), which are consumed fresh and often include both the pod and seeds, and pulses which are left on the plant to dry naturally before harvesting solely for their dry, edible seeds.

According to the Food and Agriculture Organization (*FAO*, 1994), the terms "pulses" exclude crops harvested green for food (green peas, green beans, etc.) which are classified as vegetable crops as well as oilseed legumes and leguminous crops e.g. seeds of clover (genus Trifolium L) and alfalfa (Medicago sativa L) that are used specially for sowing purposes (*FAO*, 1994). The FAO recognizes 11 types of pulses: dry beans (*Phaseolus vulgaris* L.), dry broad beans (*Vicia faba*), dry peas (*Pisum sativum* L.), chickpeas (*Cicer arietinum*), cowpeas (*Vigna unguiculata*), pigeon peas (*Cajanus cajan*), lentils (*Lens culinaris*), bambara beans (*Vigna subterranea*), vetches (*Vicia sativa*), lupins (*Lupinus* spp.), and pulses nes ("not elsewhere specified," representing minor pulses) *(Vigna spp)* (*FAO*, 1994).

In the United States, commonly consumed pulses include varieties of dry beans such as pinto, black, and kidney beans, along with dry peas, chickpeas, and lentils (Mitchell et al., 2009). Pulses are essential food crops that hold significant potential for addressing future global food security and environmental challenges while promoting healthy diets (Calles, 2016).

Nutritional benefits of pulses

Pulses are nutrient-dense foods that offer substantial amounts of protein, dietary fiber, starch (Osorio-Díaz et al., 2003), and essential minerals and vitamins (Kutoš et al., 2003). Their high protein content (20-25% by weight) is two to three times greater than that of cereals, making pulses a valuable and affordable protein source globally (Calles, 2016; Siddiq & Uebersax, 2022). Legumes enhance protein quality by providing essential amino acids, particularly lysine, which is deficient in cereal-based diets, especially in Asian countries. While cereals are rich in sulfur-containing amino acids, they lack lysine. Combining cereals with legumes creates a

complementary amino acid profile, resulting in a high-quality protein source—an especially valuable solution in developing regions worldwide (Ratnayake & Naguleswaran, 2022).

A diet rich in beans may reduce the risk of chronic diseases, including conditions like certain cancers, type 2 diabetes, and heart disease—leading causes of death in the United States and globally (Bennink, 2002; Geil & Anderson, 1994). The benefits stem from both their macronutrient and bioactive compound composition. Pulses are particularly rich in water-soluble fiber, which effectively lowers blood cholesterol levels, and insoluble fiber, which aids digestion by increasing bulk and speeding food transit through the digestive tract. They also elicit a low glycemic response due to their high fiber and resistant starch content, which may aid in diabetes prevention and management and potentially lower the risk of colon cancer (Ludwig, 2002; Mathers, 2002; Michels et al., 2006). Additionally, common beans are naturally low in sodium (Augustin & Klein, 1989; Buttriss & Stokes, 2008), making them a suitable food choice for individuals following low-sodium diets. Studies suggest that regular consumption of dry beans could significantly improve dietary quality in the United States, where obesity rates are rising (Mitchell et al., 2009). Regular consumption of dry beans and other legumes has been shown to have positive effects in managing metabolic diseases (Dilis & Trichopoulou, 2009; Flight & Clifton, 2006; Raju & Mehta, 2008).

The health benefits of dry beans in disease prevention, including cancer, stem not only from their fiber content but also from the combined effects of their nutritional and non-nutritional components. Anti-nutritional factors in dry beans, such as phytates, saponins, and oligosaccharides, may contribute to cancer prevention by fostering antioxidant activity, inhibiting the growth of cancer cells, and improving gut microbiota (Geil & Anderson, 1994). Polyphenols, for instance~~,~~ in dry beans, act as antioxidants that help prevent free radical formation, potentially reducing disease risk (Boateng et al., 2008; Oomah et al., 2007).

Pulses have been widely studied for their role in improving cardiometabolic health. A study conducted by Mitchell et al. (2009) suggested that increased levels of intake from dry beans and peas may result in higher intakes of fiber, folate, zinc, iron, and magnesium while lowering intakes of total fat and saturated fat in the diets of Americans. Systematic reviews and meta-analyses (SRMAs) of both prospective cohort studies and randomized controlled trials (RCTs) examining the effect of legume intake on cardiometabolic outcomes were reviewed by (Viguiliouk et al., 2017). Due to the absence of SRMAs focused solely on pulses, the review included studies on all legumes (e.g., pulses, soybeans, peanuts). Cohort studies suggested a reduced coronary heart

disease risk at intakes of four or more 100 g servings of legumes per week, though associations with cardiovascular, diabetes, and stroke risk were inconclusive. For RCTs specifically targeting pulses (dry beans, peas, lentils, and chickpeas), pulse intakes of 120–132 g/day (~one serving/day) were linked to reductions in cardiometabolic risk factors like HbA1c, LDL cholesterol, and body weight. Additionally, one SRMA reported blood pressure reductions with a higher dose of ~162 g/day (Jayalath et al., 2014).

Promoting beans as a cost-effective and nutrient-rich food source could play a critical role in addressing dietary deficiencies, managing obesity, and reducing the prevalence of diet-related diseases, particularly in regions with limited access to high-quality protein sources (Guenther et al., 2006). These findings highlight the importance of incorporating beans into daily diets as a sustainable solution to improve global health outcomes.

Environmental benefits of pulses

Pulses offer significant ecological benefits and have the potential to contribute to sustainable agriculture and food systems. One key advantage is their ability to fix atmospheric nitrogen through symbiotic relationships with soil bacteria. This reduces the reliance on synthetic nitrogen fertilizers, which can have detrimental environmental effects like water pollution and greenhouse gas emissions (Reckling et al., 2016). Moreover, pulses play a crucial role in enhancing soil health and fertility by improving soil water retention, reducing erosion, and increasing nutrient availability for subsequent crops (Wezel et al., 2014). Additionally, when grown in rotation with other crops, pulses promoted microbial diversity and improved soil health compared to cereal-based systems (Gan et al., 2015).

Pulses are a sustainable food choice due to their low carbon footprint, as they have a much lower global warming potential (GWP). The average GWP value for beef is approximately 29 kg carbon dioxide equivalents (CO_2-eq) per kg, for cheese around 9 kg CO_2-eq per kg, and for chicken about 4 kg CO_2-eq per kg. In contrast, dried pulses have an average GWP value of only 0.7 kg CO_2-eq per kg. This means that the GWP per kg of protein for pulses is far lower than that for animal-derived protein sources, making pulses a more climate-friendly option (Clune et al., 2017). Research has also revealed that the carbon footprint of pulses is just one-tenth that of beef per unit of protein produced (Poore & Nemecek, 2018). A study by Röös et al., (2020) demonstrated the potential impact of replacing 50% of the meat consumed in Sweden with domestically grown grain legumes. Despite some agronomic challenges, this transition was projected to reduce the climate

impact of the Swedish diet by 20% and land use by 23%. It would also reduce the need for nitrogen fertilizers, lower nitrogen loads from wastewater plants and significantly increase dietary fiber and folate intake in the population. Furthermore, a study by (Springmann et al., 2018) found that replacing 50% of animal-based protein with plant-based sources, including pulses, could reduce greenhouse gas emissions by approximately 30%. Pulses also stand out for their lower water footprint, making them a sustainable crop amid growing concerns over water scarcity. Agriculture accounts for a significant portion of global water use, yet pulses require considerably less water than other protein sources. A global assessment by (Mekonnen & Hoekstra, 2012) reported that the water footprint of pulses is 50% lower than that of chicken and pork and approximately 10 times lower than beef.

Overall, the nitrogen-fixing ability, soil health benefits, and lower carbon footprint of pulses make them a valuable component of sustainable agricultural and food systems (Clune et al., 2017; Vasseur et al., 2013).

Pulse consumption trends and challenges

Low pulse production and consumption

Despite these benefits, pulse consumption has stagnated or even declined in several regions, particularly in developing countries in Asia and sub-Saharan Africa, where they offer an affordable, protein-rich food source that is crucial for combating protein-energy malnutrition (Van Heerden & Schönfeldt, 2004). This trend reflects changing consumer preferences and, in some cases, governmental focus on cereal production over pulses to achieve self-sufficiency in staple grains. In Latin America, limited genetic improvements in pulse crops, such as beans, have allowed crops like corn and soybeans to outcompete them for arable land (Evenson, 2004). In regions where declines in pulse consumption were not offset by increased intake of livestock/animal products, overall diet quality has likely diminished, even as caloric intake has risen. In India, for instance, pulses are a primary protein source for the largely vegetarian population (Hopper, 1999). However, approximately 60% of dietary protein in India comes from cereals, which have lower digestibility and protein quality compared to pulses. Surveys conducted by the National Nutrition Monitoring Board (NNMB) over the past 25 years have assessed protein intake across various demographics, including urban, rural, slum-dwelling, and tribal populations. Findings indicate that disadvantaged groups, such as those in slums, tribal communities, and sedentary rural areas, consume about 1 g of protein per kg of body weight daily, mostly derived from cereals (Swaminathan et al., 2012). In

the future, pulse consumption in developing countries is expected to remain steady, with per capita annual intake projected to stay around 7–8 kg (Evenson, 2004).

In the United States, pulse availability has also decreased, with the USDA Economic Research Service reporting an annual per capita availability of vegetables and pulses averaging 414 pounds from 2017 to 2022—a 4% drop compared to the previous decade (USDA , 2024). In the United States, approximately 2.9 million tons of common beans, peas, chickpeas, and lentils are produced annually, based on a five-year average from 2016 to 2020. Common beans (*Phaseolus vulgaris, L.*) are the most widely produced pulse crop globally and in the U.S. (FAO, 2024), with around one million tons harvested each year, primarily consumed as canned beans (White et al., 2022).

The 2020–2025 Dietary Guidelines for Americans (DGA) recommend a weekly intake of 1.5 cups equivalents of beans, peas, and lentils for individuals on a 2000-calorie healthy U.S.-style or Mediterranean-style dietary pattern, and 3 cups equivalents per week for those on a 2000-calorie vegetarian diet (Haven, 2021a). Despite legumes being an affordable, nutritious, and sustainable protein source, per capita intake in the U.S. remains below recommended dietary guidelines. Lucier et al. (2000) reported that in the 1994-1996 Continuing Survey of Food Intakes by Individuals (CSFII), only 14% of Americans consumed foods containing cooked dry beans over 2 days. Data from 1999-2002 National Health and Nutrition Examination Survey (NHANES), focused on adults aged 19 and older, showed that only 7.9% of adults consumed dry beans and peas, with an average intake of ~122 g/day (Mitchell et al., 2009). However, subsequent NHANES data from 2003–2014 for adults (≥19 years) showed an increase in the percentage of consumers, with 27% of adults consuming pulses over a 2-day intake period. Despite this increase in prevalence, the average intake declined to 70.9 ± 2.5 g/day, representing a notable reduction from the earlier ~122 g/day levels observed in 1999–2002 (Mitchell et al., 2021). Additionally, in the NHANES 2017–2018 24-hour dietary recall, only 20.5% of 4,741 adults reported consuming any legumes (dry, canned, or frozen) in the previous 24 hours (Semba et al., 2021). The 2025–2030 Dietary Guidelines for Americans recommended higher intakes from legumes or beans of 2.5 cups/week, and lower intakes from red/processed meats and sugar-sweetened beverages (2025 Dietary Guidelines Advisory Committee, 2024).

Reasons for low pulse consumption

Studies highlight several common barriers to pulse consumption in the U.S., including a general dislike of their sensory profile, lack of familiarity, and insufficient preparation knowledge. These

barriers vary across demographics. Older adults over 65 often cite concerns about flatulence, abdominal discomfort, and the limited incorporation of pulses into traditional diets (Doma et al., 2019). Beans contain antinutritional factors such as tannins, lectins, phytic acid, and oligosaccharides which interfere with nutrient metabolism in humans (Francis et al., 1999; Kan et al., 2017). For instance, raffinose-family oligosaccharides are indigestible carbohydrates that ferment in the large intestine, producing gases that cause flatulence (Bohn et al., 2008; Glahn et al., 2002). Phytic acid forms a complex with proteins and decreases protein solubility while lectins adversely affect the activity of digestive enzymes, thereby reducing the in vitro digestibility of proteins (Thompson et al., 1986). Additionally, phenolic acids, tannins, and flavonoids are linked to bitter taste and dark color in pulses (Y. Kumar et al., 2022).

Insufficient time and knowledge about cooking pulses further reduce their appeal. In a study on younger populations, specifically Midwestern U.S. university students aged 18–30, barriers included limited time, lack of culinary skills, and unfamiliarity with the health benefits of pulses (Winham et al., 2020). Many students reported on not knowing how to prepare pulses, which contributes to their exclusion from daily diets. Similarly, low-socioeconomic women in Iowa, with an average age of 34.7 years, found dry pulses challenging to prepare, as shown in a study on socio-ecological influences on pulse consumption (Palmer et al., 2018). Across all age groups, the lack of knowledge related to pulse preparation and cooking, combined with aversion to taste and texture, remain significant deterrents. Sensory characteristics strongly influence food acceptability, particularly for plant-based proteins. Pulses differ in sensory characteristics from meat, which may further deter their consumption (Niva et al., 2017).

Strategies to increase pulse consumption

Although canned pulses are readily available, consumers might prefer incorporating pulses into familiar foods, as a more convenient source of protein (Doma et al., 2019; Winham et al., 2020). Milled pulse flour can address these challenges by offering an easy way to incorporate pulses into traditional food products. Pulse flour can replace or supplement wheat flour in products like bread, muffins, cookies, and pasta, providing convenient and ready-to-eat options for consumers (Shevkani & Singh, 2014; Shukla et al., 2023; R. Simons, 2011; Ziobro et al., 2013, 2016). This approach reduces the need for lengthy cooking processes and addresses barriers such as lack of knowledge and limited inclusion in traditional diets. Most of the anti-nutritional compounds responsible for bitter and astringent tastes in pulses are present in the seed coat and are sensitive

to heat and hence can be substantially reduced by milling, cooking, germination, fermentation and heat processing (Y. Kumar et al., 2022). Expanding the range of ready-to-eat processed pulse flour products—particularly plant-based and gluten-free options that are palatable, affordable, and widely available—could significantly boost pulse consumption, especially in Western countries (Niva et al., 2017).

Consumption trend of pulse-based/gluten-free products

Over the past decade, consumer adoption of plant-forward diets and the utilization of plant-based ingredients have positively influenced the incorporation of pulses in various food products (Chigwedere et al., 2022). These consumer choices are increasingly driven by considerations of human health, animal welfare, and the environmental impact of food value chains. Consequently, the food industry is exploring plant-based ingredients and products to meet these evolving consumer demands.

This trend has spurred the development of various pulse-based products such as meat substitutes, snacks, pasta, flours, starches, and dairy alternatives (Davis & Lucier, 2021). Between 2016 and 2020, 1,666 new U.S. food products featured pulse flour, starch, or protein as ingredients, with peas comprising 65% of these formulations (Mintel Group Ltd. 2022; Sadohara et al., 2022). An online survey conducted by (Sadohara et al., 2022) among 75 food industry professionals involved in regular wheat and gluten-free product development revealed that chickpea and pea flours were the most preferred options due to their favorable functional and sensory characteristics. In contrast, common bean flour remains underutilized despite being the most widely produced pulse globally and in the U.S. (*FAO*, 1994; White et al., 2022). Over half of the industry professionals in the survey were unfamiliar with bean flour as an ingredient, highlighting a potential barrier to its adoption. Moreover, off-flavors associated with pulses continue to hinder their acceptance and limit market expansion (Karolkowski et al., 2021). Future research comparing the sensory properties of chickpea and bean flours could explain chickpea's popularity as a preferred wheat flour alternative and provide valuable guidance for dry bean flour production and product development.

According to a study by (M. B. Magrini et al., 2023; M.-B. Magrini et al., 2018) the market for pulses as ingredients in the French food industry is growing and estimated at 120,000 metric tons per year. A substantial portion of this market (over 80,000 metric tons per year) is attributed to protein-rich peas. In comparison, the market for direct consumption of pulses, including lentils,

beans, and chickpeas, is estimated at 100,000 metric tons per year, with more than half of this quantity being imported to France. Of the direct consumption market, over half of the pulses are processed into flour or canned products, while the remaining portion is sold as whole pulses for cooking. As a result, the market for food ingredients produced through advanced processing technologies has outpaced traditional pulse consumption. This shift can be attributed to advancements in nutritional knowledge and the recognition of other functional properties, which have influenced food-processing practices.

A comprehensive review by Wijeratne & Nelson (1987) outlined traditional and regional techniques for utilizing legumes, summarizing common preparation methods such as decortication, boiling, grinding, roasting, frying, puffing, germination, fermentation, curdling, and pasta-making. For instance, dry-roasted pulses are widely consumed as snacks in Africa and India, where the roasting process imparts a high-temperature, short-time heat treatment, resulting in a nutty flavor that appeals to both children and adults. In India, pulses are incorporated into snacks like *waddai* and *murukku*, where ground legumes and cereal flours are mixed with water to form dough, which is then deep-fried in oil. Similar culinary applications include oil cakes made from dry bean paste in Brazil and ready-to-eat fried snacks produced from ground legume pallets in Nigeria. Another example is *filafi*, an oil-fried food made from chickpea paste. Among pulses, the common bean (*Phaseolus vulgaris, L.*) holds global prominence and is widely consumed in the form of canned beans.

Pulses and their derivatives—such as whole flours, protein-rich flours, and starch-rich flours—are incorporated into food formulations to enhance nutritional value, fortify products, or partially or fully replace conventional starch- and protein-rich ingredients (Chigwedere et al., 2022). The functional properties of pulses, such as their ability to form emulsions, foams, and gels, make them versatile substitutes for other ingredients, particularly in dairy products. For instance, lupine flour is used in the baking sector as an egg replacement due to its emulsifying properties (KohaJdoVá et al., 2011). Similarly, faba bean flour has been utilized in bread-making to achieve a lighter crumb color (Awulachew, 2024). Studies have demonstrated the positive effects of pulse proteins in gluten-free baking. (Ziobro et al., 2013, 2016) reported that pea and lupine proteins improve bread quality by increasing the batter's viscosity, which retains more air/gas bubbles during mixing and baking. This results in gluten-free muffins and cakes with enhanced aeration, springiness, and crumb volume. Similarly, Alvarez et al. (2017) created muffins by replacing 50% of wheat flour

with chickpea flour and found no significant difference in overall acceptability between the two products. Mancebo et al. (2016) found that incorporating pea proteins into gluten-free cookies increased dough hydration and consistency, resulting in reduced hardness and darker, more desirable cookies. A study by R. Simons, (2011) evaluated gluten-free cookies made with raw, cooked, and germinated pinto bean flours, finding that germinated flours improved sensory quality and increased the bioavailability of nutrients.

Pulse proteins have also been shown to improve the quality of pasta, and noodles. In noodles, Sofi et al. (2020) observed that incorporating germinated chickpea proteins enriched rice noodles with antioxidative properties, better cooking performance, and improved dough elasticity. Similarly, Shukla et al. (2023) used pea and faba bean proteins to prepare gluten-free pasta, demonstrating that specific ratios (30:70 and 43:57) produced pasta comparable to those made with semolina. Faba bean proteins enhanced extrudability and water uptake while reducing cooking loss, whereas pea proteins contributed to harder pasta.

Despite these advancements, pulse-based snacks and flours face challenges in reducing antinutritional factors and achieving consumer acceptance. The absence of gluten in baked pulse-based snacks often results in crumbly textures, poor color, and other quality defects (Naqash et al., 2017). Studies demonstrate that the overall flavor acceptability of products tends to decrease as the level of pulse-ingredient supplementation increases. This decline has been observed in various products, including bread supplemented with coarse navy bean flour (Borsuk, 2011), muffins containing cowpea flour Jeong et al. (2021), noodles formulated with pea, lentil, or faba bean flour Kaya et al. (2018), crackers with germinated lentil extract Polat et al., (2020), and yogurt fortified with pea and lentil flour (Zare, 2011).

Hence, although commercial production and usage of pulse flour has increased, their market presence remains limited due to sensory barriers, particularly the "beany" off-flavors (Karolkowski et al., 2021; Sadohara et al., 2022).

Off-flavors in pulses

Consumers possess specific sensory memories of preferred flavor experiences; therefore, any deviation in taste, aroma, or overall flavor is often perceived as less acceptable. Off-flavors are defined as unpleasant sensory characteristics, including undesirable taste, aroma, and other sensory effects, that deviate from the expected flavor profile. Since Western diets are predominantly cereal-based, the incorporation of pulses into familiar food products such as breads, muffins and pasta

may result in sensory differences that consumers perceive as off-flavors. Interestingly, extruded snacks made with pulse flour received higher liking scores from assessors with lower food neophobia, highlighting the role of individual preferences and familiarity in shaping flavor acceptance (Proserpio et al., 2020).

While the popularity of pulses is rising, their full potential as whole foods or ingredients remains underutilized due to sensory challenges, including their inherent tastes, aromas, flavors, and trigeminal sensations. Off-notes in pulses are commonly characterized by sensory descriptors such as beany, green, pea-like, earthy, hay-like, fatty, pungent, and metallic (Roland et al., 2017). In a comprehensive review, Chigwedere et al., (2022) analyzed the frequency of sensory descriptors as a percentage of the total terms from 71 studies on pulse-based products. The findings revealed that beany (43%) and bitter (12%) sensations were the most commonly reported olfactory and basic taste perceptions, respectively. Examples of less acceptable flavors include the beany and grassy notes of pinto bean flour in cookies C. W. Simons & Hall, (2018) and the bitterness of lupin and cowpea in beverages (Nawaz et al., 2022). Flavors with low threshold values are the primary contributors to the perception of off-flavors in foods (Roland et al., 2017).

The "beany" flavor is a distinct yet challenging characteristic of dry beans and other legumes, often regarded as an off-flavor in products incorporating pulses as ingredients (Bott & Chambers IV, 2006; Hooper et al., 2019; Kinsella, 1979). The beany or legume-y attribute is a defining characteristic of pulse-based products and can be described as notes of raw or cooked pulses and legumes in general, though it remains difficult to clearly define (Mkanda et al., 2007; Plans et al., 2014; Troszyńska et al., 2006). Pea protein isolate used as an egg replacer in cake formulations was reported to impart a distinct off-flavor characteristic of pea (Hoang, 2012). Similarly, brownies made with 100% dry bean flour, or a mixture of dry bean flour (75%) and wheat flour (25%) were described as having bitter, sour, nutty, bland, and beany flavor notes (English et al., 2019). Research on pulse flavor describes beany characteristics using similarity/resemblance to pulse variety. For instance, aqueous slurries of raw pea flour (10% by weight in water) Price et al. (1985), lupin protein isolate Schlegel et al. (2019) and aqueous slurries of whole faba bean flour (5% by weight in water) Hinchcliffe et al. (1977) demonstrated a distinct “pea-like” flavor. This beany attribute encompasses several sub-character notes and has been widely reported in various pulses. Vara-Ubol et al. (2004) identified sub-notes such as musty/earthy, musty/dusty, sour aromatics, green/pea pod, nutty, and brown in processed chickpea and dry bean products. Similarly, simmered

pastes of fermented water-cooked bambara groundnut cotyledons exhibited beany and nutty aromas (Akanni, 2017). Distinct off-notes have also been identified in lupin flour, with GC-O analysis detecting meaty, woody, green, mushroom, and soil-like aromas, depending on processing (Kaczmarska et al., 2018). Interestingly, Xu et al. (2019) reported similar mushroom-like and green descriptors for treated and untreated pea, chickpea, and lentil products, further underscoring the overlapping sensory attributes across different pulses.

In addition to these aroma descriptors, certain pulses exhibit astringency. Astringent attributes were identified in aqueous slurries of raw pea flour (Price et al., 1985), fresh lentil sprouts Troszyńska et al., 2011), and water-cooked dry bean cultivars (Koehler et al., 1987). Other studies have also shown that although all basic tastes have been associated with pulses, bitterness is the most frequently reported, especially in boiled pulses, particularly in cultivars such as pea (Malcolmson et al., 2014), dry bean (Bassett et al., 2021; Mkanda et al., 2007) and cowpea (Penicela, 2010). Research has shown that off-odors, off-tastes, and off-flavors in pulses vary widely across cultivars and processing methods, imparting distinct sensory experiences depending on the species and treatment. For example, differences in sensory profiles were observed among cultivars of the same pulse type. Boiled white-colored beans were described as starchy and sweet, while darker-colored cultivars, including dark red kidney, light red kidney, and red mottled genotypes, exhibited more intense vegetative and earthy flavors (Bassett et al., 2021). In low-fat pork bologna formulations, whole chickpea or pea flours were incorporated at equal substitution levels; however, products containing pea flour exhibited stronger off-flavors, whereas those made with chickpea flour were rated higher in flavor desirability (Sanjeewa et al., 2010).

The off-flavors in pulses are influenced not only by species but also by market class, cultivar, crop year, growing location, and storage conditions (Malcolmson et al., 2014). This challenge in sensory acceptability highlights the need for further exploration in cultivar selection and innovation in processing techniques to mitigate undesirable flavors while retaining the nutritional benefits of pulses. For industrial applications, pulses with milder flavors and limited flavor variability are often preferred. Pretreatment methods, such as roasting or moist heat application, can significantly alter the flavor and aroma profiles of pulses in final products. For instance, Mcwatters & Heaton, (1979) demonstrated that treating pea flour with moist heat before incorporating it into ground beef patties reduced the beany flavor in the final product. Similarly, Ma et al., (2013) found that roasted lentil flour provided the highest flavor scores when used in salad dressings, compared to

dressings supplemented with roasted seeds or pre-cooked spray-dried lentil flour. These findings emphasize the importance of cultivar selection and pretreatment methods in managing and enhancing the sensory properties of pulse-based products.

Studies focusing on the sensory profiles of pulse flour are limited and primarily emphasize off-flavors in pulse-based products. To maximize the potential of pulse flours derived from different pulse types and pre-treatments, understanding their sensory profiles is essential. This knowledge can streamline product development by identifying the optimal pulse types with mild flavors and processing treatments that minimize off-flavors, ultimately enhancing consumer acceptability of pulse-based products.

Volatile organic compounds in pulses

Volatile organic compounds responsible for off-flavors in pulses and their origin

Off-flavors in pulses originate from volatile organic compounds (VOCs) (Menis-Henrique et al., 2019). VOCs serve various purposes in plants, including defense mechanisms to combat pathogen invasions and herbivore attacks (Castro et al., 2017; Dicke & Loreto, 2010; Maffei et al., 2007; Mutyambai et al., 2016). In pulse crops, volatile emission naturally occurs in leaves, flowers, seeds, and roots (Fineschi & Loreto, 2012; Loreto & Schnitzler, 2010; Mumm & Hilker, 2006) and can continue even after harvesting (Karolkowski et al., 2021). However, this process is often amplified under stress conditions such as elevated temperatures (Centritto et al., 2011; Fares et al., 2011), water scarcity (Centritto et al., 2011; Holopainen & Gershenzon, 2010), or herbivore and pathogen attacks, serving as a protective mechanism (López et al., 2011).

VOCs responsible for off-flavors in pulses often develop due to lipid oxidation, a process that not only generates undesirable flavor compounds but also leads to the degradation of bioactive compounds and fat-soluble vitamins. Lipid oxidation is a complex phenomenon that can occur via enzymatic (lipoxygenase-mediated) or non-enzymatic pathways, including autoxidation and photooxidation, leading to the formation of primary oxidation products like hydroperoxides. These hydroperoxides subsequently decompose into volatile secondary lipid oxidation products such as ketones, alcohols, and aldehydes, which are primarily responsible for off-flavors. Polyunsaturated fatty acids (PUFAs) are particularly susceptible to oxidation, making them a significant contributor to off-flavor development (Saffarionpour, 2024).

Even though individual volatile compounds possess distinct odor characteristics, naturalistic aroma perception generally results from a complex mixture of aroma notes produced by multiple

molecules (Guichard, 2012). While some volatile compounds are responsible for undesirable odors, others contribute to pleasant and desirable flavors. Understanding the types and concentrations of these compounds is crucial for improving sensory quality and developing innovative pulse-based food products. The presence of specific volatiles at concentrations above their threshold levels—the minimum detectable concentration—can significantly influence the sensory profile, often imparting unpleasant aromas and off-flavors to foods (Saffarionpour, 2024). The aroma threshold, typically measured in parts per billion (ppb) or parts per million (ppm), varies widely among compound types. For instance, the thresholds for saturated, monounsaturated, and diunsaturated aldehydes range from 0.014–1 ppm, 0.04–2.5 ppm, and 0.002–0.6 ppm, respectively. Similarly, the thresholds for alcohols, furans, and ketones range from 0.001–3 ppm, 1–27 ppm, and 0.0002–5.5 ppm, respectively (Shahidi & Abad, 2019). Notably, heterocyclic compounds derived from Maillard reactions, which contain sulfur and nitrogen, exhibit much lower thresholds ($\leq$ 1 μg/L) than lipid-derived volatiles. As a result, higher concentrations of lipid-derived components are required to contribute noticeable aroma characteristics (Kerth & Miller, 2015).

Hexanal, 3,5-octadien-2-one, 1-penten-3-ol, and benzaldehyde have been identified as volatile marker compounds in common beans (Buttery et al., 1975). Additionally, hexanol and 2-pentyl furan have been frequently cited in the literature as contributors to the beany aroma and flavor in pulses. These compounds are part of the complex mixture responsible for the beany odor, with earlier studies (Arai et al., 1967; Chiba et al., 1979; Hoffmann, 1962; HSIEH et al., 1982; Z. H. Wang et al., 1997; Wilkens & Lin, 1970). Using sensory analysis and Headspace Solid-Phase Microextraction coupled with Gas Chromatography-Mass Spectrometry (HS-SPME-GC-MS–MS), Vara-Ubol et al. (2004) reported that hexanol, 1-octen-3-ol, and 2-pentyl furan were associated with musty and earthy odors, while hexanal was described as having a green pea pod-like aroma. Additionally, 1-octen-3-one, 1-octen-3-ol, pentanol, and acetophenone were also linked to beany notes (Roland et al., 2017; Vara-Ubol et al., 2004). A range of other volatile flavor compounds including n-hexanal, 3-cis-hexenal, 2-pentyl furan, 1-penten-3-one, n-pentanol, n-hexanol, n-heptanol, 1-octen-3-ol, trans,trans-2,4-nonadienal, trans,trans-2,4-decadienal, trans-2-nonenal, trans,cis-2,4-nonadienal, butyric acid, 2-methyl butyric acid methyl ester, 2-pentyl-pyridine, pentanal, and acetophenone have also been attributed to beany and other off-flavors (C. W. Simons & Hall, 2018). These compounds are typically formed through processes such as the Maillard reaction, Strecker degradation, lipid oxidation, ethanol fermentation, degradation of

phenolic acids, carotenoids, or thiamine, as well as caramelization or the decomposition of carbohydrates (Bicas & Rodriguez-Amaya, 2021; Sharan et al., 2022). Additionally, pyrolysis of amino acids and peptides contributes to the formation of compounds responsible for grassy, beany, and bitter notes in final food products (Bicas & Rodriguez-Amaya, 2021; Damodaran & Arora, 2013; Leonard et al., 2023; Shahidi & Abad, 2019).

Aldehydes. Hexanal ($C_6H_{12}O$), also known as hexanaldehyde or caproaldehyde, is an alkyl aldehyde commonly associated with off-flavors characterized by "green," "grassy," or "fresh" (Leonard et al., 2023; Roland et al., 2017). It is identified as a principal aldehyde in navy beans, red kidney beans, green lentils, and yellow peas (Ma Zhen et al., 2016). Hexanal is frequently reported in faba beans, soybeans, and peas, where it is formed via Strecker degradation of amino acids or through lipoxygenase (LOX)-catalyzed oxidation of unsaturated fatty acids (Chang et al., 2019; Gao et al., 2020; Sharan et al., 2022; C. Zhang et al., 2020). In raw pulse seeds, linoleic acid undergoes oxidation to hydroperoxides in the presence of oxygen, and hexanal is generated through the cleavage of 13-hydroperoxylinoleic acid by lyases (Belitz, 1999). This process is particularly prominent in seeds that are physically disrupted during processing, resulting in hexanal contributing to the characteristic green and grassy flavor of legumes. Another compound, (E)-2-hexenal, is a medium-chain unsaturated aldehyde (6–12 carbon atoms) and is classified as a fatty aldehyde. It is commonly formed in grain legumes, imparting "grassy" or "green" odors (Sharan et al., 2022; Vaughn & Gardner, 1993; Y. Wang et al., 2020). Additional fatty aldehydes in grain legumes, such as heptanal, octanal, nonanal, (E,E)-2,4-decadienal, and (E,E)-2,4-nonadienal, are typically produced through the degradation of polyunsaturated fatty acids (Leonard et al., 2023; X. Zhang et al., 2020). These aldehydes contribute a variety of off-flavors, including grassy, beany, earthy, fishy, or fatty notes, which are commonly considered undesirable in pulse-based food products.

Alcohols. In leguminous grains, the presence of alcohol oxidoreductase plays a key role in the conversion of LOX pathway products, such as aldehydes and ketones, into alcohols (Fischer et al., 2022). The formation of n-hexanol, including 1-hexanol and 3-hexanol, is typically facilitated by the transformation of n-hexanal in the presence of alcohol oxidoreductase (Matoba et al., 1989). Among these, 3-hexanol was identified as the most abundant volatile compound, with the highest relative peak area (RPA) observed in navy beans, red kidney beans, green lentils, and yellow peas (Ma Zhen et al., 2016). Alcohol oxidoreductase activity, reported to range from 0.0031 to 0.0064

units/mg protein, has been detected in green beans at a pH of 8.8 (De Lumen et al., 1978). A similar pathway leads to the formation of 1-penten-3-ol: linolenic acid is oxidized to form 16-hydroperoxide, which undergoes enzymatic isomerization to produce 1-penten-3-one. This intermediate is subsequently reduced to 1-penten-3-ol in the presence of alcohol oxidoreductase (Fischer et al., 2022). Alcoholic off-flavors, such as 1-hexanol and 1-pentanol, have been associated with fresh or grassy notes in chickpeas. This is attributed to the activity of three isoenzymes of alcohol dehydrogenase that catalyze their formation (Gomes et al., 1982; Khrisanapant et al., 2019). Other alcoholic off-flavors include 1-octen-3-ol and 1-penten-3-ol, which impart earthy, mushroom-like, or bitter notes, and nonanol, which contributes fatty or floral flavors. The latter is formed from the respective aldehyde, nonanal (Fischer et al., 2022; Khrisanapant et al., 2019; Leonard et al., 2023).

Ketones. Ketones are carbonyl compounds formed through LOX activity, resulting from the breakdown of unsaturated fatty acid hydroperoxides. They are also produced via the conversion of aldehydes by alcohol dehydrogenase (ADH) (Fischer et al., 2022). Methyl ketones, such as 2-heptanone and 2-hexanone, can be generated through aldol condensation of aldehydes like hexanal or (Z)-2-butyl-2-octenal, with an aldol intermediate (Leonard et al., 2023). Additionally, they can form conventionally from saturated fatty acids and the decarboxylation of 3-oxo-acids (Grebenteuch et al., 2021). Ketones have been reported in navy beans, red kidney beans, lentils, yellow peas, and black beans, highlighting their widespread presence in pulses (Ma Zhen et al., 2016; Oomah et al., 2007). Major ketones found in leguminous grains include 2-butanone, 2-heptanone, 2-hexanone, 2-nonanone, 1-octen-3-one, and acetophenone. These compounds contribute to a variety of odors, such as fruity, soapy, green, beany, and pungent notes, which can significantly influence the flavor profiles of pulses (Sharan et al., 2022; Trindler, Annika Kopf-Bolanz, et al., 2022). The flavor impact of these ketones varies with their carbon chain length, affecting their potency and sensory characteristics.

Aromatic Compounds. In pulses, aromatic compounds and furans, characterized by their cyclic structures, are present in small quantities. These are primarily formed through the oxidation of unsaturated fatty acids in pulse seeds (Oomah et al., 2007). Furans are also commonly produced via the Maillard reaction and the thermal degradation of sugars, amino acids, carotenoids, and polyunsaturated fatty acids (PUFAs) such as linoleic acid (Izzotti & Pulliero, 2014; Min et al., 2003). Specific furans, such as 2-methyl-furan, have been detected in navy beans, red kidney

beans, green lentils, and yellow peas (Azarnia et al., 2011). Additionally, lipid-derived aromatic compounds such as o-xylene and p-xylene have been identified in beans, split peas, and lentils (Del Rosario et al., 1984; Lovegren et al., 1979; Oomah et al., 2007). Other aromatic compounds, including 2-ethylfuran and 2-pentylfuran, have been reported in peas, faba beans, and soybeans. These compounds contribute earthy, green, or beany notes, which are characteristic of leguminous grains (Sharan et al., 2022; Trindler, Annika Kopf-Bolanz, et al., 2022; C. Wang et al., 2021).

Nitrogenous compounds. During heating processes such as cooking and roasting, nitrogenous compounds including alkylated pyrazines and pyrroles, are typically formed or significantly increased. Their formation is primarily attributed to the Maillard reaction, which involves the condensation of amino-carbonyl compounds to produce dehydropyrazines. These dehydropyrazines lose hydroxyl groups during dehydration, leading to the generation of pyrazines (Yu et al., 2021). Pyrazines are generally formed through the reaction between amino acids and reducing sugars, but they can also result from the dry-thermal degradation of proteins (Kato et al., 1981). However, protein isolates typically do not produce pyrazines under wet heat conditions, such as high-moisture treatments (Stevenson & Chen, 1996). Pyrazines are associated with desirable sensory properties, such as chocolate or roasted nut flavors, and a sharp taste (Azarnia et al., 2011). Alkylated pyrazines have been shown to form or increase markedly during the roasting of soybeans (Kato et al., 1981). Similarly, Ma Zhen et al. (2016) reported significant increases in compounds such as 2-ethyl-5-methyl-pyrazine, 1H-pyrrole-2,3,5-trimethyl-, and pyrimidine-5-methyl-pyrazine in roasted and cooked samples of navy beans, green lentils, and yellow peas. Among alkylated pyrazines, mono-ethyl-mono-methyl-pyrazines exhibit the lowest odor detection threshold, making them potent contributors to aroma (Koehler et al., 1971). The formation of compounds like 2-ethyl-5-methyl-pyrazine, 2-ethyl-6-methyl-pyrazine, 2-methyl-6-propyl-pyrazine, and 2-methyl-5-propyl-pyrazine during roasting can effectively mask the undesirable beany flavor of pulses (Buttery et al., 1971; X. Wang et al., 1998). On the other hand, common pyrazines such as 2-isobutyl-3-methoxypyrazine, 2-isopropyl-3-methoxypyrazine, and 2-methoxy-3-isopropyl-(5 or 6)-methyl pyrazine contribute green, earthy, or bell pepper aromas to pulses and legumes (Trindler, Annika Kopf-Bolanz, et al., 2022; B. Wang et al., 2021; C. Zhang et al., 2020). The low odor detection thresholds ($\leq$ 1 μg/L) of these compounds make them particularly perceptible even at low concentrations (Gao et al., 2020; Lin et al., 2019; Roland et al., 2017; Y. Zhang et al., 2022).

Sulfurous compounds. Sulfurous compounds are a significant source of off-flavors in pulses and grains, contributing to unpleasant aromas and tastes (Saffarionpour, 2024). These compounds can occur naturally in foods and are also formed during heat processing and storage (Ma Zhen et al., 2016). Sulfur-containing compounds are highly flavor-active due to their extremely low flavor thresholds (<1 μg/L) and distinctive odors (Gao et al., 2020; Y. Zhang et al., 2022). Dimethyl disulfide and methanethiol are notable sulfur compounds associated with pulses. Methanethiol, characterized by its intense onion-like odor, is the predominant sulfur compound identified in navy beans, red kidney beans, green lentils, and yellow peas. Dimethyl disulfide is believed to form from the decomposition of methanethiol, which is produced through the Strecker degradation of methionine. Methionine undergoes further oxidation to generate methional, leading to the formation of dimethyl disulfide (Leonard et al., 2023; Mishra et al., 2019). The presence of dimethyl disulfide has been reported in both raw green peas and cooked French beans, highlighting its relevance across different processing stages (Azarnia et al., 2011). These sulfur compounds play a crucial role in shaping the sensory profile of pulses, often contributing undesirable notes that challenge their use in food products.

The abundance of volatile compounds in pulses is influenced by various factors, including storage conditions, cultivar, growing location, and crop year (Azarnia et al., 2011; N. Singh, 2017), and the processing treatments applied (Ma Zhen et al., 2016).

Factors affecting volatile profiles and off-flavors in pulses

Effect of cultivar selection

The volatile profile of pulses varies significantly due to differences in chemical precursor composition, environmental stress during cultivation, storage conditions, and LOX activity (Akkad et al., 2019).

These variations influence flavor development, with specific volatile classes dominating different pulse types. Aldehydes are one of the predominant volatile classes in pulses; however, their concentration varies by pulse type. In general, whole peas and dehulled peas contain fewer aldehydes, whereas pea protein concentrates, isolates, and faba beans exhibit higher aldehyde levels. In contrast, common beans, such as black beans, pinto beans, and dark red kidney beans, contain higher percentages of aromatic hydrocarbons instead of aldehydes (Karolkowski et al., 2021). Ma Zhen et al. (2016) reported that among common beans, untreated navy bean flour had the highest total aldehyde content, while red kidney beans had the lowest. Among pulses, chickpeas

contain the highest relative percentage of acetic acid, which imparts a vinegar-like odor, compared to high- and low-tannin faba beans (Akkad et al., 2019; Azarnia et al., 2011). Faba beans tend to have lower concentrations of styrene, cumene, and p-xylene and lack volatile compounds such as 1,2,3-trimethyl benzene and 1,3,5-trimethyl benzene, which are often found in common beans (Oomah et al., 2007, 2011). Geosmin, an oxygenated hydrocarbon responsible for a musty off-flavor, has been detected in dry white navy beans at concentrations above the sensory threshold (Buttery et al., 1975).

Alcohol, alkane, and ester content also varies by pulse cultivar. Among common beans, AC Harblack (black beans) and Redhawk (dark red kidney beans) showed alcohol percentages between approximately 3.6% and 5.4%, while other pulses such as pea, chickpea, and faba bean presented significantly higher percentages, ranging from 15.4% to 19.3% (Akkad et al., 2019; Murat et al., 2013; Oomah et al., 2007, 2014; Zhao et al., 2021). High alkane levels have been reported in AC Pintoba and Maverick (pinto beans) and CDC Rio and Onyx (black beans) (Oomah et al., 2007). Regarding terpene content, AC Harblack (black beans) and Redhawk (dark red kidney bean) cultivars have the lowest percentages, whereas CDC Rio, Onyx (black beans), and Maverick (pinto beans) cultivars exhibit similar terpene profiles (Burdock, 2016; Karolkowski et al., 2021; Oomah et al., 2007). Chickpea cultivars also differ in their volatile composition. The Kabuli cultivar demonstrates a higher relative percentage of esters, such as 5-isobutylnonane and 4-dodecanoyloxybutyl dodecanoate, compared to the Desi cultivar (Zhao et al., 2021). Additionally, differences were observed in the percentages of octanal, nonanal, and (Z)-2-decenal, with (E,E)-2,4-nonadienal absent in the Desi cultivar (Zhao et al., 2021). Faba bean flours prepared from different cultivars showed significant variations in 1-octen-3-ol (mushroom-like) aromas.

Thus, understanding the role of pulse genetics is essential for optimizing volatile profiles, which is critical for enhancing sensory quality and promoting the use of pulses in diverse food applications.

Impact of harvest year and storage

The harvest year significantly influences the volatile profiles of pulses due to variations in environmental factors such as soil composition, temperature, precipitation, and crop management practices.

When comparing the volatile profile of pulse samples from consecutive years, distinguishing the effects of harvest year from storage duration before analysis is challenging, and most research

primarily focuses on peas. Manouel et al., (2024) reported that the newer 2022 harvest and 2020 harvest sample exhibited the higher concentrations of unsaturated fatty acids, particularly linolenic and linoleic acids, and elevated LOX activity, while the oldest sample from 2018 showed the lowest activity. The higher LOX activity observed in newer pulse harvests, compared to older crops, is likely due to the enzymatic degradation that occurs over time, while differences in fatty acid compositions among pea seeds across harvest years and locations are primarily influenced by varying weather conditions. Trindler, Kopf-Bolanz, et al. (2022) observed that enzymes such as LOX and peroxidase lose their activity during storage. These changes are more pronounced in older harvests stored under suboptimal conditions, as seen in studies on faba beans and chickpeas (Akkad et al., 2021; Noordraven et al., n.d.).

Beany volatile compounds such as aldehydes, alcohols, and aromatic compounds were more closely associated with older seeds from 2018 and 2019 harvests. Manouel et al. (2024) found that hexanal concentration in pea flours followed the order 2018 > 2019 > 2020 > 2022, demonstrating that seed age plays a critical role in volatile compound formation. Similarly, the Eclipse and CDC Minuet pea cultivars grown in 2006 had the greatest total RPA of aromatic compounds, sulfur compounds, and ketones, whereas the 2005 crop exhibited the highest RPA of alcohols and aldehydes (Azarnia et al., 2011).

This highlights the importance of studying variations in volatile profiles in pulses stored at different periods to better understand the storage period within which pulse flours can be utilized before off-flavors develop, potentially affecting their sensory quality. Moreover, while pea flour has been extensively studied in the context of crop year variations, there is a lack of literature addressing this phenomenon in other pulse types.

Storage conditions also critically influence the evolution of VOCs in pulses, significantly affecting their sensory quality and the development of off-flavors over time. According to Gao et al. (2020), compounds responsible for the beany flavor are either inherent or emerge from the degradation of fatty acids during storage and processing. Key factors such as temperature, oxygen exposure, moisture levels, and storage duration determine the extent of lipid oxidation and protein degradation, which drive the production of volatile compounds. Pea flours and protein isolates stored at a moisture content of about 13.5% and 30°C for one year were reported to change from a fresh pea odor to a fishy odor, while samples with moisture levels below 10% did not develop unpleasant odors (A. K. Sumner et al., 1979).

Additionally, elevated storage temperatures accelerate lipid oxidation and Maillard reactions, resulting in the formation of aldehydes (e.g., hexanal, nonanal), ketones, sulfur compounds, and furans. Akkad et al. (2021) reported significantly higher concentrations of aldehydes in faba bean flour stored at room temperature compared to refrigerated or frozen conditions. Elevated temperatures and moisture levels intensify the production of unpleasant odor-active molecules, as noted by (Pattee et al., 1982). In contrast, low-temperature storage at 4°C slows lipid oxidation and amino acid degradation, reducing the formation of aldehydes and sulfur compounds in pea seeds stored for 12 months compared to those stored at 22 °C (Azarnia et al., 2011). Other volatile families, such as alcohols, ketones, and furans, are stable at 4°C due to reduced degradation and volatilization rates. High-temperature storage at 22°C and 37°C accelerates lipid oxidation and the breakdown of sulfur precursors, resulting in elevated concentrations of aldehydes and sulfur compounds, while destabilizing other volatile families (Azarnia et al., 2011). In contrast, storage at 4°C slows enzymatic activity, although LOX remain active to some extent, but gradually lose activity over time (Liagre et al., 1996). Freezing unblanched peas at –18°C reduces LOX activity by approximately 80%, maintaining stability for up to a year. Similarly, peroxidase activity decreases continuously, dropping to about 50% over the same period (Gökmen et al., 2005).

Despite these reductions in enzymatic activity, freezing temperatures alone may not be sufficient to preserve optimal pea quality. For instance, unblanched peas stored at –10°C for eight months were deemed inedible, and storage at –26°C for 1–2 months did not fully inhibit the development of off-flavors (Bengtsson & Bosund, 1964). Destructive enzymatic processes, including lipid hydrolysis, can persist even at low temperatures (Bengtsson & Bosund, 1966; Mattick & Lee, 1961). Storage at –30°C appears to significantly suppress volatile formation, offering improved preservation of sensory quality (Bengtsson & Bosund, 1964). To achieve long-term reduction of off-odors, a heat pre-treatment prior to storage at –20°C is essential. While raw peas are prone to developing off-odors during storage, blanched or cooked peas are better preserved, retaining an acceptable odor profile (Rhee & Watts, 1966). Oxygen exposure during storage promotes the formation of sulfur-containing volatiles and ketones, which are associated with rancid and cabbage-like off-notes. Anaerobic storage conditions can mitigate these changes, preserving sensory quality (Noordraven et al., n.d.).

Hence, it is important to study how storage conditions impact the volatile profiles of pulses to identify optimal methods for preserving sensory quality. While research on cooked pea products

and faba beans is extensive, more studies are needed on other pulse flours. Exploring low-temperature, humidity-controlled storage and anaerobic packing solutions could significantly reduce lipid oxidation and off-flavor generation in pulses.

Processing strategies to mitigate off-flavors in pulses

Germination and fermentation

Traditionally, germination and fermentation have been key methods for enhancing the nutritional and sensory properties of pulses by generating aroma compounds and sugars. Germination, commonly known as sprouting, has gained popularity in health foods due to its ability to improve both taste and nutritional value. The germinated grains can be consumed as sprouts or further processed through drying or roasting. Sprouting has long been used to reduce antinutritional factors such as trypsin inhibitors and phytic acid in pulses. Additionally, it breaks down raffinose family oligosaccharides (ROFs) into shorter carbohydrates (Bourré et al., 2019) and reduces phytates, while also mitigating unpleasant beany off-flavors through the degradation of lipids and LOX activity influenced by factors such as light (Eum et al., 2020; Nam et al., 2005) and temperature (V. Kumar et al., 2006) during germination (Cabej, 2019; Roland et al., 2017; P. Singh et al., 2022). Vidal-Valverde et al. (1994) investigated the effects of soaking, cooking, and germination on antinutritional factors in lentils (Lens culinaris var. vulgaris) using distilled water, citric acid, and sodium bicarbonate solutions. They found that soaking reduced phytic acid content without affecting trypsin inhibitor activity, while also increasing tannins and catechins. Subsequent germination and cooking significantly decreased trypsin inhibitor activity and phytic acid levels while further elevating tannin and catechin contents, potentially influencing bitterness and astringency in lentils. Similarly, Fernández et al. (1996) observed increased tannins and catechins in faba beans after soaking in similar solutions, suggesting these compounds may impact the sensory profiles of legumes. Germination improves protein solubility and water-holding capacity by generating free amino acids (Setia & others, 2019). Kaczmarska et al. (2018) demonstrated its positive influence on the flavor profile of soybean seeds by increasing methoxypyrazine content and sweet notes through elevated levels of 2,3-butanedione, guaiacol, and (E, Z)-2,6-nonadienal. Similarly, germination of faba bean flour effectively reduced bitter compounds and beany flavors, such as hexanal, nonanal, 2-heptanone, and 2-pentyl furan (Akkad et al., 2021). Studies on pea varieties by Xu et al. (2019) confirmed that germination reduced off-flavors such as hexanal, (E, E)-2,4-nonadienal/decadienal, 3-methyl-1-butanol, 1-hexanol, and 2-pentylfuran in chickpeas.

Rajhi et al. (2022) found that germination in different faba bean cultivars increased aldehydes, decreased phenols and esters, and formed new flavor compounds such as ketones and alkenes. Using gas chromatography/mass spectrometry-olfactometry (GC-MS/O) Xu et al. (2019), demonstrated that flour from yellow peas and lentils exhibited similar aroma attributes before germination but differed significantly after germination. Flour from germinated seeds showed more pronounced meaty, sweet, and sulfur-like aromas compared to non-germinated lupin seeds (Kaczmarska et al., 2018).

Fermentation is commonly carried out using solid-state or submerged methods, often in the presence of fungi or bacteria that produce protease enzymes (Çabuk et al., 2018; Rahate et al., 2021). The production of protease enzymes partially degrades proteins, enhances digestibility, and inhibits the activity of digestive enzyme inhibitors like trypsin and chymotrypsin (Çabuk et al., 2018; Rahate et al., 2021). Microbial fermentation has been extensively employed to reduce beany flavor components in pulses through two main approaches. The first approach utilizes microbial pathways to degrade beany flavor compounds or their precursors, reducing these compounds below their odor thresholds (Zhu & Damodaran, 2018). The second approach focuses on generating new aromatic compounds during fermentation, which not only mask the original beany flavors but also modify the overall aromatic profile. For instance, Pei et al. (2022) utilized *Lactobacillus rhamnosus* L08 to ferment pea flour, resulting in a significant reduction of unpleasant odorants such as nonanal, decanal, octanal, 1-hexanol, and 2-ethyl-1-hexanol. The fermentation process also increased the diversity of acids and esters while enhancing the amino acid content, emulsion stability, and foam stability of the fermented pea flour. Similarly, El Youssef et al. (2020) observed a significant reduction in the leguminous and green sensory properties of pea protein when co-cultured with lactic acid bacteria (*VEGE 047 LYO*) and yeast strains (*Kluyveromyces lactis Clib 196, Kluyveromyces marxianus 3810, Torulaspora delbrueckii TD 291*). This co-culturing also introduced new sensory characteristics. (Sun et al., 2022) demonstrated that fermenting soybeans with *Naematelia aurantialba* increased the levels of aldehydes such as pentanal and benzene acetaldehyde, which introduced fruity and sweet aromas that masked the beany and grassy notes associated with hexanal. Additionally, the fermentation process elevated the concentration of 1-octen-3-ol, contributing to a distinct mushroom-like aroma. In agreement with these findings, (Yang et al., 2021) reported that yogurt made from fermented peas reduced beany and grassy off-flavors caused by 1-hexanol and (E)-2-hexenal, while

generating sweet, cheesy, and buttery aromas from volatile compounds like acetoin and 2-pentanone.

Overall, these studies highlight that germination and fermentation represent promising strategies to enhance the sensory and nutritional attributes of pulses by mitigating off-flavors, reducing antinutritional factors, and introducing desirable flavor compounds, thereby broadening their appeal and versatility in various food applications.

Thermal treatment

Heat treatments are widely used to modify the sensory and structural properties of pulses, offering an economical and efficient method to mitigate off-flavors. Elevated temperatures facilitate lipid and amino acid degradation reactions, leading to the formation of odor-active molecules that influence flavor profiles (Murat et al., 2013). Common thermal processes, including boiling, roasting, blanching, UHT treatment, and spray drying, induce structural changes in pulse proteins. These changes involve partial denaturation, reducing α-helix structures while increasing β-sheets, β-turns, and random coils, which can enhance protein interaction with flavors (Tang et al., 2019). However, excessive heating can lead to protein aggregation or further denaturation, which may decrease flavor-binding capacity by increasing the content of β-sheets in the protein structure. (K. Wang & Arntfield, 2015) demonstrated that extended heating increased the interaction of aldehydes, such as hexanal, heptanal, and octanal, with canola protein isolate, while reducing ketones like 2-octanone due to protein aggregation. Similarly, hexanal was observed to bind irreversibly to pea protein isolate, likely due to the availability of hydrophobic binding sites, thereby enhancing flavor retention. Heat treatments also impact enzyme activity in pulses.

While both wet and dry heat treatments influence volatile composition, they differ in their mechanisms and resulting flavor profiles. Wet heat treatments, such as boiling and autoclaving, primarily function by the development of stable lipo-protein complexes, and leaching of volatiles, whereas dry heat treatments, like roasting inactive enzymes and promote Maillard reactions that generate pyrazines, leading to more complex aroma development.

Wet heating

Wet heating methods, such as cooking pulses in water (boiling), autoclaving, and steaming are widely utilized to reduce off-flavors in pulses by protein denaturation and inactivating key enzymes like LOX and peroxidase, which contribute to fatty acid oxidation and the formation of undesirable aromas. Ma Zhen et al. (2016) examined the effects of wet heating on the volatile

flavor profiles of various pulses, including navy beans, red kidney beans, green lentils, and yellow peas. The study found that cooked samples produced through soaking and boiling exhibited a reduction in total volatile concentration compared to untreated samples. This reduction was attributed to protein denaturation, which led to the formation of lipoprotein complexes and altered the intensity of flavor compounds. Studies indicate that blanching at 90–100°C for 60 seconds deactivates LOX and reduces peroxidase activity to below 2% (Gökmen et al., 2005; RHEE & WATTS, 1966). Further research by (Gökmen et al., 2005) indicated that blanching at 80°C for 2 minutes eliminated LOX activity while reducing peroxidase activity to below 10%. However, Williams et al. (1986) observed that certain LOX and peroxidase enzymes exhibited high thermal stability, particularly in whole peas compared to homogenized ones, emphasizing the importance of optimizing blanching conditions. Wet heating techniques such as blanching and steaming have also been particularly effective in mitigating off-flavors in peas and navy beans (Bourré et al., 2019).

Despite the reduction in LOX activity and overall volatile concentrations, wet heating often increases sulfurous compounds, contributing to undesirable sensory attributes. Compounds such as dimethyl sulfide and dimethyl trisulfide can impart metallic, cabbage, egg, and onion-like off-flavors, which are highly disliked by consumers (Chigwedere et al., 2022; Vurro et al., 2024). Mishra et al. (2017) reported that autoclaved red kidney beans developed an aroma characterized as earthy and beany. This was attributed to the increased presence of methanethiol, methional, diethyl sulfide, dimethyl disulfide, and dimethyl trisulfide, which were identified as key contributors to the “cooked kidney bean” aroma.

Overall, wet heating methods effectively inactivate LOX and reduce total volatiles, but they may also increase sulfurous volatiles, requiring further optimization to minimize their impact on sensory quality.

Dry Heating

While boiling effectively reduces total volatile concentrations and mitigates off-flavors, dry heating methods, particularly roasting, offer additional advantages. Roasting is often favored as a convenient pre-treatment method prior to milling pulses and incorporating them into various plant-based, gluten-free products. The effectiveness of roasting depends significantly on the method and technology employed. For instance, Revtech roasters provide advantages such as low energy consumption, uniform heating, and minimal maintenance (Revtech, 2015). Infrared (IR) roasting

further enhances efficiency by preventing overheating and oxidation, reducing energy costs, and improving product quality (Rahimi et al., 2018). For instance, Shariati-Ievari et al. (2016) examined the impact of infrared heat treatment on LOX activity and volatile compounds in green lentils during micronization. The study revealed a significant reduction in LOX activity at 130°C, with further decreases observed at 150°C compared to untreated flour. This reduction was accompanied by lower levels of hexanal and 2-hexenal. Burgers made with heat-treated lentil flour exhibited good overall flavor and acceptability, whereas those made with untreated flour retained a pronounced beany off-flavor (Der, 2010). Similarly, Navicha et al. (2018) found that soybeans roasted at 110–120°C for extended durations exhibited a marked reduction in beany flavors due to LOX inactivation. Bi et al. (2021) also highlighted the effectiveness of roasting in transforming the odorants of raw adzuki beans from "green" and "grassy" to "roasted" and "nutty," further solidifying its suitability as a processing technique for enhancing flavor properties. Roasting not only reduces undesirable flavors but also enhances the concentration of volatile compounds, particularly pyrazines, which mask beany flavors and contribute to a more appealing flavor profile (Kato et al., 1981). However, it can also increase sulfur compounds that intensify beany off-flavored notes. Ma Zhen et al. (2016) observed that roasting navy beans, red kidney beans, green lentils, and yellow peas significantly increased total volatile concentrations compared to non-roasted samples. This increase was characterized by a reduction in alcohols and the emergence of pyrazines, which add to the flavor complexity of pulse flours. However, sulfur compounds increased, including methanethiol, which has an objectionable odor reminiscent of decomposing cabbage or garlic, particularly in navy beans, red kidney beans, and yellow peas. Roasting has been identified as a potential method to mitigate beany off-flavors in lupin seeds (*Lupinus albus* cv. Multolupa). Yáñez et al. (1986) examined the effects of roasting lupin seeds at temperatures of 80–90°C for varying durations. While longer roasting times (20–40 minutes) significantly reduced protein quality, a shorter roasting time of 10 minutes was recommended for off-flavor reduction. However, sensory evaluations were not conducted to confirm this finding. Roasting has been shown to reduce aldehydes, alcohols, and ketones while increasing the concentrations of pyrazines and furanoids would in soybeans roasted at temperatures between 140 and 230°C as demonstrated by (Cai et al., 2021). Similarly, Frohlich et al. (2021) found that roasting navy beans, yellow peas, and faba beans significantly diminished beany and bitter flavors in pita bread made with pulse flours. Additionally, Young et al. (2020) reported that bread made with roasted pea flour exhibited

less intense pulse aromas and off-flavors compared to bread made with untreated peas. In summary, careful control of roasting conditions is necessary to minimize the formation of sulfurous notes and preserve overall product quality.

In conclusion, processing methods like germination, fermentation, wet heating, and dry heating significantly influence the sensory and nutritional profiles of pulses. While these methods reduce off-flavors and enhance desirable attributes, challenges such as the formation of sulfur-like notes persist. Future research should focus on optimizing processing parameters to balance flavor improvement with the minimization of undesirable compounds, thereby expanding the utility of pulses in diverse food applications.

Methods of off-flavor analysis

Traditionally, the profiling of taste and aroma attributes has been conducted using sensory evaluation (Ashurst, 1999; Lopetcharat & McDaniel, 2005). Sensory analysis still remains one of the most frequently used methods and is considered the benchmark for food quality evaluation. However, this method has several limitations (Ashurst, 1999; Shurmer & Gardner, 1992) including high cost and time required, and lack of direct information on causal molecules. Furthermore, because sensory analysis is time-consuming and costly, it is unsuitable for real-time or online monitoring. To address these limitations, analytical techniques have emerged as more efficient methods for evaluating the VOCs responsible for flavor in pulses and other food products. Chromatographic techniques, particularly GC-MS, are widely utilized for identifying and characterizing volatile compounds in food due to the high separation power of the GC system, which is complemented by the high sensitivity and identification capability of MS. The combination of gas chromatography and olfactometry (GC-O), introduced by Fuller et al. (1964) marked a significant breakthrough in aroma research by enabling the identification of specific odor-active compounds. In addition to GC-O, instruments based on electronic sensors, such as electronic noses (e-noses) and electronic tongues (e-tongues), are increasingly used as alternatives. These techniques not only complement traditional sensory methods but also provide practical solutions for high-throughput and real-time flavor evaluation in food research and development.

Traditional VOC analysis methods

GC is the most used method for characterization and quantification of individual VOCs within complex blends, particularly in studies involving pulses (Jansen et al., 2011). During VOC analysis it accurately samples reactive compounds that are difficult to detect directly, while maintaining

sensitivity even at low concentrations (Dudareva et al., 2006; Materić et al., 2015; Qualley & Dudareva, 2009; Tholl et al., 2021). In GC-MS, an inert carrier gas, typically helium, acts as the mobile phase, facilitating VOC transport through a column containing a stationary phase made of a polymer-coated solid support. The properties of the column, including its length, diameter, and stationary phase composition, are crucial in determining the separation efficiency of volatiles (X. Liu et al., 2012). VOCs are separated based on their retention times as they elute from the column and are subsequently identified and quantified using a mass spectrometer or another detector (Materić et al., 2015).

A fundamental step in volatile analysis is the extraction of volatiles from the sample, which can be achieved through chemical extraction or headspace collection. Chemical extraction methods utilize solvents to isolate volatiles, whereas headspace techniques collect volatile compounds directly from the gas phase above the sample. Solvent-Assisted Flavor Evaporation (SAFE) is a commonly used chemical extraction technique that combines vacuum distillation and solvent extraction, enabling the isolation of volatile compounds with minimal thermal degradation (Engel et al., 1999). While SAFE allows for quantification using an internal standard, it requires an extended extraction time and the use of organic solvents, which may introduce additional complexity (Murat et al., 2012). Previous studies have used SAFE in combination with GC-MS to assess volatile profiles in dehulled pea flour (Murat et al., 2013).

Headspace sampling methods are generally categorized into two main types: static and dynamic. Static sampling uses Solid Phase Microextraction (SPME), which has been widely utilized due to its simplicity, rapidity, and effectiveness in preventing impurities from continuous air streams. SPME is particularly well-suited for detecting low-abundance VOCs without requiring solvents, as the molecules are concentrated on the SPME fiber. SPME allows for the rapid and efficient collection of VOCs, achieving detection limits in the parts-per-billion by volume (ppbv) range. SPME is particularly valued for its portability and its ability to integrate collection, concentration, and VOC introduction into a single stage, significantly reducing preparation time while enhancing sensitivity compared to other methods (Papet et al., 2010; Rering et al., 2020; Vangoethem, 2017; Vas & Vekey, 2004; Z. Zhang & Li, 2010). SPME involves the adsorption and subsequent thermal desorption of volatile compounds from an inert fiber coated with adsorbents of varying polarity and thickness, tailored to the specific type and concentration of the targeted compounds (Tholl et al., 2021). These adsorbent phases include diverse polymers like polydimethylsiloxane (PDMS),

polyacrylate (PA), or polyethylene glycol (commonly referred to as CW or carbowax), as well as porous polymers such as divinylbenzene (DVB) or carboxen (CAR) (Jansen et al., 2011). PDMS, DVB, and CAR are among the most commonly used materials for extracting volatiles from pulses (Murat et al., 2012).

On the other hand, dynamic headspace sampling (DHS) allows for a more exhaustive extraction of VOCs compared to static techniques. In DHS, an actively pumped air stream entrains VOCs and directs them toward a trap via a packed cartridge, enabling a greater capture of volatiles (Stierlin, 2020). During this process, volatiles adsorb onto a polymer within a closed chamber featuring continuous air circulation. The trapped volatiles can then be eluted from the adsorbent matrix using solvent extraction or thermal desorption for subsequent GC analysis (Tholl et al., 2006).

A significant advancement in aroma research was the introduction of gas chromatography-olfactometry (GC-O) by Fuller et al. (1964), a technique that combines the resolution power of capillary GC with the selectivity and sensitivity of the human nose (Plutowska & Wardencki, 2008, 2012). GC-O employs the human nose as a detection device, operating in parallel with standard chromatographic detectors such as flame ionization detectors (FID) or mass spectrometers. This technique enables the rapid identification of odorant zones in a chromatogram. During analysis, a trained evaluator or panel detects the aromatic impressions of the eluate from the column and correlates these impressions to retention times. For instance, Xu et al. (2019) utilized HS-SPME-GC-MS/O to characterize changes in the volatile components of germinated chickpea, lentil, and yellow pea flours over six days of germination. The study revealed that lentil and yellow pea flours exhibited similar aromatic profiles, while chickpea flours showed a decrease in beany flavor compounds alongside the emergence of unpleasant flavors. Six beany flavor markers—hexanal, (E, E)-2,4-nonadienal, (E, E)-2,4-decadienal, 3-methyl-1-butanol, 1-hexanol, and 2-pentyl-furan—were identified and used to quantify beany flavor formation during germination. This highlights the utility of GC-O in identifying key odorants and monitoring flavor changes during food processing.

Novel VOC sensing methods

While traditional methods for VOC detection offer numerous advantages and a broad range of applications, they are often associated with drawbacks such as high cost, bulky equipment, and the need for specialized expertise and training. As a result, there is a growing demand for inexpensive,

portable, and user-friendly alternatives. One promising approach involves the use of gas-sensing technologies to detect VOCs (Fang & Ramasamy, 2015; Liu et al., 2012; Tisch & Haick, 2010). Increasingly, novel equipment based on electronic sensors is being utilized. Instruments such as the electronic nose (e-nose) and electronic tongue (e-tongue) have gained traction for their ability to perform rapid and objective analyses, making them invaluable for flavor profiling in food products (Ciosek et al., 2004, 2006; Deisingh et al., 2004; Rodríguez Méndez et al., 2010). The e-nose is designed for the analysis of volatile compounds in the gaseous phase without separating the individual components, while the e-tongue focuses on medium- and low-volatility compounds in the liquid phase, complementing the capabilities of the e-nose (Leake, 2006). Both devices utilize arrays of non-selective gas or liquid sensors paired with a pattern recognition system, enabling the identification of both simple and complex taste and aroma profiles (Rodríguez Méndez et al., 2010). The e-nose is particularly noteworthy for its speed, ease of operation, and non-invasive nature, making it a practical alternative to sensory analysis (Mielle, 1996). The sensors, under the influence of an odor stimulus, generate a unique "fingerprint" that can be classified and identified using a database and trained pattern recognition systems (Martí et al., 2005; Shurmer & Gardner, 1992). Recent advancements have introduced complementary technologies, including e-nose systems based on mass spectrometry or fast gas chromatography (Wilson & Baietto, 2009).

Depending on their operational principles, e-nose sensors can be categorized into three groups: conductivity sensors, gravimetric sensors, and optical sensors (Plutowska & Wardencki, 2012). Conductivity sensors operate based on changes in conductivity or resistance when exposed to gases. They often use materials such as conducting polymers (CP) or metal oxide semiconductors (MOS). Gravimetric sensors detect mass changes in the piezoelectric sensor coating caused by gas absorption, leading to alterations in resonant frequency when exposed to VOCs. Optical sensors rely on changes in chemical properties, such as reactivity, redox potential, and acid-base interactions. They incorporate a wavelength-selectable light source, a light detector, and sensor materials that interact with gases. Techniques such as colorimetry and fluorometry are commonly used to analyze signals from optical sensors. The analysis of signals from artificial nose and tongue systems involves signal processing and pattern recognition, often through comparison with a standard. Preliminary analysis focuses on smoothing sensor signals, averaging responses, and minimizing carryover effects from previous measurements (Ortega et al., 2000). The raw sensor

responses, often noisy, are refined during feature extraction, which reduces dimensionality and enhances data usability. Feature extraction methods can be divided into quantitative techniques, which construct databases of known samples, and pattern analysis methods like principal component analysis, as well as discriminant function analysis and canonical correlation analysis (Ortega et al., 2000; Pearce et al., 2003; Röck et al., 2008). Signal analysis techniques for e-nose data fall into three categories: graphical, multi-variable, and network analysis. Among these, partial least squares regression (PLS) stands out as a robust method in chemometrics, combining features of multiple linear regression and PCA to handle collinear data and reduce noise. PLS has been widely applied to estimate sensory panel indicators from e-nose data, demonstrating its utility in reducing calibration efforts while maintaining accuracy (Fujioka, 2021; Geladi & Kowalski, 1986; Lozano et al., 2007). While PLS is not inherently unique to e-nose applications—a key advantage of e-nose over HS-SPME-GC-MS lies in its ability to rapidly classify and correlate sensor activation patterns with sensory attributes, offering a time-efficient approach for flavor profiling and sensory evaluation.

Comparison of traditional and novel methods

Cai et al. (2021) compared the utility of e-nose and HS-SPME-GC-MS techniques in a study investigating the effects of roasting levels on the physicochemical, sensory, and volatile profiles of soybeans. They utilized a commercial PEN3 e-nose equipped with 10 semiconductor metal oxide chemical sensors designed to detect specific volatile substances in the headspace gas of roasted and unroasted soybean flours. This rapid screening approach identified overall volatile profile differences and provided holistic aroma insights. Additionally, HS-SPME-GC-MS analysis was performed using a DVB/CAR/PDMS fiber needle for VOC extraction, followed by GC-MS analysis. This method enabled precise identification and quantification of 41 volatile compounds, including 2,5-dimethylpyrazine, the most abundant compound detected. While GC-MS offers high sensitivity and selectivity for complex mixtures, it is time-intensive due to sample preparation, separation, and data processing. Conversely, e-nose provided rapid, high-throughput screening with simpler operation and lower costs but lacked selectivity due to overlapping sensor responses and reliance on pattern recognition. Similarly, (Asikin et al., 2018) compared the ripening stages of dogfruit *(Pithecellobium jiringa)* and stink bean *(Parkia speciosa)* using HS-SPME-GC-MS and an MS-based E-nose. HS-SPME-GC-MS identified key VOCs, including 3-methylbutanal, acetaldehyde, and sulfurous compounds like 1,2,4-trithiolane, which increased significantly during

ripening. These results provided detailed chemical profiles and insights into the aroma changes. In contrast, the E-nose used discriminant ion masses (e.g., m/z 41, 43, 58, 78, and 124) to produce overall aroma profiles and rapidly differentiate ripening stages through principal component analysis (PCA). The GC-MS approach highlighted specific marker compounds, while e-nose demonstrated its strength in rapid screening and quality control by analyzing overall aroma profiles.

Traditional methods such as GC-MS and GC-O enable simultaneous qualitative and quantitative evaluation of individual aromas after chromatographic separation (Plutowska & Wardencki, 2008). They can determine whether a compound exceeds the sensory detection threshold, its odor characteristics, sensory activity duration, and odor intensity (Van Ruth, 2001). Despite its advantages, results may be unreliable due to its focus on individual compounds rather than the overall sensory experience. This limitation underscores the need for instruments like e-nose, which combines high sensitivity and correlation with human sensory panel data. E-noses offer several advantages, including mobility, short analysis times, lower costs, and ease of use, making them suitable for industrial applications far from well-equipped laboratories and specialized expertise. They enable rapid, high-throughput analysis with high sensitivity, effectively detecting complex odor mixtures without requiring separation. However, their accuracy may be limited by sensor aging, sensitivity to moisture, and partial specificity. In contrast, GC-MS and GC-O excel in providing compound-specific data and detailed insights into the relevance of individual volatiles to aroma (Wardencki et al., 2013). Overall, e-nose instruments are well-suited for rapid screening and high-throughput applications, while GC-MS and GC-O remain useful for in-depth aroma profiling and studies requiring compound-specific analysis (Dymerski et al., 2011; Van Ruth, 2001).

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Chapter 3: Effect of crop year, processing, and cultivar on volatile composition in pulses and pulse flours analyzed by headspace-solid phase microextraction gas chromatography-mass spectrometry

Abstract

America faces a challenge of low pulse consumption due to barriers such as their lengthy cooking times, lack of knowledge on preparation, and aversion to their taste or texture. Incorporating pulse flours into convenience products presents a promising approach to increasing consumption; however, off-flavors hinder their widespread adoption in food formulations. Understanding the factors influencing volatile organic compounds (VOCs) responsible for off-flavor formation is critical for improving the sensory quality of pulse-based products. This study aimed to investigate and quantify the effects of cultivar, harvest year, and processing (roasting and boiling) on the volatile composition of eight pulse cultivars using targeted headspace-solid phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS). Pulse samples were produced by boiling whole or milling into flour, with a subset roasted before milling. The resulting flours were also cooked into model products (porridge: roasted and non-roasted) to assess volatile changes due to roasting and cooking. Results showed significant differences in total estimated volatile concentration across processing treatments and harvest years. Processing significantly reduced aldehydes and alcohols while increasing nitrogenous and sulfurous compounds. Boiling resulted in the lowest in total volatile concentration (1.09e-08 mol/L), whereas the non-roasted product exhibited the highest concentration (3.51E-07 mol/L), followed by the roasted product (1.06E-07 mol/L), milled roasted flour (1.03E-07 mol/L), and milled non-roasted flour (5.33E-08 mol/L). Hierarchical clustering and principal component analysis revealed separation of samples by harvest year and distinct volatile profiles across cultivars, suggesting that environmental and post-harvest conditions influence volatile composition over time. These findings highlight the influence of cultivar selection, harvest year, and trade-offs due to processing on pulse volatile profiles, providing insights that can mitigate off-flavor formation and support the development of more widely accepted pulse-based products.

Introduction

Pulses are dry, edible seeds of leguminous crops, including dry beans, peas, chickpeas, and lentils. Their incorporation in food products is driven by increasing consumer demand for plant-based diets, influenced by health and environmental concerns (Chigwedere et al., 2022). Pulses and pulse flours are rich in protein (17%–30%) and complex carbohydrates (60%–67%), including both soluble and insoluble fiber, and provide a valuable source of essential vitamins and minerals (J. Boye et al., 2010; Campos-Vega et al., 2010; Tosh & Yada, 2010; Vaz Patto et al., 2015; N. Wang & Daun, 2004). In addition to their nutritional benefits, pulses contribute to sustainable agriculture by improving soil health through nitrogen fixation and phosphorus release (Nulik et al., 2013). Their genetic diversity also supports climate change adaptation, allowing for the selection and breeding of varieties suited to diverse environmental conditions (Russel, 2015).

Milling pulses into flour has facilitated their incorporation into cereal-based products, enhancing nutritional value and fortifying food formulations (Chigwedere et al., 2022). While the popularity of pulses is rising, their full potential as whole foods or ingredients remains underutilized due to sensory challenges such as off-flavors, described as “beany” and “grassy” in pinto bean flour-based cookies (C. W. Simons & Hall, 2018) or “bitter” in lupin and cowpea-based beverages (Nawaz et al., 2022), limiting wider consumer acceptance. Consequently, as the food industry continues to explore plant-based ingredients, improving the sensory properties of pulses is essential to meet consumer expectations.

Volatile organic compounds, particularly those with low odor thresholds, are key contributors to off-flavors in foods (Roland et al., 2017). Volatile compounds in legumes primarily originate from three sources. The first and most significant source is the oxidation of free fatty acids (FFAs). Lipases hydrolyze lipids into FFAs like oleic, linoleic, and linolenic acids (Dundas et al., 1978), which are then oxidized by lipoxygenase (LOX) or through auto-oxidation in the presence of heat, light, or metal ions (Frankel, 1980). This process generates hydroperoxides, which degrade into various volatile compounds, including aldehydes, alcohols, ketones, and furans (Clemente et al., 2000; Karolkowski et al., 2021). The second source is the degradation of free amino acids (AAs) into aldehydes, alcohols, acids, and pyrazines (Jakobsen et al., 1998; Spinnler, 2011). This can occur via plant metabolism, microbial degradation (Ehrlich-Neubauer pathway), or Maillard reactions at different temperatures (Bader et al., 2009; Rizzi, 1990). The third source is the breakdown of carotenoids, leading to the formation of terpenes (Maccarrone et al., 1994).

The abundance and composition of volatile compounds in pulses are influenced by multiple factors, including cultivar, growing location, crop year, storage conditions, and processing treatments (Azarnia et al., 2011; Ma et al., 2016; N. Singh, 2017). Environmental conditions such as soil composition, temperature, and precipitation impact volatiles across different harvest years. For example, pea cultivars grown in 2006 exhibited the highest total relative peak areas (RPA) of aromatic compounds, sulfur compounds, and ketones, whereas the 2005 crop had the highest RPA of alcohols and aldehydes (Azarnia et al., 2011). Similarly, storage conditions significantly impact volatile formation, with exposure to heat, light, and oxygen accelerating the production of undesirable volatile compounds (Azarnia et al., 2011). Additionally, volatile profiles vary among legume cultivars based on the predominant chemical classes. Rajhi et al. (2021) reported that fenugreek was characterized by high levels of apocarotenes and nitrogen/sulfur derivatives, while faba beans, lentils, and chickpeas exhibited the highest concentrations of non-terpene derivatives, including aldehydes, alcohols, ketones, phenols, and hydrocarbons. In contrast, dry bean cultivars such as black and red beans contained elevated levels of oxygenated monoterpenes and phenylpropanoids. Characterization of the volatile profiles of dry beans could be very important in selecting and marketing the right cultivars for targeted food applications.

Several processing techniques have been explored to improve the flavor of pulses by mitigating the formation of off-flavor compounds. Processing techniques such as soaking, blanching, steam heating, and dry heating have been widely studied in peas and chickpeas to reduce off-flavor compounds by inactivating LOX and other enzymes (Roland et al., 2017). Additional studies on processing methods, including roasting, boiling, spray drying, and freeze drying, demonstrated that new flavor compounds, such as pyrazines and alkylated pyrazines, develop during roasting and cooking, potentially masking the beany flavors associated with aldehydes, alcohols, and sulfur compounds (Ma Zhen et al., 2016). Although processing plays a key role in shaping flavor development of pulse flour, the changes in volatile compounds that occur during the final cooking step remain insufficiently explored, particularly in dry beans.

Headspace-solid phase microextraction (HS-SPME) is one of the most commonly applied techniques to extract volatile compounds. This technique can be used in combination with Gas Chromatography-Mass Spectrometry (GC-MS) where volatiles in the vapor phase are adsorbed onto a fused-silica fiber and then desorbed into the GC injector, where they are separated and identified using MS (Makhlouf et al., 2024). GC-MS has been applied in studies on various pulses,

including faba beans (Akkad et al., 2019, 2021; Oomah et al., 2014), peas (Azarnia et al., 2011), chickpeas (Zhao et al., 2021), and common beans such as black beans, pinto beans, and dark red kidney beans (Oomah et al., 2007) due to its powerful separation abilities and robust identification capabilities.

Therefore, the specific objectives of this study were to: (1) compare the volatile profile of eight selected pulse cultivars, (2) evaluate the effect of processing (roasting, and boiling), and (3) crop year on volatile compounds in the pulses using HS-SPME-GC-MS.

Materials and Methods

Germplasm selection and seed production

To assess the impact of cultivar and crop year on volatile profiles, seven bean cultivars grown during two different years (2022 and 2023) and one chickpea cultivar obtained from the market were studied. The Kabuli chickpea (Sierra) cultivar grown in 2022, obtained commercially, was chosen because of its importance in commercial production in the western U.S., while the other seven bean varieties chosen for their adaptation to Michigan dry bean agricultural conditions, and favorable agronomic characteristics and competitive seed yields. The eight pulse varieties chosen for this study are listed in Table 3.1

Table 3.1: Market class, abbreviations, and genotypes of the eight pulse varieties included in this study, with genotypes grown during the 2022 and 2023 crop years.

Market Class	Abbreviation	Genotypes grown in 2022	Genotypes grown in 2023
Navy bean	N	Alpena	Alpena
Otebo bean	O	Samurai	Samurai
Great Northern bean	GN	Powderhorn	Powderhorn
White Kidney bean	WK	WK 1601-1	WK 1601-1
Mayacoba bean	MY	Y 1802-9-1	Y 1802-11-2
Manteca bean	MN	Y 1608-7	Y 1608-14
Cranberry bean	CR	CR 1801-2-2	CR 2111-1
Chickpea	CHKP	Sierra	-

The seven dry bean varieties were grown at the Michigan State University Montcalm Research Center in Entrican, Michigan in 2022 and 2023. The seeds were planted in a randomized complete block design with three field replications on June 10, 2022, and June 14, 2023, respectively. The plot consisted of 4 rows that were each 6.1 m long, with the center two rows containing the experimental lines and the outer two rows a standard kidney bean border. Recommended field

maintenance practice was followed for weed and insect control and fertilization. Supplemental overhead irrigation was provided when needed. On September 29, 2022, and on October 11, 2023, respectively, the seeds were directly harvested with a Hege 140 plot combine harvester. Seed samples were cleaned by hand to remove gravel and damaged or foreign seeds, and cleaned samples were stored in paper bags at room temperature (22°C) until volatile analysis. The light seed coat color of specific market classes such as white colored beans- Navy, Otebo, Great Northern, and White kidney were selected due to their potential for easier adoption as flour.

Sample preparation

Five types of samples were prepared for HS-SPME-GC-MS analysis from each of the eight pulses, namely, non-roasted pulse flour (NRF), roasted pulse flour (RF), non-roasted pulse flour porridge (NRP), roasted pulse flour porridge (RP), and boiled pulses (BP).

The dry pulses were cleaned by rinsing under distilled water and then laid out on a sheet tray lined with a paper towel. A portion of the sample for each pulse type was subjected to dry heat roasting in an oven (Fisher Scientific Isotemp Gravity Oven, 100 L) at 110°C for 70 minutes, followed by a 4-hour cooling period. Both the non-roasted and roasted pulses were milled into flour using a hammer mill (Kinematica PX-MFC 90 D, Bohemia, NY) with a 0.5 mm sieve to obtain non-roasted pulse flour (NRF) and roasted pulse flour (RF), respectively.

The NRF and RF samples were stored in resealable polyethylene plastic bags under refrigeration at 2°C to minimize volatile loss (Akkad et al., 2022). For pulses harvested in September 2022, milling into flour occurred in March 2023 (6 months post-harvest), and GC-MS analysis was conducted in April 2024 (18 months post-harvest). Similarly, for pulses harvested in October 2023, milling into flour occurred in April 2024 (6 months post-harvest), with GC-MS analysis performed in September 2024 (12 months post-harvest). The NRF and RF samples were transferred from refrigeration to room temperature (22 °C) thirty minutes prior to porridge preparation and analysis by HS-SPME-GC-MS.

To investigate the effects of cooking on volatile compounds of pulse flours, model products in the form of porridges were prepared from both NRF and RF samples using a standardized procedure. Porridges were selected as the model system due to their simplicity, as water is the only added ingredient. For porridge preparation, 50 g of NRF or RF flour was mixed with 250 mL and stirred for 7 minutes on an MSE PRO LCD 4-Channel Digital Magnetic Hotplate Stirrer to ensure uniform dispersion of the flour in the water and to prevent the formation of lumps. Subsequently, 300 mL

of distilled water was added, and the mixture was cooked at an average temperature of 150°C and 1500 rpm for approximately 25 minutes. This resulted in two types of well-mixed porridges: non-roasted porridge (NRP) and roasted porridge (RP).

In addition to the porridge samples, cleaned pulses were cooked by boiling to create boiled pulse (BP) samples. Pulses were soaked in distilled water for 12 hours at room temperature using a 1:3 seed-to-water ratio. After draining the soaking water, pulses were boiled in distilled water, maintaining the same seed-to-water ratio (1:3), using a Duxtop 1800W Portable Induction Cooktop Countertop Burner. Cooking times were determined using a Mattson pin drop cooker and varied by cultivar: Otebo (16 min), Navy (24 min), Great Northern (23 min), White Kidney (30 min), Chickpea (45 min), Manteca (20 min), Mayacoba (33 min), and Cranberry (50 min).

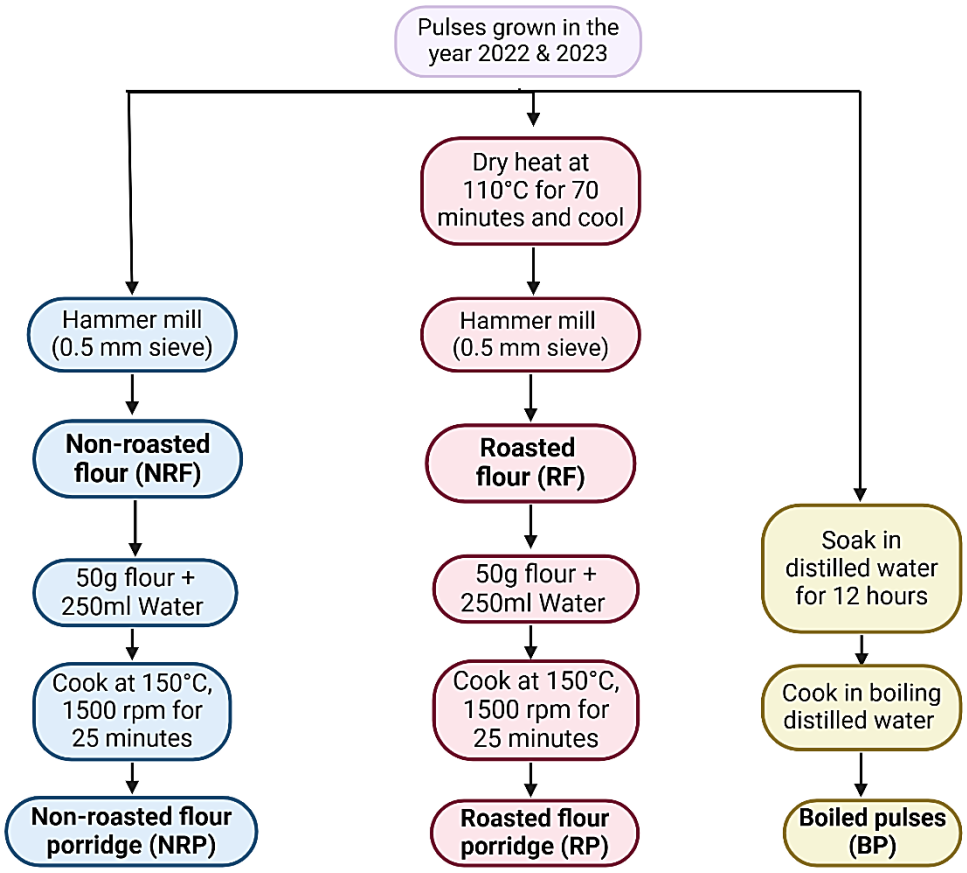

Figure 3.1: Flowchart of sample preparation methods for five types of samples, namely NRF, RF, NRP, RP, and BP. Each sample type was prepared from each of the 7 beans, namely Navy, Otebo, Cranberry, Manteca, Mayacoba, White Kidney, and Great Northern grown in the years 2022 and 2023, as well as Chickpea (market sample grown in 2022 acquired commercially), for GC-MS analysis.

Solid phase microextraction (SPME)

NRP, RP, and BP samples were prepared fresh on the day of analysis, immediately transferred to 20mL glass headspace vials to minimize volatile loss, and analyzed within 8 hours of preparation. The following sample quantities for each of the eight pulses were individually placed into vials: 2g of NRF, 2g of RF, 5g of mashed BP, 5g of NRP (mixed with 1g NaCl), and 5g of RP (mixed with 1g NaCl). Adding salt to the sample matrix during solid phase micro-extraction (SPME) induces a "salting-out" effect, which lowers the partitioning coefficient (K) for some analytes and increases their concentration in the headspace, thereby enhancing extraction efficiency for polar compounds and organic volatiles (Westland, 2021). For increased volatilization of compounds, the samples were first held at 50 °C for 30 min in a water bath. Following this period, the SPME fiber

(carboxen/polydimethylsiloxane/divinylbenzene (CAR/PDMS/DVB) 2 cm, 30/50 µm, Supelco, Sigma–Aldrich) was introduced into the headspace of each sample and exposed for an additional 30 minutes at 50 °C in the same water bath.

Gas chromatography-mass spectrometry (GC-MS) analysis

A gas chromatograph and mass spectrometer were used to separate and detect the headspace aroma compounds and to collect detection frequency data on separated aroma compounds. Absorbed volatiles were desorbed for 20 seconds from the fiber coating by inserting the SPME fiber through a predrilled septum (Thermogreen LB-2, Supelco Co., Bellefonte, PA) and into a glass-lined, split/spitless injector port (200 °C) of a gas chromatograph (Agilent 6890 Gas Chromatograph, Hewlett-Packard Co., Wilmington, DE). Volatiles were separated on a 30 m × 0.25 mm i.d. capillary column (HP-5, Hewlett-Packard) having a film thickness of 0.25 µm. Ultra-purified helium (99.999%) was used as carrier gas at a ramped flow with an initial flow rate of 1.2 mL/min held for 1 minute and then increased at a rate of 1 mL/min to a final flow rate of 1.8 mL/min. The initial linear velocity was 44 cm/s. The initial temperature of the GC oven was 32°C; it was held for 0.25 min, increased to 60°C at a rate of 20 °C/min, and again increased to 150 °C at a rate of 50 °C/min, and finally increased to 280 °C at a rate of 70 °C/min, and held for 2 min. The total analysis time was 7.4 min.

Volatile detection was done using Time of Flight Mass Spectrometry (TOFMS) with an electron ionization source (LECO Pegasus III Mass Spec, Leco Corp, St. Joseph, MI). For detection with mass spectrometry, the ion source was held at 200 °C with electron energy at 70 eV and a scan range of 29–400 mass units; the scan rate was 20 spectra per second with an acquisition voltage of 1500 to 1600V. Preliminary identification of volatiles was performed by comparison of their mass spectra with those of authenticated chemical standards. During the experiment, each volatile compound of interest was identified either by the National Institute of Standards and Technology (NIST) database (V.05) through a mass spectra library search or by comparing retention times (RT) and the mass spectra of the compounds with those of the pure commercial standards (as listed in the following section).

The identified volatile compounds were classified into eight chemical classes: aldehydes, alkanes, alcohols, ketones, terpenoids, sulfurous compounds, nitrogenous compounds, and aromatic compounds. Volatile compound identification was performed using two levels of annotation. Level 1 identification involved comparing the retention times of volatile compounds with those of

authentic chemical standards. Level 2 identification involved putative annotation of metabolites based on spectral similarity to public or commercial spectral libraries without the use of chemical reference standards (L. W. Sumner et al., 2007).

The metabolites identified by level 2 annotation were quantified by calculating the peak areas of each volatile based on the average area under the curve (AUC) from triplicate measurements and reported for a single m/z (mass-to-charge ratio) using the unique mass. The quantification of volatiles identified by level 1 annotation was achieved by estimating the volatile concentration of each compound in a sample using the area ratio method. The AUC of volatiles in a sample was compared to the peak areas of a 25-component external standard mixture prepared at 0.2 μL in 4.4 L. For a volatile compound with known density ρ in g/mL and molar mass M in $\mathrm{g/mol}$, the molar concentration of the standard $C_{standard}$ in mol/L was calculated as:

$$C_{standard} = \frac{\rho \times 0.2\mu L}{M \times 4.4L \times 25}$$

The estimated concentration of the volatile in the sample C_{sample} in mol/L was determined by the area ratio of the sample to the standard as follows:

$$C_{sample} = \left(\frac{AUC_{sample}}{AUC_{\ standard}}\right) \times C_{standard}$$

The final estimated concentration of a volatile compound was calculated by taking the average of the triplicate estimated volatile concentrations in a sample.

Standards

Authenticated pure commercial standards of 2-butanone, 2-methyl butanal, butanol, 2-ethylfuran, 3-methylbutanol, dimethyl disulfide, 1-pentanol, hexanal, (E)-2-hexenal, 1-hexanol, o-xylene, 2-heptanone, styrene, heptanal, methional, 2,5-dimethyl pyrazine, benzaldehyde, 1-octen-3-ol, 6-methyl-5-hepten-2-one, octanal, decane, L-limonene, nonanal, decanal, and geosmin purchased from Sigma-Aldrich (St. Louis, MO, United States) were combined in equal volume aliquots to create a twenty five-component mixture. Every week, 0.2 μL of the mixture was injected on a glass microfiber filter and placed in a glass volumetric flask of 4.4 L fitted with a specially made ground glass stopper containing a gastight Mininert valve (Alltech Associates, Inc., Deerfield, IL). The flask was held at 22 °C until the liquid standards were fully volatilized (Song, et al., 2009).

Statistical Analysis

The GC-MS AUC and estimated volatile concentration data were analyzed using R statistical computing software (version 4.2.2; R Core Team, 2022) to assess sample differences. Analysis of Variance (ANOVA) was conducted using the agricolae v. 1.3.5 (de Mendiburu, 2021) package, followed by Least Significant Difference (LSD) post-hoc multiple comparisons tests ($\alpha = 0.05$). For multivariate analysis, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were conducted using the FactoMineR v. 2.8 (Lê et al., 2008) package. Visualization of PCA results was carried out using ggplot2 v. 3.5.1 (Wickham, 2016).Heatmaps were generated using the pheatmap v. 1.0.12 (Kolde, 2018) package.

A 3-factor ANOVA was used to evaluate the effects of cultivar, processing, and year on the total estimated volatile concentrations of all pulse samples from harvest years 2022 and 2023. The model included two-way interactions (cultivar:year, cultivar:processing, and year:processing) and a three-way interaction (cultivar:year:processing), enabling the evaluation of how these factors and their interplay influenced volatile profiles. For all statistical tests, an α of 0.05 was used to determine statistical significance.

To further evaluate the impact of processing treatments on volatile concentrations across key chemical classes, a separate ANOVA model was applied. The volatiles were grouped by their chemical class for each pulse type from its respective harvest year, and the total estimated volatile concentration per class was calculated by summing all volatiles for each of the chemical classes. One-way ANOVA was conducted with processing as the independent variable, followed by an LSD post hoc test to identify pairwise differences.

To investigate broader patterns in volatile content across two growing seasons from 2022 and 2023, estimated volatile concentration data were mean-centered and normalized prior to PCA analysis. HCA analysis was also applied to cluster samples into subgroups with shared volatile profiles.

For heatmap visualizations, the mean-centered AUC of volatiles identified through level 1 and level 2 annotation was log-transformed to emphasize differences in volatile compound profiles across cultivars in NRF and NRP samples from the 2022 harvest year.

Results and Discussion

A total of 32 volatile compounds were identified across the pulse samples, 25 of which were annotated as level 1 and quantified using authentic chemical standards and visualized in Figures 2, 3, and 5. (E)-2-Hexenal and 1-hexanol were the most abundant volatiles. The identified volatiles included alcohols (5), aldehydes (8), ketones (3), aromatics (4), terpenoids (1), alkanes (1), nitrogenous compounds (1), and sulfurous compounds (2) (Table 3.3). Consistent with previous studies, targeted GC-MS identified alcohols (18.2%), aldehydes (51.7%), and ketones (21.6%) as the most abundant chemical classes as an average across all samples (Khrisanapant et al., 2022; Mishra et al., 2017; Oomah et al., 2007). Volatiles significantly varied across samples, mainly driven by the effects of processing (p=2.2E-17) and harvest year (p=3.3E-11) (Table 3.2).

Table 3.2: Summary of analysis of variance (ANOVA) results in a 3-way ANOVA evaluating the effects of cultivar, year, processing, and their interactions on the total volatile concentrations from HS-SPME-GC-MS analysis. Df = degrees of freedom, SS = sum of squares, MS = mean sum of squares.

Interaction	Df	SS	MS	F-value	p-value
cultivar	7	1.2E-13	1.7E-14	1.7	0.113
year	1	5.2E-13	5.2E-13	50.8	3.3E-11
processing	4	1.1E-12	2.8E-13	27.5	2.2E-17
cultivar:year	7	1.7E-13	2.4E-14	2.4	2.5E-02
cultivar:processing	28	7.6E-13	2.7E-14	2.6	8.1E-05
year:processing	4	6.0E-13	1.5E-13	14.6	3.4E-10
cultivar:year:processing	28	8.7E-13	3.1E-14	3.0	7.0E-06
Residuals	160	1.6E-12	1.0E-14		

Effect of processing on volatile profiles

Figure 3.2 and Figure 3.3 illustrate how the thermal treatment of pulses affects the distribution of volatile compounds. The ANOVA results indicated that processing significantly affected total volatile concentration (p = 2.2E-17) (Table 3.2).

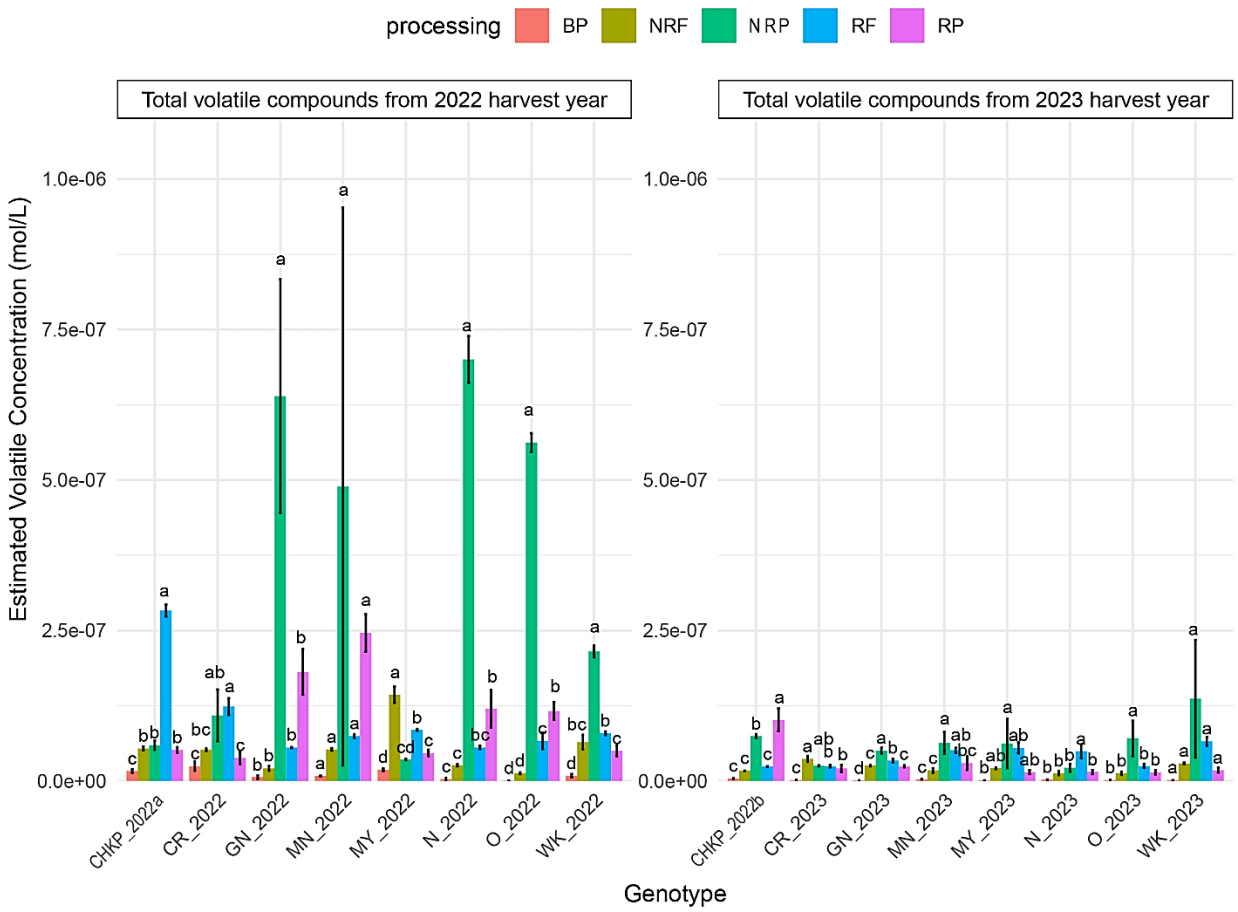

Figure 3.2: Total estimated volatile concentration of pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN) grown in Michigan during the harvest years 2022 and 2023, and a market sample of Chickpea (CHKP) obtained commercially, harvested in 2022. Samples marked 2022 and 2022a were analyzed in April 2024; samples marked 2023 and 2022b were analyzed from August through September 2024. Volatile concentrations are presented for five processing treatments: non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP), and boiled pulses (BP). Results represent the average values from triplicate measurements. Mean values for each pulse type that do not share a letter are significantly different ($p < 0.05$) as determined by the LSD post hoc comparison test.

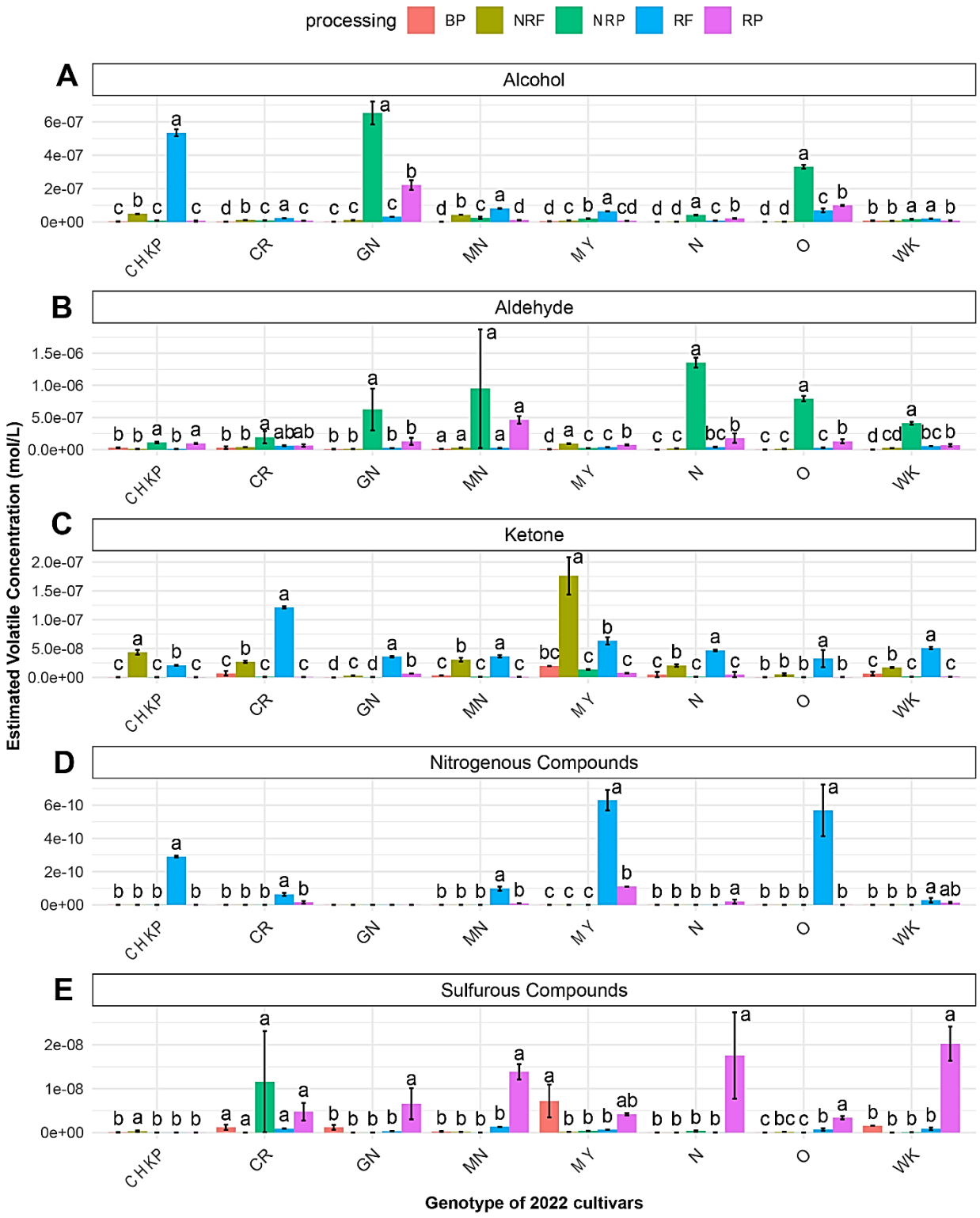

Figure 3.3: Effect of processing (roasting; boiling) on the estimated volatile concentration of (A) alcohols; (B): aldehyde; (C): ketone; (D): nitrogenous compound; (E): sulfurous compound of eight cultivars grown in 2022: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP),

Figure 3.3 (cont'd)

Manteca (MN), Mayacoba (MY), White Kidney (WK), and Great Northern (GN) in non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP) and boiled pulses (BP). Results are the average value from triplicates. For each type of pulse, mean values that do not share a letter are significantly different ($p < 0.05$) as per the LSD post hoc comparison test.

Effect of roasting

Roasted flour

Alcohols and ketones were the most abundant volatiles in roasted flour, accounting for an average of 37% and 30% of the total estimated volatile content, respectively. Generally, ketones and alcohols increased slightly, and pyrazines increased substantially in RF compared to NRF, depending on cultivar type (Figure 3.3A, 3C). Consequently, the total estimated volatile concentration also increased significantly ($p<0.05$) after roasting in RF samples of (CHKP, CR) and white-colored (O) pulses compared to NRF (Figure 3.2).

Interestingly, this increase could be attributed to the formation of a new group of volatile compounds, characterized by a significantly higher concentration of pyrazines due to roasting, in RF samples (Figure 3.3D). These compounds were absent from NRF samples, indicating that pyrazines are primarily formed during roasting. Roasting significantly increased ($p<0.05$) the concentration of nitrogenous compounds in RF samples of yellow-colored (MN, MY), white-colored (O, WK) and other (CHKP, CR), pulse cultivars, compared to NRF (Figure 3.3D). A five-fold increase in nitrogenous compounds was observed in CHKP, MY, and O cultivars (Table 3.3). Nitrogenous compounds, particularly pyrazines, often impart chocolate, roasted nutty, and sharp flavors to pulses (Azarnia et al., 2011). Particularly, 2,5-dimethyl pyrazine, characterized by a nutty, roasted, musty, and grassy aroma (The Good Scents Company) was the most abundant in RF samples of yellow-colored (MN, MY), white-colored (O, WK) and other pulses (CHKP, CR) (Table 3.3).

Additionally, roasting significantly increased ($p<0.05$) total ketones in RF samples of all pulses except MY and CHKP compared to their NRF counterparts (Figure 3.3C). The identified ketones included 2-butanone, 2-heptanone, and 6-methyl-5-hepten-2-one. 2-butanone (camphoreous, acetone, fruity, ethereal) odor was the most abundant ketone in RF samples across all cultivars except MY, CHKP (Table 3.3). Additionally, 2-heptanone, known for its fruity, spicy, cinnamon,

green, and banana-like odor (Burdock, 2016) also increased after roasting in the RF samples of all cultivars compared to NRF (Table 3.3).

Furthermore, roasting also led to a slight but significant increase ($p < 0.05$) in total alcohol content across all cultivars except GN (Figure 3.3A). The alcohols identified in the pulse samples were 1-pentanol, 1-hexanol, 1-octen-3-ol, 1-butanol, and 3-methylbutanol. Among these, roasting increased the concentration of 1-butanol and 3-methyl butanol in RF samples compared to NRF across all cultivars, with the highest concentration of 1-butanol in Otebo and 3-methyl butanol in Great Northern beans (Table 3.3).

Although, in our study, no significant differences in aldehyde concentration were found between NRF and RF samples for any of the pulse cultivars (Figure 3.3B), previously, Ma Zhen et al. (2016) reported higher aldehyde concentrations in roasted navy and red kidney bean flours and Lee et al. (2023) reported elevated levels of hexanal and benzaldehyde in roasted soybeans compared to their raw counterparts.

Our results align with Akkad et al. (2023), who reported a higher relative abundance of pyrazines and ketones in heat-treated faba bean flour crackers than in untreated flour. Similarly, Ma Zhen et al. (2016) found higher alcohol concentrations in roasted green lentils and yellow peas flour than in untreated flour. These findings indicate that roasting fundamentally alters the volatile profile of pulses by inducing several chemical reactions between sugars, proteins, and minerals, alongside the breakdown of hydroxyl amino acids and the degradation of pigments. As a result, roasting leads to the formation of various volatile compounds, including sulfur compounds, pyrazines, pyridines, pyrroles, oxazoles, aldehydes, ketones, phenols, and carbon dioxide (Bhattacharya, 2014). Ketones in legumes primarily form through the oxidation of saturated fatty acids at high temperatures and decarboxylation of 3-oxo-acids (Grebenteuch et al., 2021). Lee et al. (2023) further reported that 2-heptanone, absent in untreated soybeans, appears after roasting. This suggests lipid oxidation (Oomah et al., 2014), and Maillard reactions contribute to its formation. Additionally, alcohol dehydrogenase activity can convert lipoxygenase pathway products, transforming aldehydes or ketones into alcohols (Fischer et al., 2022).

The Maillard reaction, a non-enzymatic browning process driven by amino acids and reducing sugars, is a key driver of pyrazine formation during heat treatment (Yu et al., 2020). A GC-O study by Bi et al. (2020) found that roasted pea flour contained high levels of pyrazines such as 2-ethyl-3,5-dimethylpyrazine and 2,6-dimethylpyrazine, which contributed to nutty and caramel-like

aromas. In contrast, raw pea flour was dominated by 3-methylbutanoic acid and hexanal, which impart fatty, green, and grassy notes. Similarly, Kato et al. (1981) observed that D-methyl- and 2-ethyl-5-methyl-pyrazines increased in roasted soybeans, masking beany flavors produced from aldehydes and alcohols. This suggests that roasting alters the volatile profile of pulses by generating pyrazines with roasted and nutty aromas that may help mask the grassy, green, and beany notes produced from alcohols and aldehydes.

Overall, roasting significantly increased ketone and alcohol concentrations due to lipid oxidation while also driving pyrazine formation through Maillard reactions in roasted pulse flours.

Roasted model product

In the roasted products (RP) made from RF, alcohols and aldehydes were significantly lower ($p<0.05$) while, sulfur concentrations were significantly ($p<0.05$) higher in white-colored (GN, N, O, WK) beans compared to NRP (Figure 3.3E). Additionally, the total volatile concentration of targeted compounds reduced significantly ($p<0.05$) by 70-80% in the RP samples of white-colored beans (GN, N, O, WK) compared to their NRP counterparts (Figure 3.2). This decrease may also be attributed to the targeted GC-MS approach used in this study, which primarily quantified alcohols and aldehydes, leading to an overall reduction in the total estimated volatile concentration. Roasting and subsequent cooking into the model product significantly ($p < 0.05$) reduced the total alcohol concentration by an average of 57% in RP samples of white-colored (GN, N, O, WK) and by 62% in yellow-colored (MN, MY) beans compared to their NRP counterparts (Figure 3.3A). The high standard deviations observed in total volatile concentrations of MN could be attributed to instrumental variation between different days of GC-MS runs and potential inconsistencies in porridge preparation. Aliphatic alcohols such as 1-hexanol, 1-octen-3-ol, and 1-pentanol were markedly reduced, while 1-butanol and 3-methyl butanol were almost absent in RP samples (Table 3.3). Several of these alcohols have been identified as key contributors to beany flavors: 3-methyl-1-butanol, which imparts an alcohol-like odor (Gao et al., 2020); 1-pentanol and 1-octen-3-ol, associated with grassy, beany, and mushroom-like odors (Xu et al., 2019). Additionally, 1-hexanol contributes grassy, green, or leafy odors (Bott & Chambers IV, 2006; Vara-Ubol et al., 2004; Xu et al., 2019). Thus, reducing alcohol content through roasting may help mitigate common off-flavors in pulses.

The aldehydes detected in pulse samples included 2-methyl butanal, hexanal, (E)-2-hexenal, heptanal, benzaldehyde, octanal, nonanal, and decanal. Among these, (E)-2-hexenal, which

contributes to grassy, green, and herbal flavors characteristic of the beany flavor in pulses, was the most abundant volatile and exhibited the highest concentration in the NRP samples of GN, N, and O cultivars (Oomah et al., 2014; Park et al., 2011; Sharan et al., 2022; Y. Wang et al., 2020) (Table 3.3). Roasting specifically decreased the concentration of hexanal (grassy, green, and herbal aroma), (E)-2-hexenal (green, grassy aroma), benzaldehyde (roasted, hazelnut, and almond odors), 2-methyl butanal (pungent, fresh, fruity aroma), decanal (bitter gourd), heptanal (fatty, herbal, green odor) and nonanal (fatty, citrus, green aroma) in RP samples compared to their NRP counterparts (Table 3.3) (Burdock, 2016; The Good Scents Company, 2021; Viana & English, 2021). Aldehydes have been previously reported to produce green off-flavors in peas and beany off-flavors in soybeans (Roland et al., 2017; Sessa & Rackis, 1977). Akkad et al. (2021) identified aldehydes (nonanal, octanal, hexanal, decanal, and 3-methyl butanal) as key contributors to beany flavors in faba bean flours. Hexanal has also been identified as a source of off-flavors in peas; the more hexanal was present, the less the peas were liked (Bengtsson & Bosund, 1966). Thus, roasting may be a valuable pre-treatment method as it significantly reduced ($p < 0.05$) total aldehyde concentrations by an average of 83% in white-colored (GN, N, O, and WK) beans, particularly for those volatile compounds typically perceived as off-flavors (Figure 3.3B). These observed reductions in alcohol and aldehydes may result from the inactivation of alcohol oxidoreductase and lipoxygenases during roasting (Akkad et al., 2023; De Lumen et al., 1978).

On the other hand, roasting significantly increased ($p<0.05$) the concentration of sulfurous compounds such as dimethyl disulfide in RP samples of white-colored (GN, WK, N, O) and yellow-colored (MN, MY) beans compared to their NRP counterparts (Figure 3.3E). Additionally, methional exhibited the highest concentration in RP samples of WK, N, and MY cultivars (Table 3.3). Our targeted GC-MS approach identified a fifty-fold increase in the total sulfur concentration due to roasting and cooking in RP compared to NRP (Table 3.3). Previous research has demonstrated that thermal processing leads to sulfur compound formation. Mishra et al. (2017) detected dimethyl sulfide, diethyl sulfide, methanethiol, dimethyl disulfide, and dimethyl sulfone in kidney beans exclusively after cooking (Chin & Lindsay, 1994). Similarly, Bi et al. (2020) identified dimethyl sulfide, which imparts cabbage, sulfur, and sickly odors, as unique to roasted pea flour. These sulfurous compounds primarily arise from the degradation of methionine and cysteine amino acids during roasting and cooking. Methionine undergoes Strecker degradation during the final stages of the Maillard reaction, converting into methional, which has a low odor

detection threshold (0.2 μg/L) and contributes to sulfurous and beany aromas in cooked kidney beans (Mishra et al., 2019). Further oxidation of methional produces methanethiol, which subsequently forms dimethyl disulfide and dimethyl trisulfide (Chin & Lindsay, 1994).

Our results align with previous studies that have reported reductions in aldehydes, alcohols, and terpenes after cooking, alongside increases in sulfur-containing compounds and pyrazines (Mishra et al., 2017). Similarly, Shariati-Ievari, (2013) demonstrated that burgers made with non-micronized chickpea/lentil flours were characterized by higher concentrations of 'beany' alcohols and aldehydes such as hexanol, 2-hexenal, heptanal, hexanal, octanal, and nonanal compared to micronized flour at 130℃.

These shifts indicate that roasting alters the volatile composition by increasing ketones, alcohols, and pyrazines in flours, but their subsequent cooking further modifies these profiles by decreasing alcohol and aldehydes but increasing sulfurous compounds, resulting in a net decrease in total volatile content for roasted and cooked samples.

Table 3.3: Estimated concentration in mol/L of volatiles quantified using authentic chemical standards across non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP), and boiled pulses (BP) from the pulse cultivars (Cranberry, Great Northern, Navy, Otebo, White Kidney, Manteca and Mayacoba) grown in harvest year 2022 from Michigan and a market sample of Chickpea obtained commercially (harvested in 2022). These samples were analyzed in April 2024. Values represent the average of triplicate measurements grouped by chemical class. nd: not detected. Odor descriptions reflect the top three odor notes as reported by The Good Scents Company (2009).

White colored beans (estimated volatile concentration in mol/L)											
	Great northern bean					White kidney bean					
Compound Name	NRF	RF	NRP	RP	BP	NRF	RF	NRP	RP	BP	Odor Description
ALDEHYDE											
2-Methyl butanal	1.6E-09	3.9E-09	1.0E-09	2.6E-09	nd	1.2E-09	1.1E-08	1.7E-07	1.7E-09	5.3E-10	malty, musty, fermented
Hexanal	8.9E-10	4.8E-09	6.2E-09	3.4E-10	3.2E-10	5.0E-09	7.4E-09	9.1E-09	4.7E-10	1.2E-10	vegetable, aldehydic, clean
(E)-2-hexenal	1.5E-09	2.2E-09	3.0E-07	6.0E-08	3.2E-09	3.2E-09	3.9E-09	2.2E-08	3.1E-08	nd	sweet, vegetable, bitter almond
Heptanal	1.4E-10	3.2E-10	2.0E-10	3.9E-11	nd	4.2E-10	9.8E-10	4.2E-10	3.9E-11	nd	aldehydic, fatty, herbal
Benzaldehyde	1.8E-10	5.0E-10	1.5E-09	5.8E-10	5.8E-10	5.2E-10	9.1E-10	6.8E-10	4.0E-10	2.1E-10	sweet, cherry, nutty
Octanal	1.7E-10	2.6E-10	6.6E-11	2.0E-11	nd	3.9E-10	7.8E-10	6.1E-11	2.6E-11	7.4E-12	aldehydic, fatty, herbal
Nonanal	1.1E-09	1.1E-09	3.7E-10	1.4E-10	1.6E-10	2.1E-09	3.1E-09	5.9E-10	1.6E-10	7.9E-11	aldehydic, fatty, rose
Decanal	8.1E-11	9.7E-11	5.0E-11	2.1E-11	2.9E-11	2.4E-10	3.3E-10	6.4E-11	1.9E-11	nd	sweet, aldehydic, floral
ALCOHOL											
Butanol	8.4E-10	7.0E-10	5.4E-09	nd	nd	1.1E-09	1.0E-09	5.1E-09	3.2E-10	1.2E-09	sweet, fermented, oily
3-Methylbutanol	1.4E-09	1.2E-08	5.4E-09	3.4E-09	3.1E-10	8.2E-10	7.2E-09	8.7E-10	6.0E-10	6.0E-10	musty, vegetable, cocoa
1-Pentanol	2.1E-09	1.8E-09	7.0E-10	9.5E-11	nd	1.1E-09	1.4E-09	3.4E-10	1.9E-11	4.1E-11	sweet, fermented, yeasty
1-Hexanol	9.5E-10	5.4E-10	3.1E-07	1.1E-07	3.8E-10	4.4E-10	3.5E-10	1.7E-09	2.3E-09	1.7E-09	sweet, pungent, herbal
1-Octen-3-ol	1.3E-10	1.6E-10	2.0E-09	5.7E-10	5.7E-11	1.1E-10	8.3E-11	4.0E-10	1.1E-09	1.7E-10	vegetable, mushroom, chicken
KETONE											
2-Butanone	1.3E-09	1.7E-08	1.2E-10	3.2E-09	nd	8.1E-09	2.5E-08	7.2E-10	4.7E-10	3.1E-09	camphoreous, acetone, fruity
2-Heptanone	9.9E-11	3.1E-10	8.2E-12	nd	nd	2.0E-10	4.4E-10	nd	9.1E-12	7.7E-11	sweet, spicy, banana
6-Methyl-5-hepten-2-one	2.1E-11	nd	nd	nd	nd	4.1E-11	4.6E-11	nd	1.6E-11	nd	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	6.6E-11	2.9E-10	1.3E-10	1.4E-11	3.5E-10	4.2E-10	1.5E-09	3.6E-10	2.1E-10	1.7E-10	malty, cocoa, nutty
o-Xylene	7.6E-09	8.2E-09	nd	nd	4.1E-10	3.7E-08	1.3E-08	nd	1.4E-09	nd	geranium
Styrene	7.1E-10	6.1E-10	nd	nd	nd	1.9E-09	1.2E-09	nd	nd	nd	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											

Table 3.3 (cont'd)

L-limonene	7.8E-11	7.7E-12	nd	nd	nd	1.2E-11	1.4E-11	nd	nd	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	5.4E-11	nd	nd	nd	nd	3.4E-12	1.9E-12	nd	2.0E-12	6.2E-12	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	nd	1.5E-10	6.2E-12	3.3E-09	6.0E-10	nd	4.3E-10	3.0E-11	1.0E-08	7.6E-10	vegetable, onion, cabbage
Methional	nd	nd	nd	nd	nd	nd	nd	nd	3.3E-11	nd	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	nd	nd	nd	nd	nd	1.4E-11	nd	6.6E-12	nd	nutty, peanut, musty
White colored beans (estimated volatile concentration in mol/L)											
	Navy bean					**Otebo bean**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	1.7E-09	4.0E-09	5.8E-11	7.5E-12	nd	2.6E-09	2.5E-09	3.6E-09	1.0E-10	nd	malty, musty, fermented
Hexanal	4.3E-09	1.1E-08	3.2E-09	3.0E-10	2.5E-10	1.6E-09	6.2E-09	4.9E-09	1.6E-09	1.8E-10	vegetable, aldehydic, clean
(E)-2-hexenal	nd	nd	6.7E-07	8.9E-08	nd	3.2E-10	3.0E-10	3.9E-07	6.1E-08	nd	sweet, vegetable, bitter almond
Heptanal	4.9E-10	1.1E-09	2.6E-10	2.2E-11	4.7E-11	1.9E-10	1.1E-09	3.1E-10	1.3E-10	9.4E-12	aldehydic, fatty, herbal
Benzaldehyde	3.4E-10	8.1E-10	4.3E-10	2.5E-10	9.2E-11	1.6E-10	9.0E-10	8.2E-10	8.0E-10	5.7E-11	sweet, cherry, nutty
Octanal	3.6E-10	6.4E-10	2.7E-11	8.9E-12	6.1E-11	1.4E-10	2.7E-10	1.1E-10	8.6E-11	nd	aldehydic, fatty, herbal
Nonanal	1.2E-09	2.7E-09	1.2E-09	3.5E-10	1.0E-10	8.9E-10	2.1E-09	5.2E-10	5.7E-10	4.5E-11	aldehydic, fatty, rose
Decanal	8.6E-11	1.9E-10	2.8E-11	9.9E-12	1.2E-11	6.9E-11	1.0E-10	3.6E-11	4.5E-11	8.0E-12	sweet, aldehydic, floral
ALCOHOL											
Butanol	4.4E-10	4.0E-10	nd	5.8E-11	1.8E-11	3.7E-10	2.1E-08	nd	1.3E-10	nd	sweet, fermented, oily
3-Methylbutanol	nd	2.3E-09	2.4E-10	1.9E-09	nd	5.2E-10	1.9E-09	6.5E-11	1.7E-10	nd	musty, vegetable, cocoa
1-Pentanol	5.4E-10	1.1E-09	3.2E-10	2.1E-10	nd	2.5E-10	2.5E-10	3.0E-10	4.6E-11	nd	sweet, fermented, yeasty
1-Hexanol	1.3E-10	1.7E-10	1.9E-08	8.3E-09	8.4E-11	3.5E-10	1.1E-08	1.6E-07	4.9E-08	nd	sweet, pungent, herbal
1-Octen-3-ol	6.2E-11	2.1E-10	1.2E-09	6.3E-10	3.5E-11	7.1E-11	8.0E-10	1.3E-09	6.5E-10	nd	vegetable, mushroom, chicken
KETONE											
2-Butanone	1.0E-08	2.3E-08	3.3E-10	2.3E-09	2.4E-09	2.4E-09	1.6E-08	nd	1.3E-10	1.3E-10	camphoreous, acetone, fruity
2-Heptanone	1.2E-10	1.7E-10	1.9E-11	4.8E-12	nd	9.9E-12	2.4E-10	9.1E-12	nd	nd	sweet, spicy, banana
6-Methyl-5-hepten-2-one	2.0E-11	7.0E-11	nd	nd	1.6E-12	nd	nd	nd	nd	nd	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	1.4E-10	3.3E-10	2.2E-09	4.3E-10	6.7E-11	8.5E-11	1.1E-09	1.6E-10	3.4E-11	2.9E-11	malty, cocoa, nutty
o-Xylene	5.8E-09	6.9E-09	nd	7.7E-09	nd	2.8E-09	4.8E-11	nd	nd	nd	geranium
Styrene	3.4E-10	3.2E-10	nd	nd	nd	4.6E-12	4.6E-10	nd	nd	nd	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh

Table 3.3 (cont'd)

TERPENOIDS											
L-limonene	5.4E-11	1.3E-11	nd	nd	nd	nd	2.4E-11	nd	4.2E-11	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	nd	nd	nd	nd	nd	nd	3.0E-11	nd	nd	nd	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	nd	2.7E-11	1.7E-10	8.8E-09	7.1E-12	5.0E-11	3.4E-10	2.5E-12	1.7E-09	8.9E-12	vegetable, onion, cabbage
Methional	nd	nd	nd	1.2E-12	nd	nd	4.3E-12	nd	nd	nd	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	nd	nd	9.9E-12	nd	nd	2.8E-10	nd	nd	nd	nutty, peanut, musty
Yellow colored beans (estimated volatile concentration in mol/L)											
	Manteca					**Mayacoba**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	2.6E-09	4.0E-09	7.7E-10	1.6E-09	1.2E-09	1.2E-08	5.3E-09	1.3E-09	6.6E-09	5.0E-10	malty, musty, fermented
Hexanal	9.0E-09	6.3E-09	4.5E-09	2.0E-09	1.8E-09	4.7E-09	8.5E-09	1.9E-09	8.4E-10	7.2E-10	vegetable, aldehydic, clean
(E)-2-hexenal	2.5E-10	1.4E-10	4.7E-07	2.3E-07	5.4E-10	2.5E-08	4.4E-10	5.0E-09	2.6E-08	nd	sweet, vegetable, bitter almond
Heptanal	6.9E-10	4.9E-10	1.3E-10	1.3E-10	1.5E-10	4.8E-10	1.1E-09	8.0E-11	9.3E-11	9.9E-11	aldehydic, fatty, herbal
Benzaldehyde	6.7E-10	7.7E-10	4.8E-10	5.7E-10	1.1E-09	1.1E-09	1.2E-09	3.0E-09	2.2E-09	8.2E-10	sweet, cherry, nutty
Octanal	2.3E-10	2.5E-10	5.1E-11	5.9E-11	1.2E-10	2.1E-09	4.3E-10	2.4E-10	4.1E-10	7.7E-11	aldehydic, fatty, herbal
Nonanal	1.0E-09	1.3E-09	2.8E-10	3.9E-10	9.8E-10	1.2E-09	1.7E-09	1.4E-10	3.1E-10	6.0E-10	aldehydic, fatty, rose
Decanal	4.3E-11	1.1E-10	3.2E-11	4.6E-11	8.0E-11	6.0E-11	1.2E-10	1.4E-11	4.3E-11	3.5E-11	sweet, aldehydic, floral
ALCOHOL											
Butanol	8.9E-09	1.8E-08	2.6E-09	nd	3.3E-11	2.1E-09	1.5E-08	3.3E-10	8.7E-10	3.5E-10	sweet, fermented, oily
3-Methylbutanol	1.2E-10	4.6E-09	7.7E-10	1.2E-09	nd	2.0E-10	2.9E-09	1.5E-09	3.5E-10	5.9E-10	musty, vegetable, cocoa
1-Pentanol	1.3E-10	3.8E-10	1.7E-10	5.6E-11	nd	1.3E-10	2.7E-10	3.5E-10	4.1E-11	1.2E-10	sweet, fermented, yeasty
1-Hexanol	9.9E-09	1.6E-08	7.2E-09	3.0E-09	2.4E-10	1.6E-09	1.3E-08	6.2E-09	1.5E-09	1.0E-09	sweet, pungent, herbal
1-Octen-3-ol	2.3E-09	7.5E-10	1.6E-09	1.2E-09	1.1E-10	4.1E-10	1.5E-09	1.7E-09	4.9E-10	1.5E-10	vegetable, mushroom, chicken
KETONE											
2-Butanone	1.5E-08	1.8E-08	3.4E-10	2.7E-10	1.6E-09	8.8E-08	3.1E-08	6.7E-09	3.6E-09	9.8E-09	camphoreous, acetone, fruity
2-Heptanone	1.8E-10	2.3E-10	1.3E-11	1.4E-11	nd	2.5E-11	2.4E-10	2.2E-11	1.3E-11	4.5E-11	sweet, spicy, banana
6-Methyl-5-hepten-2-one	nd	nd	5.9E-11	2.1E-11	nd	2.7E-11	nd	nd	nd	nd	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	6.6E-10	1.7E-09	3.5E-10	3.1E-10	2.6E-10	2.3E-09	1.3E-09	6.8E-09	5.3E-10	2.7E-10	malty, cocoa, nutty
o-Xylene	4.0E-11	2.1E-11	1.5E-09	1.8E-09	nd	1.6E-09	3.5E-11	nd	4.5E-11	nd	geranium
Styrene	5.9E-10	1.1E-10	nd	nd	nd	1.9E-11	2.5E-10	nd	nd	nd	sweet, plastic, floral

Table 3.3 (cont'd)

Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	1.1E-10	1.8E-11	nd	nd	nd	1.4E-10	2.6E-11	nd	nd	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	nd	1.0E-11	nd	nd	nd	4.5E-12	nd	5.1E-12	nd	5.5E-12	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	6.5E-11	6.4E-10	1.1E-11	6.9E-09	1.1E-10	6.6E-11	3.4E-10	1.9E-10	2.1E-09	3.6E-09	vegetable, onion, cabbage
Methional	nd	3.1E-12	nd	nd	nd	nd	nd	nd	8.1E-12	nd	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	4.9E-11	nd	4.4E-12	nd	nd	3.1E-10	nd	5.6E-11	nd	nutty, peanut, musty
Other pulses (estimated volatile concentration in mol/L)											
	Chickpea 2022[a]					**Cranberry**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	3.1E-09	1.7E-09	3.4E-09	nd	8.7E-11	1.8E-09	9.2E-09	2.0E-10	4.4E-10	1.2E-09	malty, musty, fermented
Hexanal	7.1E-10	1.6E-09	4.9E-08	4.5E-08	8.5E-10	8.2E-09	1.2E-08	9.7E-10	4.7E-10	3.7E-09	vegetable, aldehydic, clean
(E)-2-hexenal	nd	nd	5.0E-10	4.4E-10	nd	5.1E-09	3.8E-09	9.4E-08	3.0E-08	9.7E-09	sweet, vegetable, bitter almond
Heptanal	nd	2.0E-10	4.5E-10	4.7E-10	1.2E-10	5.1E-10	6.9E-10	2.4E-11	2.8E-11	4.4E-11	aldehydic, fatty, herbal
Benzaldehyde	6.4E-10	6.4E-10	4.3E-10	3.8E-10	3.5E-10	5.5E-10	6.3E-10	3.4E-10	4.0E-10	2.0E-10	sweet, cherry, nutty
Octanal	1.5E-10	9.9E-11	1.4E-10	1.4E-10	5.5E-11	6.2E-10	6.5E-10	1.3E-11	1.8E-11	3.3E-11	aldehydic, fatty, herbal
Nonanal	8.0E-11	6.0E-10	1.5E-09	1.6E-09	2.5E-10	2.9E-09	3.6E-09	6.4E-10	6.6E-10	4.2E-10	aldehydic, fatty, rose
Decanal	9.9E-12	5.4E-11	4.5E-11	5.4E-11	1.3E-08	2.7E-10	3.4E-10	1.4E-11	2.2E-11	2.1E-11	sweet, aldehydic, floral
ALCOHOL											
Butanol	1.5E-09	9.3E-09	nd	nd	nd	8.7E-10	9.1E-10	nd	nd	nd	sweet, fermented, oily
3-Methylbutanol	1.4E-10	4.4E-10	nd	nd	9.6E-10	1.0E-09	5.9E-09	1.0E-09	1.0E-09	2.8E-10	musty, vegetable, cocoa
1-Pentanol	6.5E-10	1.4E-09	2.9E-09	1.9E-09	7.9E-11	3.1E-09	4.2E-09	3.6E-10	3.4E-11	nd	sweet, fermented, yeasty
1-Hexanol	2.2E-08	2.6E-07	5.7E-10	6.3E-10	5.1E-10	7.8E-10	3.7E-10	1.4E-09	1.4E-09	3.2E-10	sweet, pungent, herbal
1-Octen-3-ol	3.7E-10	9.7E-10	6.6E-10	4.4E-10	1.2E-10	1.5E-10	1.1E-10	1.8E-09	1.1E-09	2.3E-10	vegetable, mushroom, chicken
KETONE											
2-Butanone	2.2E-08	1.0E-08	nd	nd	nd	1.3E-08	6.0E-08	2.9E-10	1.9E-10	3.4E-09	camphoreous, acetone, fruity
2-Heptanone	1.5E-11	1.5E-10	5.5E-11	7.5E-11	3.6E-11	nd	1.5E-10	1.2E-11	nd	3.6E-11	sweet, spicy, banana
6-Methyl-5-hepten-2-one	2.4E-12	2.3E-10	nd	nd	8.9E-12	5.9E-11	8.7E-10	2.7E-11	1.7E-11	nd	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	5.1E-10	4.4E-10	1.2E-10	1.1E-10	3.3E-11	4.2E-10	4.4E-10	5.2E-10	1.3E-10	1.3E-09	malty, cocoa, nutty
o-Xylene	2.8E-09	3.5E-11	nd	nd	nd	1.2E-08	1.8E-08	1.3E-09	nd	3.2E-09	geranium

Table 3.3 (cont'd)

Styrene	2.5E-11	1.1E-10	nd	nd	nd	4.8E-10	1.8E-09	nd	nd	7.9E-12	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	1.8E-11	3.2E-11	nd	nd	nd	1.3E-11	3.6E-10	nd	nd	2.2E-11	camphoreous, herbal, terpenic
ALKANE											
Decane	9.4E-13	nd	nd	nd	nd	nd	9.3E-12	1.4E-12	nd	nd	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	1.5E-10	1.1E-11	nd	6.5E-12	3.0E-11	nd	4.4E-10	5.8E-09	2.4E-09	5.9E-10	vegetable, onion, cabbage
Methional	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	1.4E-10	nd	nd	nd	nd	3.2E-11	nd	7.9E-12	nd	nutty, peanut, musty

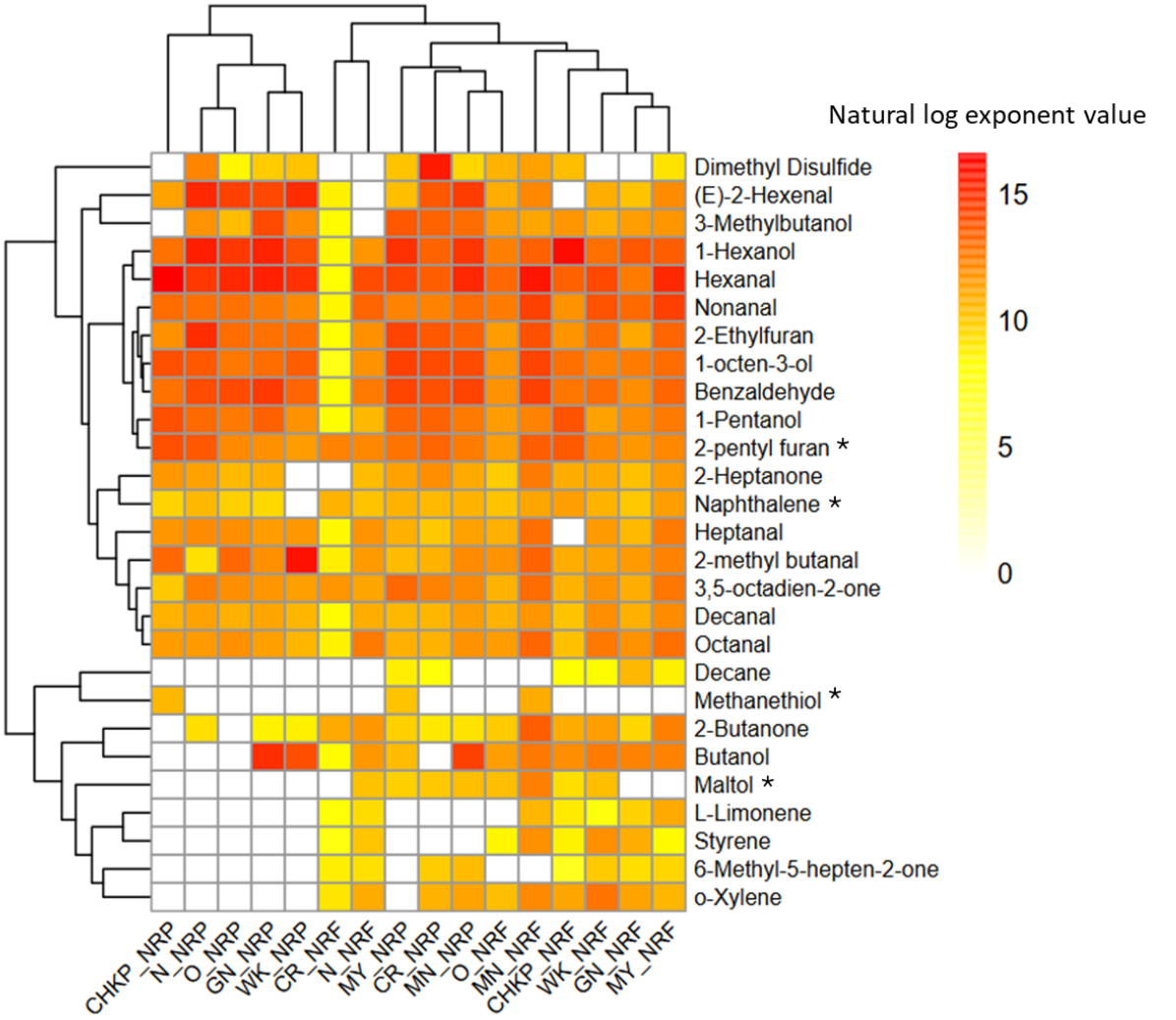

Figure 3.4: Heatmap of log-scaled GC-MS peak areas for volatile compounds varying according to pulse variety from the following eight cultivars grown in 2022- Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), and Great Northern (GN) for non-roasted flour (NRF) and non-roasted porridge (NRP) samples. The asterisks (*) refer to volatile compounds not authenticated using chemical standards. Pulse samples and volatile compounds are clustered according to hierarchical clustering analysis.

Non-roasted model product

A heatmap plot (Figure 3.4) visualizes the variation in volatile compounds between NRF and NRP samples. The flour samples are clustered on the right half of the figure, while non-roasted model products are clustered on the left, illustrating the impact of the final cooking step before consumption on volatile composition of the model product. Volatile compounds were categorized into three distinct clusters based on their response to heat treatment. The top cluster included

volatiles that increased after cooking, with higher concentrations in NRP compared to NRF. These compounds—hexanal, nonanal, 2-pentyl furan, and 2-heptanone—are known contributors to beany flavor (Akkad et al., 2023; Jiang et al., 2016). In contrast, the middle cluster consisted of long-chain aldehydes and ketones that showed moderate variations, while the bottom cluster included aromatics and terpenoids that were more abundant in NRF but decreased or disappeared after cooking into NRP.

Cooking NRF into NRP led to the highest significant ($p<0.05$) increase in total volatile concentration for white-colored beans (GN, N, O, WK) (Figure 3.2). Unlike the RP samples, cooking NRF into NRP increased the abundance of aldehydes in the top cluster of Figure 3.4 in white-colored beans (GN, N, O, WK). Additionally, cooking NRF into NRP also increased alcohols like maltol, 1-hexanol, and 3-methyl butanol in all white-colored (GN, N, O, WK) and yellow-colored (MY, MN) beans. Cooking also increased the total aromatic concentration in NRP samples of N, CR, and MY compared to NRF samples (Table 3.3). These aromatics, such as furans, are primarily produced through the Maillard reaction and the thermal degradation of sugars, amino acids, carotenoids, and polyunsaturated fatty acids (PUFAs) like linoleic acid (Izzotti & Pulliero, 2014; Min et al., 2003). On the other hand, cooking significantly reduced as the concentration of the terpene limonene, which was notably absent in the NRP samples of white-colored beans (N, O, WK, GN) but present in their NRF counterparts. Mishra et al. (2017) previously reported a significant reduction in terpenes of red kidney beans upon cooking. Similarly, Ma Zhen et al. (2016) observed a reduction in limonene content in navy and red kidney beans after cooking.

Overall cooking NRF into NRP influenced volatile formation pathways by increasing total volatiles, alcohols, and aldehydes while decreasing terpenoids in white-colored beans.

Boiling

Boiling significantly reduced total volatile concentrations across all cultivars, with BP samples exhibiting the lowest levels compared to NRP (Figure 3.2). This effect was particularly pronounced in white-colored pulses (GN, N, O, WK), where boiling led to an average 95% decrease in total volatile concentration, while CHKP and CR showed a 75% reduction. Notably, boiling effectively reduced alcohol and aldehyde content, key contributors to beany flavors in pulses (Gao et al., 2020; Roland et al., 2017; Sessa & Rackis, 1977; Xu et al., 2019). Alcohol concentrations dropped significantly ($p < 0.05$) in nearly all cultivars, averaging an 83% reduction (Figure 3.3B). Likewise, aldehyde concentrations declined by an average of 90% (Figure 3.3C).

Our findings align with previous research demonstrating significant reductions in volatile compounds during boiling. Ma Zhen et al. (2016) observed an average 61.75% reduction in targeted total volatile concentrations in boiled bean slurries of navy bean, red kidney bean, green lentil, and yellow pea compared to untreated flours. Azarnia et al. (2011) reported significantly reduced volatile concentrations in cooked peas and pea slurries, while Barra et al. (2007)found similar reductions in cooked French beans. Whitfield & Shipton, (1966) also reported a decline in volatiles in blanched peas. Similarly, Del Rosario et al. (1984) found decreased alcohol concentrations in soybean and winged bean headspace samples upon heating, and Ma Zhen et al. (2016) reported reduced alcohol and aldehyde content in boiled bean slurries of navy beans, red kidney beans, green lentils, and yellow peas. These findings suggest that boiling and extended thermal treatments cause a loss or reduction of volatile compounds, particularly aldehydes and alcohols. The denaturation of proteins during wet heating exposes active sites in proteins, such as the α-amino group of lysine and the thiol group of cysteine. These sites bind oxygenated lipid decomposition products, forming stable lipoprotein complexes that reduce the olfactory impact of volatile compounds (Beyeler & Solms, 1974). As a result, the overall volatile concentration declines significantly in BP samples (Ma Zhen et al., 2016).

The impact of thermal processing on volatiles varies depending on the processing method (roasting vs. boiling), pulse type, and final product (flour vs. model product vs. boiled whole pulse). While boiling effectively reduced key beany flavor markers (aldehydes, alcohols) in pulses, roasting may offer a more practical pre-treatment strategy because it 1) is easier to apply in the production of pulse flour used in convenience gluten-free products 2) preserves nutritional quality better than boiling 3) is more energy-efficient than other thermal treatments such as boiling and spray drying. For instance, Chukwuma et al. (2016) reported that roasting preserved the nutritional value of quality protein maize by retaining higher lysine and methionine content, while boiling led to greater nutrient loss. Roasted maize also retained significantly higher crude protein, crude fat, crude fiber, ash, and carbohydrate content compared to both boiled and raw maize. From an industrial perspective, manufacturers aim to improve product quality while reducing energy consumption. Okada et al. (1980) found that spray-drying was the most energy-intensive process, requiring 5,040 kJ/kg IC, whereas roasting required only 890 kJ/kg IC.

Thus, while boiling significantly reduces key contributors to beany volatiles, roasting, on the other hand, offers a more energy-efficient and scalable solution for processing pulse flours while preserving nutritional integrity.

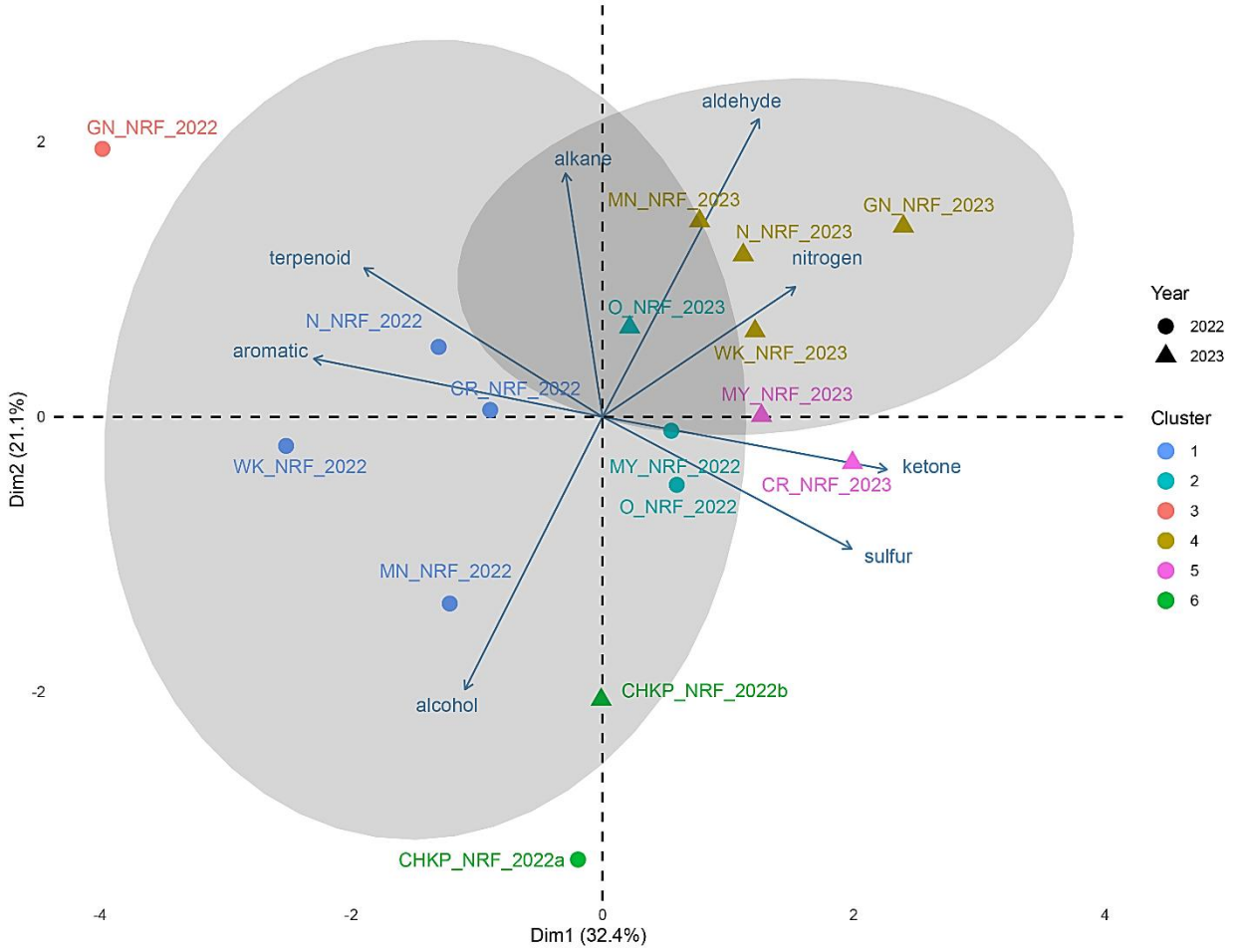

Figure 3.5: Principal Component Analysis (PCA) biplot to visualize the effect of harvest year on concentrations of volatiles grouped by chemical classes in non-roasted flour (NRF) from pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN), grown in harvest years (2022 and 2023) from Michigan, and a market sample of Chickpea (CHKP) (harvested in 2022). *CHKP_2022a: analyzed in April 2024 with 2022 samples; CHKP_2022b: analyzed in September 2024 with 2023 samples. Circles (●) represent harvest samples from 2022 and 2022a while triangles (▲) denote samples from 2023 and 2022b harvest respectively. Hierarchical cluster analysis assigned colors and grouped samples into clusters with similar volatile profiles.

Effect of Cultivar on Volatile Profiles

Harvest year and seed coat color drove key differences in the volatile profiles of pulse cultivars. Principal component analysis (PCA) revealed that PC1, PC2, and PC3 accounted for 32.4%, 21.1%, and 17.4% of the variance, respectively (Figure 3.5). Hierarchical cluster analysis (HCA) further highlighted distinct clustering patterns based on harvest year and pulse type. Cultivars from the 2022 harvest grouped into clusters 1, 2, and 3, while samples from the 2023 harvest showed distinct clustering based on seed coat color such that white (GN, N, O, WK) and yellow (MN, MY) colored beans formed cluster 4, whereas CR and CHKP grouped into clusters 5 and 6, respectively. Yellow-colored (MY, MN) beans, CR, and CHKP exhibited higher concentrations of sulfurous compounds compared to white-colored cultivars (Figure 3.4). Among NRP samples, CR had the highest total sulfur concentration, particularly dimethyl disulfide. Similarly, CHKP and MY contained the highest levels of methanethiol (Figure 3.4). These findings align with Ma Zhen et al. (2016) who reported greater concentrations of dimethyl disulfide and methanethiol in untreated red kidney beans than in white colored navy beans. Future sensory studies should investigate whether the increased sulfurous concentration in darker-colored and pigmented pulses influence their sensory perception compared to lighter-colored varieties.

In contrast, white-colored beans (GN, N, O, WK) contained higher concentrations of aldehydes, and alcohols. They exhibited elevated levels of alcohols like 1-hexanol, maltol, 3-methyl butanol and aldehydes such as hexanal, (E)-2-hexenal, benzaldehyde, and nonanal compared to CHKP and CR (Figure 3.4). (E)-2-hexenal and 1-hexanol were particularly abundant in NRP samples of white-colored cultivars in GN, N, and O (Table 3.3). Consequently, among all cultivars, the NRP samples of white-colored beans (GN, N, O, WK) had the highest total estimated volatile concentration, surpassing both yellow-colored pulses (MY, MN), CHKP, and CR. Specifically, NRP samples of Navy beans exhibited the greatest volatile concentration, followed by Great Northern, Otebo, and White Kidney beans (Figure 3.2). Navy beans also had the highest aromatic content among all cultivars, with 2-ethyl furan and 2-pentyl furan dominating its NRP sample (Figure 3.4). These findings align with previous research by Ma Zhen et al. (2016) which reported that untreated navy bean flour contained the highest volatile abundance among Saskatchewan pulse varieties, whereas untreated red kidney bean flour had the lowest.

Previous research suggests that carotenoid degradation contributes to the formation of terpenoids and hydrocarbons (Murray et al., 1976; K. Wang & Arntfield, 2017). Olumide O. Fashakin et al.,

(n.d.) found that pigmented NRF samples of yellow-colored beans (MY, MN) contained the highest carotenoid concentrations compared to white-colored beans (GN, N, O, WK). Consequently, our study showed that NRF samples of yellow-colored beans (MY, MN) exhibited the highest concentrations of terpenoids, particularly limonene, compared to white (GN, N, O, WK) and other (CHKP, CR) pulses (Figure 3.4). Previous research has also demonstrated that terpene content varies significantly by cultivar in common beans. Pinto beans, for instance, contain approximately 16 times more terpenes than black beans, while dark red kidney bean cultivars contain the lowest terpene content (Karolkowski et al., 2021; Oomah et al., 2007).

Overall, darker-colored pulses were characterized by higher concentrations of sulfurous compounds, yellow-colored beans contained the most terpenoids, and white-colored beans were abundant in alcohols and aldehydes.

Effect of year

The ANOVA results demonstrated that harvest year had a significant effect on total volatile concentrations across all samples ($p = 3.3E-11$) (Table 3.2). HCA and PCA further revealed distinct volatile profiles based on harvest year. Specifically, NRF samples from 2022 clustered in quadrants 2 and 3, while those from 2023 grouped in quadrants 1 and 4 (Figure 3.5). Within these clusters, samples from the 2022 harvest—N, WK, CR, and MN—grouped in cluster 1, while GN formed a distinct cluster 3 in quadrant 2. For the 2023 harvest, N, WK, GN, and MN clustered together (cluster 4) in quadrant 1, while MY and CR formed cluster 5. Notably, CHKP, analyzed at two time points, formed cluster 6 in quadrant 3, while the O cultivar from the 2022 and 2023 harvests grouped in cluster 2. This difference in clustering patterns across harvest years may also be attributed to the varying time intervals between harvest and volatile analysis, as pulses harvested in 2022 were analyzed 18 months post-harvest, whereas those from 2023 were analyzed 12 months post-harvest.

NRP and NRF from the 2022 harvest year exhibited substantially higher total volatile concentrations compared to those from 2023 (Figure 3.2). This suggests seed maturity due to a prolonged storage period (18 months post-harvest) in the mature 2022 harvest year samples could have influenced the accumulation of volatiles, whereas 2023 samples were analyzed after 12 months. The NRF from the 2022 harvest showed higher concentrations of alcohols, ketones, and aromatics such as xylene and styrene across all cultivars (Table 3.3, Table S1), while NRF from the 2023 harvest exhibited higher concentrations of aldehydes than mature 2022 samples (Figure

3.5). This contrasts with previous studies by Manouel et al. (2024) where the concentration of hexanal in pea flours followed the order 2018 > 2019 > 2020 > 2022, indicating that increased seed age significantly increased hexanal content.

Interestingly, in our study, hexanal concentrations in NRF followed the order 2023> 2022, except for CHKP (Table 3.3, Table S1). Since CHKP was commercially sourced, it was grown and harvested in a different location in 2022 compared to the other dry bean cultivars, although it was processed and analyzed within the same overall time frame. For instance, CHKP_2022a was analyzed after 18 months of storage in the same batch as the 2022 dry bean samples, and CHKP_2022b was analyzed after 30 months, alongside the 2023 dry bean samples. Despite this difference in storage time, both mature CHKP_2022b and newer CHKP_2022a flours exhibited comparable volatile profiles and concentrations. This suggests that growing year and environmental conditions a pulse crop endures in a specific harvest year may have a greater influence on volatile profiles than storage time alone.

The influence of storage time and temperature on volatile profiles was studied by Akkad et al. (2022), who observed that volatiles like hexanal, nonanal, 2-pentyl furan, and 2-heptanone increased with prolonged storage in faba beans. However, our finding of lower hexanal content with increased seed age in the 2022 harvest NRF reinforces that other factor related to harvest year, rather than storage duration, likely contributed to the differences observed.

Environmental conditions such as temperature, light exposure, water availability, and soil composition play a significant role in lipid metabolism, as plants under stress often produce more saturated fatty acids to stabilize cellular membranes. Additionally, genetic and biochemical responses specific to the growing environment may alter the activity of enzymes responsible for fatty acid synthesis, further impacting volatile profiles. Other differences in fatty acid composition due to location, harvest year, and storage duration, could further influence the production of volatile compounds (Manouel et al., 2024). These combined factors likely explain the differences in volatile profiles observed between the two years. These insights are crucial for determining optimal storage time and temperature while considering crop year variations and the environmental and soil conditions during cultivation.

Conclusion

This study examined how cultivar, harvest year, and processing methods influenced the volatile composition of pulses. Cultivar differences were primarily driven by seed coat color, which played

a key role in shaping volatile profiles. Understanding these differences can aid in selecting pulses for targeted food applications. The distinct clustering pattern of CHKP flours despite variation in seed maturity suggests that environmental and growing conditions may have a greater influence on volatile profiles across harvest years than prolonged storage period alone. Processing methods altered VOC composition, with major differences observed between non-roasted and roasted samples. Cooking roasted flour was more effective in reducing key volatiles compared to direct cooking of non-roasted flours. Since these targeted volatiles have been cited as beany flavor markers, roasting may serve as an effective pre-treatment strategy to reduce these flavors in cooked pulse-based products. Further research is needed to optimize roasting conditions based on seed size and color to minimize sulfur compound formation and to identify specific volatile markers associated with off-flavors in pulses. Additionally, investigating the role of nitrogenous compounds generated during heat-treatment is essential to identify if they mask or intensify off-flavors in pulses.

Future research should incorporate sensory analysis to better understand how volatile compounds influence odor perception and acceptability in pulse-based products. Additionally, developing and validating instrumental methods for rapid profiling could identify volatile markers and predict sensory characteristics in pulse-based products, ultimately reducing reliance on time-intensive sensory panels.

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Chapter 4: Evaluating the impact of cultivar and processing on pulse off-flavor through descriptive analysis, GC-MS, and e-nose

Abstract

Pulses are nutrient-dense and have a low carbon and water footprint but remain underutilized in the United States. A potential strategy to boost pulse consumption involves milling pulses into flour and incorporating them into convenience products traditionally made from wheat flour. However, addressing off-flavors—commonly described as beany, green, musty, or vegetative—is essential for sustained adoption. This study evaluated the impact of cultivar selection and processing methods (boiling, roasting) on off-flavor reduction in eight pulse cultivars using Descriptive Analysis (DA) and rapid volatile profiling with gas chromatography-mass spectrometry (GC-MS) and electronic nose (e-nose). DA revealed significant differences ($p < 0.05$) across cultivars and processing treatments for 20 sensory attributes, with roasting reducing green/vegetative and earthy/mushroom/musty off-flavors but increasing beany characteristics, especially in roasted navy bean flour. We identified 8 key volatiles via GC-MS, including ketones, aldehydes, and alcohols that were strongly correlated to vegetative and mushroom flavors. However, GC-MS had limitations in predicting beany off-flavors, likely due to the chosen targeted analytical approach. In contrast, the untargeted e-nose approach effectively distinguished non-roasted and roasted flours, identifying discriminant ions that correlated with sensory attributes like toasted and beany odors. E-nose data aligned better with DA results, highlighting its potential as a first screening tool for rapid flavor profiling. Findings highlight the importance of refining pre-treatment methods and selecting cultivars with milder flavors. E-nose and GC-MS can be used to optimize the sensory quality of pulse flour, supporting increased consumer acceptance of pulse-based products.

Introduction

Pulses are edible seeds of plants in the legume family (Fabaceae), harvested specifically for their dry grain, excluding oilseeds. Common pulse types include *Phaseolus vulgaris* (common beans such as kidney beans, navy beans, and pinto beans), *Lens culinaris* (lentils), *Cicer arietinum* (chickpeas), and *Pisum sativum* (peas) (FAO, 1994). Research highlights extensive health benefits from incorporating pulses into daily diets. Pulses have demonstrated their ability to prevent heart disease (Geil & Anderson, 1994) and reduce colon cancer risk due to their rich content of protein, fiber, and folate (Michels et al., 2006). The high fiber and resistant starch content of pulses induces a low glycemic response, which aids in diabetes prevention and management (Ludwig, 2002). Additionally, the nitrogen-fixing ability, soil health benefits, and lower carbon footprint of pulses make them a valuable component of sustainable agricultural and food systems (Reckling et al., 2016). For instance, despite the similar protein contents in pulses and meats (typically between 18 and 26%), it was observed that pulses have a significantly lower global warming potential of 0.7 kg carbon dioxide equivalents (CO_2 eq)/kg compared to animal-derived sources such as boneless beef of 29 kg CO_2 eq/kg of (Clune et al., 2017).

Despite their numerous benefits, pulse consumption in the U.S. remains notably low. While annual production reaches 2.9 million tons, National Health and Nutrition Examination Survey (NHANES) (2003–2014) revealed that only 27% of adults (≥19 years) reported consuming pulses, with an average intake of just 70.9 ± 2.5 g/day over two days—equivalent to less than 0.5 cup equivalents per day. The 2025 Dietary Guidelines Advisory Committee (2024) reported that 83% of Americans consume pulses below the recommended dietary intake level. The 2025–2030 Dietary Guidelines for Americans propose increasing the recommended intake of beans, peas, and lentils to 2.5 cups/week, up from the previous recommendation of 1.5 cups/week in the 2020–2025 guidelines (2025 Dietary Guidelines Advisory Committee; Garden-Robinson & West, 2023; Haven, 2021a; Mitchell et al., 2021; Sadohara et al., 2022). Common barriers to pulse consumption include a general dislike of their taste and texture, lack of familiarity and preparation knowledge, and limited interest among specific demographics, such as Midwestern U.S. university students aged 18–30 and adults over 65 (Doma et al., 2019; Winham et al., 2020).

To encourage greater pulse consumption, milling pulses into flour and using them in products typically made with wheat flour can be an effective approach (Sadohara et al., 2022). Pulses are particularly suited for the growing gluten-free market, offering superior nutritional profiles

compared to traditional gluten-free alternatives like corn, rice, and potato flour. However, maintaining the acceptable taste and texture of gluten-free pulse-based products remains a challenge for their sustained adoption (Sozer et al., 2017). Adding to this difficulty is the presence of off-flavors, often described as "beany," which further limits the appeal of pulse flour in convenience products (Sadohara et al., 2022). This broad term encompasses sub-character notes such as musty, earthy, green, and pea pod aromas (Chigwedere et al., 2022; Vara-Ubol et al., 2004), which aligns with previously reported findings on undesirable flavors in pulse-based products (Troszyńska et al., 2011; Vara-Ubol et al., 2004). In this study, these sub-character notes are collectively referred to as "known off-flavors" (Roland et al., 2017; Sadohara et al., 2022). However, consumer acceptance studies are needed to determine whether "known off-flavors," such as vegetative/green and earthy/musty notes, negatively influence consumer perception of pulses. Additionally, while the beany flavor has often been classified as an off-flavor, its impact on consumer liking and acceptability may vary depending on the product context and hence in this study isn't referred as an off-flavor (Chigwedere et al., 2022).

Off-flavors arise from chemical and biochemical reactions, primarily the oxidation of unsaturated fatty acids like linoleic and linolenic acids through enzymatic lipoxygenase (LOX) activity or non-enzymatic pathways to generate hydroperoxides that decompose into volatile compounds (MacLeod et al., 1988; Rackis et al., 1979). The concentration and intensity of these volatiles vary between pulse types and cultivars largely due to differences in macronutrient composition (N. Singh, 2017). Additionally, pre-treatments such as roasting, boiling, spray drying, freeze drying, and germination can alter the volatile abundance, depending on the pulse variety (Akkad et al., 2019; Azarnia et al., 2011; Chang et al., 2019; Ma et al., 2016). Volatile compounds responsible for off-flavors in pulses, including aldehydes, alcohols, ketones, acids, pyrazines, and sulfur, can be minimized through cultivar selection and process optimization (Roland et al., 2017). LOX-derived volatiles, including hexanal, 3-cis-hexenal, n-pentyl furan, 2-(1-pentenyl) furan, and ethyl vinyl ketone, have been identified as key contributors to grassy, green, and beany off-flavors (Rackis et al., 1979). It is essential to identify the specific volatile compounds most responsible for off-flavors to reduce their impact on the overall perception of pulses. Hence an ideal approach to studying off-flavors in pulses would involve combining instrumental analysis with sensory evaluation for a more comprehensive understanding (Viana & English, 2021). However, time-intensive panel training and the high costs associated with sensory evaluation make it less practical

for mild-flavored cultivar selection and rapid process optimization to reduce off-flavors in pulses (Shurmer & Gardner, 1992). To address these limitations, instrumental analytical methods have become integral for efficiently evaluating volatile organic compounds (VOCs) that drive flavor in pulses and other foods.

The most commonly used method for analyzing volatile compounds in pulses is Headspace Solid-Phase Microextraction (HS-SPME) Gas Chromatography coupled with Mass Spectrometry (GC-MS). It is particularly effective for identifying and characterizing individual volatile compounds due to its high sensitivity and resolution (Karolkowski et al., 2021; Khrisanapant et al., 2019). For instance, Murat et al. (2012) reported that SPME and solvent-assisted flavor evaporation (SAFE) offered a better representation of yellow pea flour odors than dynamic headspace techniques like the Purge and Trap method. New methodologies integrating electronic sensors, such as electronic noses (e-noses) and electronic tongues (e-tongues), have emerged as promising alternatives. Over the past decade, e-nose systems integrating mass spectrometry or fast gas chromatography have been developed (Wilson & Baietto, 2009). These systems operate at higher temperatures and flow rates for rapid volatile analysis. Volatile compounds are separated via chromatographic columns and detected using surface acoustic wave (SAW) sensors or flame ionization detectors (FID), producing a profile of volatile constituents (Wardencki et al., 2013).

Discriminant ions from e-nose, such as m/z 78 and 124, have been previously used as markers for distinguishing ripening changes in legumes based on the increased relative concentration of sulfuric compounds, particularly 1,2,4-trithiolane, in matured legumes (Asikin et al., 2018). However, the application of e-nose technology to pulse-based products remains limited. Efforts are needed to develop calibrated models capable of identifying discriminant ions responsible for off-flavors in pulses. Additionally, while e-nose shows potential for rapid flavor monitoring, its ability to represent overall odor perception in pulse products accurately requires further investigation, alongside comparative studies with traditional extraction techniques.

Hence, this study aims to: 1) characterize the sensory attributes of pulses through descriptive sensory analysis, and 2) identify chemical markers associated with off-flavors using instrumental techniques. By examining the effects of cultivar variation and processing methods (boiling and roasting), the study seeks to identify cultivars with milder flavor profiles and evaluate the sensory trade-offs involved in processing to reduce off-flavors. These findings aim to enhance the sensory quality and consumer acceptance of pulse-based food products.

Materials and Methods

Germplasm selection and seed production

The dry bean market classes selected for this study with their respective abbreviations and cultivar (cv.) or genotypes are listed as follows: Navy (N, cv. 'Alpena'); Otebo (O, cv. 'Samurai'); Great Northern (GN, cv. 'Powderhorn'); White Kidney (WK, cv. 'WK 1601-1'); Mayacoba (MY, cv. 'Y 1802-9-1'); Manteca (MN, cv. 'Y1608-07'); and Cranberry (CR, cv. 'CR1801-2-2') (Figure 4.1). The rationale for selection of these beans was based on their adaptation to Michigan's agricultural conditions, seed yield potential, and representation across market classes. For the potential higher acceptance of pulse flour, cultivars with white or lighter seed coat colors, such as Navy, Otebo, Great Northern, and White Kidney, were chosen.

These beans were cultivated at the Michigan State University Montcalm Research Center in Entrican, Michigan, during the year 2022. The seeds were sown in a randomized complete block design with three field replicates, with plots consisting of four 6.1 m rows, where the center rows contained the experimental lines, and the outer rows were standard bordered with kidney beans. Field maintenance practices included weed control, fertilization, and insect management, with supplemental irrigation as needed. The seeds were harvested on September 29 using a Hege 140 plot combine harvester. Post-harvest, the seeds were cleaned manually to remove debris and stored in paper bags at room temperature for further analysis. Additionally, a Kabuli Chickpea (CHKP, cv. 'Sierra') obtained commercially, grown in 2022 on a Montana commercial farm was chosen in this study for its industrial significance in U.S. production. Non-roasted pulse flour (NRF), non-roasted pulse flour porridge (NRP), roasted pulse flour (RF), roasted pulse flour porridge (RP), and boiled pulses (BP) were produced from each of the eight pulse genotypes (Figure 4.2).

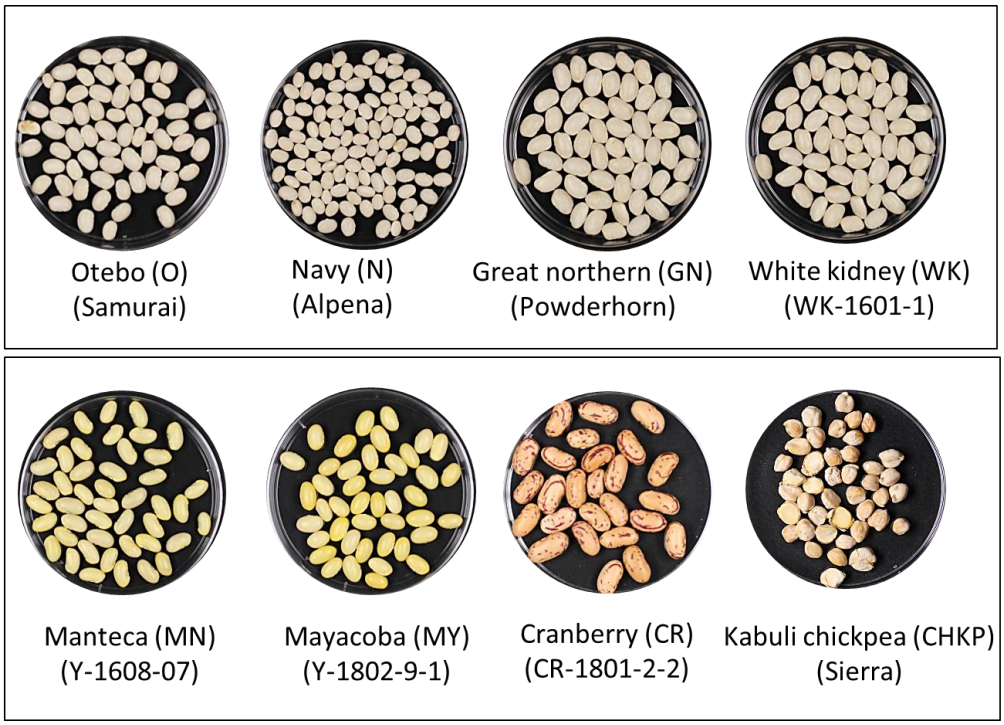

Figure 4.1: Image of the eight cultivars included in this study, arranged by market class, abbreviation, and corresponding genotypes (shown in parentheses).

Pulse flour production

The pulses were rinsed under distilled water, spread on a tray lined with paper towels, and allowed to air dry for 12 hours. Some of the cleaned and dried pulses were roasted by dry heat in an oven (Fisher Scientific Isotemp Gravity Oven, 100 L) at 110°C for 70 minutes, then allowed to cool for 4 hours.

Once dried, the non-roasted and roasted seeds from each of the eight pulse varieties were milled into flour using a hammer mill (Polymix® Laboratory Grinding Mills, PX-MFC 90 D, Kinematica), fitted with a 0.5 mm sieve to produce NRF and RF samples.

Pulse porridge and boiled pulse preparation

Both NRF and RF samples were used to prepare porridges for sensory and volatile analyses using the same procedure to understand the cooked properties of the pulse flour. To prepare the porridge, 50 g of pulse flour (non-roasted or roasted) was mixed with 250 mL of water to form a slurry and stirred for 7 minutes. An additional 300 mL of distilled water was then added, and the mixture was cooked at 150°C and mixed at 1500 rpm for 25 minutes using an MSE PRO LCD 4-Channel Digital Magnetic Hotplate Stirrer, producing NRP and RP samples. BP samples were prepared by soaking pulses in distilled water for 12 hours at room temperature, followed by boiling on a Duxtop

1800W Portable Induction Cooktop until fully cooked (Figure 4.2). Cooking times were determined using a Mattson pin drop cooker as follows Otebo (16 min), Navy (24 min), Great Northern (23 min), White Kidney (30 min), Chickpea (45 min), Manteca (20 min), Mayacoba (33 min), and Cranberry (50 min). NRP, RP, and BP samples were prepared fresh on the day of testing for sensory and GC-MS volatile analysis. NRF and RF samples were stored in sealed bags after milling under refrigeration at 2°C to reduce volatile loss (Akkad et al., 2022).

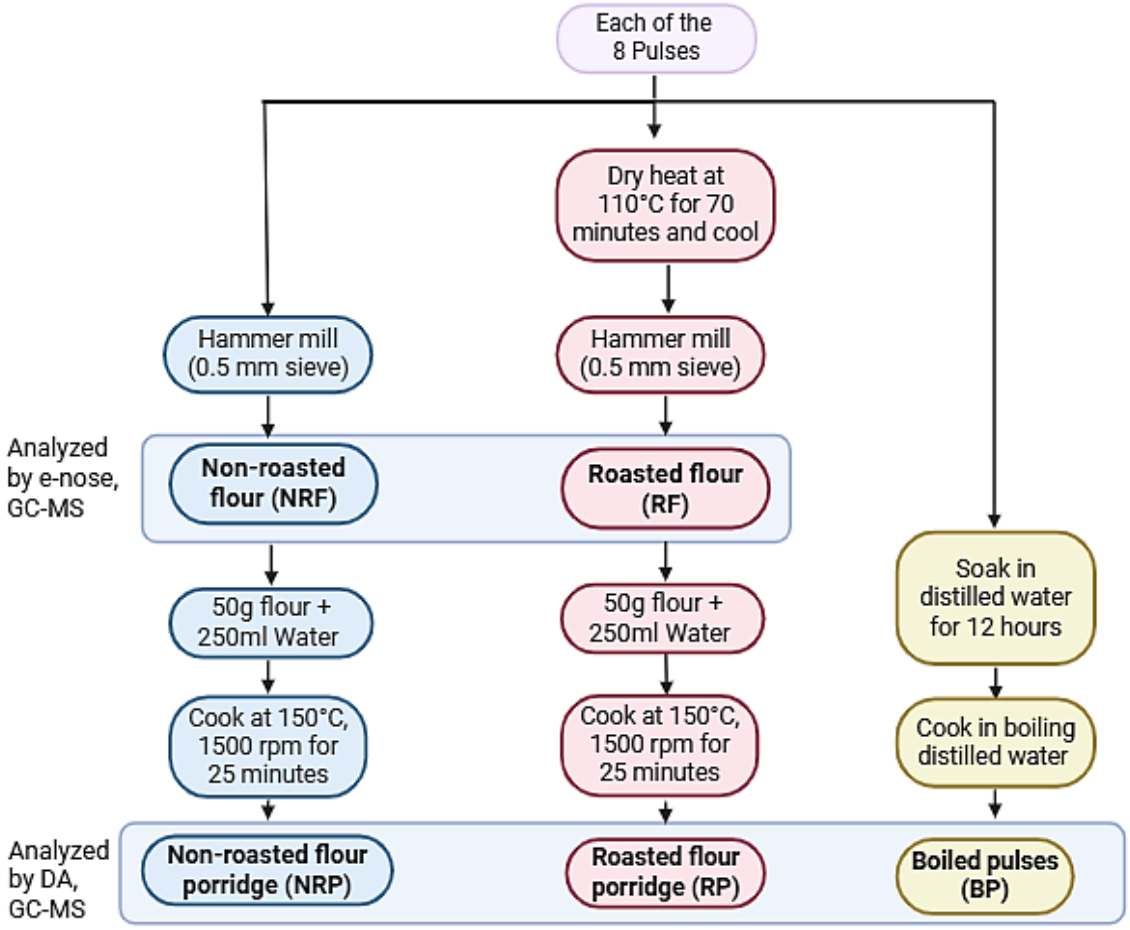

Figure 4.2: Flowchart of preparation methods for five types of samples. Electronic nose (e-nose) and gas chromatography-mass spectrometry (GC-MS) analyses were conducted on NRF and RF samples; GC-MS and descriptive analysis (DA) were performed on NRP, RP, and BP samples from each of the eight pulse types of Navy, Otebo, Great Northern, White Kidney, Mayacoba, Manteca, Cranberry and Chickpea.

Descriptive analysis

The NRP, RP, and BP samples were characterized for their sensory profile using quantitative descriptive analysis (DA, ISO 11035:1994). Since flour cannot be directly consumed by human panelists, to understand the characteristics of pulse flour in its simplest form, pulse porridges from the pulse flour and boiled pulses from raw seeds were prepared as described above for sensory assessment.

Sensory panelists were recruited and screened for taste acuity and verbal ability to participate in a six-week descriptive analysis (DA) panel. The panel consisted of 9 panelists (2 males, 7 females) aged 18-41. The panelists underwent a training program consisting of 27 one-hour sessions.

During the initial 15 training sessions of the study, panelists received instruction on DA methodology, engaged in term generation and refinement, and reference selection. The subsequent 3 sessions included reference scaling, followed by 9 sessions dedicated to group sample evaluation practice and panel calibration exercises. Each day, a rotating, balanced subset of pulse samples was provided for panel training and practice. The attributes generated and evaluated by the panel, along with references, definitions, and sample evaluation instructions, are listed in Table 4.1.

Between tasting samples, the panelists used a rinse procedure that included the following steps: expectorating the sample, rinsing with room temperature water and expectorating the water, biting into a cracker to cleanse the palate and expectorating, and finally, rinsing with room temperature water and expectorating the water again.

After their training, the panelists evaluated samples in individual sensory booths in duplicate using the RedJade sensory software (RedJade Sensory Solutions LLC, Pleasant Hill, CA, USA). Pulse samples were presented following a randomized complete block design, blinded with random 3-digit codes, across four evaluation sessions on four consecutive days. Before each evaluation session, panelists were instructed to recalibrate themselves using freshly prepared reference samples. These references were labeled with their identity and served in plastic cups with lids. The panelists rated attribute intensities of the samples on a questionnaire using a continuous, visual analog scale from 0-15 anchored at the ends by none and strong for most attributes, except for saturation, which was anchored by dull and bright.

Table 4.1: Lexicon used to characterize pulse samples, including sensory attributes used in the descriptive analysis, corresponding codes, definitions, references, evaluation procedures for pulse samples, and reference ratings on a 0 to 15 scale. Attributes are organized by sensory modality.

Attribute	Abbreviation	Definition	Reference	Reference Rating
Appearance **Protocol for sample:** Lid off and evaluate each sample cup over white paper and use the respective color swatches as references for assessment				
Value	color_value	The value of the sample from light to dark	Greyscale (Munsell Color Company)	1-3-4-7-9-12-14
Saturation	color_saturation	The saturation of the sample from dull to bright	10YR hue page (Munsell Color Company)	1-3-5-7-9-11-13-14
Aroma **Protocol for sample:** Shake samples and crack the corner of the lid to sniff				
Kidney bean	aroma_kidney.bean	Aroma of canned kidney beans	Canned kidney beans	13
Chickpeas	aroma_chickpeas	Aroma of canned chickpeas	Canned chickpeas	14
Pinto beans	aroma_pinto.bean	Sweet aroma of canned pinto beans	Canned pinto beans	11
Great northern beans	aroma_great. northern.bean	Sour aroma of canned great northern beans	Canned great northern beans	11
Mushroom	aroma_mushroom	Musty aroma of fresh mushroom	Uncooked sliced mushroom	14
Boiled Potato	aroma_boiled.potato	Aroma of peeled, boiled and mashed potato	Boiled potato	11.5
Boiled rice	aroma_boiled.rice	Aroma of boiled rice	Boiled rice	12
Toasted bread	aroma_ toasted.bread	Aroma of fresh white Toasted bread	White Toasted bread	12
Tofu	aroma_tofu	Fermented aroma of uncooked tofu	Firm tofu	10
Grainy	aroma_grainy	Aroma of cooked grains	Cream of wheat	10
Aroma-by-mouth/Flavor **Protocol for sample:** Chew one piece of the whole beans thoroughly with back teeth for 3 sec. Move a spoonful of porridge thoroughly around the mouth for 3 sec.				
Kidney bean	flavor_kidney.bean	Flavor of canned kidney beans	Canned kidney beans	13
Chickpeas	flavor_chickpeas	Flavor of canned chickpeas	Canned chickpeas	13
Pinto beans	flavor_pinto.bean	Sweet flavor of canned pinto beans	Canned pinto beans	11
Great northern beans	flavor_great. northern.bean	Sour flavor of canned great northern beans	Canned great northern beans	12
Mushroom	flavor_mushroom	Musty flavor of fresh mushroom	Uncooked sliced mushroom	14.5
Boiled Potato	flavor_boiled.potato	Aroma of peeled, boiled and mashed potato	Boiled potato	8.8
Tofu	flavor_tofu	Fermented flavor of uncooked tofu	Raw tofu	7
Vegetable	flavor_vegetable	Flavor of cooked green vegetables	Canned green bean	13
Taste **Protocol for sample:** Chew one piece of the whole beans thoroughly with back teeth for 3 sec. Move a spoonful of porridge thoroughly around the mouth for 3 sec.				
Sour	taste_sour	Sour taste of Citric acid solution	0.05% Citric acid Solution	11

Table 4.1 (cont'd)

Umami	taste_umami	Umami taste of MSG solution	0.05% MSG solution	11.2
Bitter	taste_bitter	Bitter taste of caffeine solution	0.05% Caffeine Solution	9
Aftertaste Protocol for sample: Chew one piece of the whole beans thoroughly with back teeth for 5 sec and expectorate. Move a spoonful of porridge thoroughly around the mouth for 5 sec and expectorate.				
Astringent	aftertaste_astringent	Lingering dryness after swallowing	0.05% Alum solution	13.5
Bitter	aftertaste_bitter	Bitter aftertaste of caffeine solution	0.05% Caffeine Solution	9

Headspace Solid-Phase Microextraction coupled with Gas Chromatography-Mass Spectrometry (HS-SPME-GC-MS) analysis

NRF, NRP, RF, RP, and BP samples were analyzed for HS-SPME-GC-MS. Volatile profiles of all five samples were obtained using the same equipment, procedure, and conditions.

The following quantities of each sample were placed in 20 mL headspace vials: 2 g each of NRF and RF, 5 g of mashed BP, and 5 g of NRP and RP (each porridge mixed with 1 g NaCl). NaCl addition enhanced volatile extraction by lowering the partitioning coefficient (K) for some analytes and increasing their concentration in the headspace (Westland, 2021).

Samples were then analyzed by the HS-SPME-GC-MS method described previously (Chapter 3). Briefly, samples were first equilibrated at 50 °C for 30 minutes followed by exposing a carboxen/polydimethylsiloxane/divinylbenzene (CAR/PDMS/DVB) 2 cm, 30/50 µm, (Supelco, Sigma–Aldrich) SPME fiber to the headspace for an additional 30 minutes at 50 °C. Volatile compounds were desorbed for 20 sec in a split/splitless injector port (200 °C) of a gas chromatograph (Agilent 6890 Gas Chromatograph, Hewlett-Packard Co., Wilmington, DE) and separated on a 30 m × 0.25 mm i.d. HP-5 (Hewlett-Packard) capillary column (0.25 µm) with helium carrier gas at a ramped flow rate initially at 1.2 mL/min and then increased at a rate of 1 ml/min to a final flow rate of 1.8 mL/min. The initial GC oven temperature was set at 32 °C and increased to 60 °C at a rate of 20 °C/min. It was then ramped to 150 °C at a rate of 50 °C/min, followed by a final increase to 280 °C at a rate of 70 °C/min, where it was held for 2 minutes. The total run time for the analysis was 7.4 minutes. Detection was carried out using TOF-MS (LECO Pegasus III) with electron ionization at 70 eV and a mass range of 29–400 m/z. Volatile compounds were identified through comparisons with the National Institute of Standards and Technology (NIST) mass spectra library database (V.05) and/or by matching retention times of authenticated standards. The following volatiles were identified using authenticated pure commercial standards:

2-butanone, 2-methyl butanal, butanol, 2-ethylfuran, 3-methylbutanol, dimethyl disulfide, 1-pentanol, hexanal, (E)-2-hexenal, 1-hexanol, o-xylene, 2-heptanone, styrene, heptanal, methional, 2,5-dimethyl pyrazine, benzaldehyde, 1-octen-3-ol, 6-methyl-5-hepten-2-one, octanal, decane, L-limonene, nonanal, decanal, and geosmin, all obtained from Sigma-Aldrich (St. Louis, MO, United States).

The peak areas of volatiles collected from the HS-SPME GC-MS analysis were obtained from the average triplicates of the area under the curve (AUC) and reported for a single m/z (mass-to-charge ratio) corresponding to the unique mass (Chapter 3, Table S2).

E-nose analysis

The volatile profile analysis of pulse flours was also conducted using an ultra-fast chromatographic system Heracles Neo (Alpha MOS, Toulouse, France). The instrument was equipped with two metal capillary columns working in parallel mode and characterized by different polarity and stationary phase: a non-polar column (MXT5: 5% diphenyl, 95% methylpolysiloxane, 10 m length and 180 µm diameter) and a polar column (MXT-1701: 14% cyano-propyl phenyl, 86% dimethyl polysiloxane, 10 m length, 180 µm diameter). An FID detector was connected at the end of each column and the acquired signal was digitized every 0.01 s.

NRF & RF samples of all eight cultivars were subjected to e-nose analysis. For each sample, 1 g of flour was placed in a 10 mL glass vial. The headspace extraction was conducted in a septa-sealed screw cap vial that was equilibrated for 20 min at 60°C. Afterward, the headspace above the sample was injected into the electronic nose at the speed of 500 µL /s with a pressure of 10 kPa, a flow rate of 60 mL/min, and an injection time of 60 sec using an automatic headspace sampler (CTC Analytics company, Zürich, Switzerland). The column oven temperature program used for the experiment started at 50°C, held for 2 s, and then ramped at a rate of 3°C/s until it reached 250°C and then held for 5s. The injection temperature of the injector and detector were set at 240°C and 270°C, respectively.

For calibration of the method, an alkane solution (from n-hexane to n-hexadecane) was used to convert retention time in Kovats indices to identify possible compound matches using the AroChemBase database (Version 4.6, Alpha MOS Corporation, Toulouse, France). The peak areas indicate the relative concentration of the odor components.

Statistical Analysis

Sensory and instrumental volatile data were analyzed for sample differences using the R statistical computing software (version 4.2.2; R Core Team, 2022) to conduct Analysis of Variance (ANOVA) and Least Significant Difference (LSD) post hoc multiple comparisons tests using the following packages: tidyverse v. 2.0.0 (Wickham et al., 2019), and agricolae v. 1.3.5 (de Mendiburu, 2021). Principal component analysis (PCA), hierarchical cluster analysis (HCA), and Pearson's correlation were also conducted and visualized using R statistical computing software (version 4.2.2; R Core Team, 2022) using the following packages: FactoMineR v. 2.8 (Lê et al., 2008), ggplot2 v. 3.5.1 (Wickham, 2016) and Hmisc v. 5.1.2 (Harrell Jr, 2024).

The data from the descriptive sensory analysis were analyzed using ANOVA. The multifactorial ANOVA model included interactions (panelist:sample, panelist:day, and sample:day), with panelists treated as a random effect and sample and day as fixed effects. A pseudo-mixed model was applied to verify whether sample effects were significant independently of interactions with panelist and day. Sensory attributes with significant panelist or day interaction effects were excluded, and LSD post hoc analysis was performed on the remaining significant sensory attributes to identify differences in attribute ratings between samples. For all statistical tests, an α of 0.05 was used to determine statistical significance. Mean intensity ratings from duplicate reps for significantly different sensory attributes were used for PCA analysis to identify relationships among pulse samples based on their sensory attributes, and HCA analysis was conducted to segment samples into subgroups sharing common sensory patterns. Radar plots were generated using Microsoft Excel (Microsoft Corporation, Seattle, WA, U.S.A.)

The volatile peak areas from the HS-SPME GC-MS analysis represent the average of three replicates (Chapter 3, Table S2). The identified volatile compounds using HS-SPME GC-MS-were categorized according to their chemical class as follows- aldehydes, alkanes, alcohols, ketones, terpenoids, sulfurous, nitrogenous, and aromatic compounds and analyzed using ANOVA followed by LSD post hoc multiple comparisons tests. The mean-centered AUC values were analyzed using PCA to examine relationships between volatile profiles and processed pulse samples, as well as HCA to group samples with similar volatile patterns grouped by chemical class.

The peak areas for each discriminant ion in a sample from e-nose analysis were obtained from the average of triplicates. Partial least squares regression (PLS) was used to identify discriminant ions from e-nose volatile profiles to correlate chromatograms with mean sensory intensity scores using

the Alpha MOS software (Version 2023, Toulouse, France) (Cevoli et al., 2022; Lozano et al., 2007; Ravi et al., 2019). Mean-centered peak areas of discriminant ions were used for PCA to visualize the relationship between pulse flour and discriminant ions, as well as HCA to segment samples into subgroups sharing common discriminant ion markers.

PCA coordinate distance matrices from the first three dimensions of the following- descriptive sensory analysis mean ratings (DA), mean peak areas of discriminant ions from e-nose analysis, and means of AUC of volatiles analyzed by HS-SPME-GC-MS were used to conduct Pearson's correlation test and depicted in a scatter plot.

Results and Discussion

Descriptive analysis

Panelists consistently and significantly (ANOVA, $p < 0.05$) differentiated pulse varieties based on appearance, aroma, aroma-by-mouth, taste, and aftertaste. The ANOVA results showed that out of twenty-five sensory descriptors, twenty descriptors were significantly discriminating ($p < 0.05$). The following attributes did not show significance: mushroom odor, boiled potato odor, boiled potato flavor, bitter taste, and bitter aftertaste. Mean panel attribute ratings and least significant difference (LSD) values for the significantly discriminating ($p < 0.05$) descriptive sensory attributes grouped by modality are reported in Table 4.2.

Table 4.2: Mean ratings on a 0 to 15 intensity scale for attributes that showed significant differences between samples (ANOVA, $p < 0.05$) from descriptive analysis grouped by modality for non-roasted porridge (NRP), roasted porridge (RP) and boiled pulse (BP) of eight pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN). Means are the average ratings for attributes from nine panelists over two replications. Least Significant Difference (LSD) and sample effect p values for each sensory attribute in a column are also reported. For each attribute column, mean values that do not share a letter are significantly different ($p < 0.05$).

Modality: Appearance, Taste and Aftertaste					
Sample	**Color Value**	**Color Saturation**	**Taste Sour**	**Taste Umami**	**Aftertaste Astringent**
p-value	6.8E-81	4.6E-67	8.3E-05	5.0E-14	2.0E-07
LSD value	0.55	0.49	0.99	1.04	1.17
N_NRP	2.25^{l}	2.51^{jklm}	1.46^{bcdefg}	4.61^{a}	2.82^{bcd}
N_RP	3.01^{j}	3.36^{fg}	1.97^{abcd}	4.69^{a}	3.36^{abc}
N_BP	2.36^{kl}	2.78^{hijkl}	0.88^{efgh}	1.71^{k}	1.41^{ef}
CHKP_NRP	4.72^{fg}	5.07^{b}	1.57^{bcdef}	3.94^{abcde}	3.39^{abc}
CHKP_RP	5.32^{de}	5.25^{b}	1.44^{bcdefg}	4.83^{a}	3.97^{ab}
CHKP_BP	6.19^{c}	7.69^{a}	1.47^{bcdefg}	$3.1^{defghij}$	2.53^{cde}
CR_NRP	7.19^{b}	2.33^{lm}	1.49^{bcdefg}	3.53^{bcdef}	4.04^{a}
CR_RP	7.51^{b}	2.56^{ijklm}	$1.39^{bcdefgh}$	3.52^{bcdefg}	4.15^{a}
CR_BP	8.92^{a}	3.15^{fgh}	0.58^{fgh}	2.91^{efghij}	2.33^{cde}
GN_NRP	2.57^{jkl}	2.48^{klm}	1.08^{defgh}	4.01^{abcd}	2.56^{cde}
GN_RP	4.08^{hi}	4.03^{cde}	1.55^{bcdef}	4.41^{ab}	2.52^{cde}
GN_BP	3.61^{i}	4.28^{cd}	0.52^{gh}	2.41^{hijk}	2.29^{cdef}
O_NRP	1.64^{m}	2.14^{m}	1.16^{cdefgh}	4.34^{abc}	2.07^{def}
O_RP	2.79^{jkl}	2.99^{ghij}	1.24^{cdefgh}	3.97^{abcd}	3.44^{abc}
O_BP	3.59^{i}	3.91^{de}	0.44^{h}	2.27^{jk}	1.79^{def}
WK_NRP	2.9^{jk}	3.01^{ghi}	1.86^{abcde}	$3.34^{cdefghi}$	2.02^{def}
WK_RP	4.74^{fg}	4.25^{cd}	2.09^{abc}	4.58^{a}	2.66^{cd}
WK_BP	4.82^{efg}	5.37^{b}	0.71^{fgh}	2.31^{ijk}	2.01^{def}
MN_NRP	3.74^{i}	3.56^{ef}	$1.4^{bcdefgh}$	4.35^{abc}	1.85^{def}
MN_RP	5.46^{d}	4.52^{c}	2.32^{ab}	4.91^{a}	2.37^{cde}
MN_BP	5.07^{def}	5.16^{b}	0.72^{fgh}	2.48^{ghijk}	1.87^{def}
MY_NRP	3.02^{j}	2.86^{hijk}	1.17^{cdefgh}	2.87^{fghij}	1.76^{def}
MY_RP	4.3^{gh}	3.39^{fg}	2.73^{a}	$3.43^{bcdefgh}$	2.31^{cdef}
MY_BP	3.81^{hi}	4.06^{cd}	0.52^{gh}	2.51^{fghijk}	1.16^{f}

Table 4.2 (cont'd)

Modality: Aroma								
Sample	**Aroma Tofu**	**Aroma Toasted Bread**	**Aroma Boiled Rice**	**Aroma Cream Of Wheat**	**Aroma Kidney Bean**	**Aroma Chickpea**	**Aroma Pinto Bean**	**Aroma Great Northern Bean**
p-value	9.3E-59	3.3E-06	1.3E-09	4.2E-03	7.4E-33	2.9E-38	3.2E-13	1.8E-09
LSD value	0.95	1.02	1.13	1.26	0.92	1.20	1.12	1.38
N_NRP	4.59^{c}	2.94^{efghij}	3.53^{cd}	3.84^{abc}	2.43^{hijkl}	2.85^{efgh}	2.3^{ghi}	4.14^{bcdef}
N_RP	2.75^{fghij}	3.1^{cdefghij}	3.46^{cde}	3.07^{cdef}	2.63^{hijkl}	2.71^{efgh}	2.98^{defghi}	2.47^{hij}
N_BP	1.68^{kl}	3.19^{cdefghi}	2.37^{efg}	2.01^{f}	2.63^{ghijkl}	3.73^{cde}	3.29^{cdefgh}	3.69^{efghi}
CHKP_NRP	9.63^{a}	2.6^{ghij}	4.94^{ab}	4.41^{ab}	1.79^{l}	4.41^{bc}	2.11^{i}	2.16^{j}
CHKP_RP	10.24^{a}	2.56^{hij}	5.43^{a}	4.44^{a}	2.02^{jkl}	5.61^{b}	2.69^{efghi}	2.57^{ghij}
CHKP_BP	3.24^{defgh}	4.44^{a}	3.34^{cdef}	2.66^{cdef}	2.47^{hijkl}	11.84^{a}	1.96^{i}	2.38^{ij}
CR_NRP	2.81^{fghij}	3.13^{cdefghij}	2.37^{efg}	3.54^{abcd}	3.71^{cd}	2.85^{efgh}	3.02^{defghi}	3.68^{efghi}
CR_RP	2.46^{ghijk}	4.06^{abcd}	2.74^{defg}	2.83^{cdef}	4.68^{b}	1.95^{gh}	4.49^{b}	3.17^{fghij}
CR_BP	2.12^{ijkl}	3.09^{defghij}	2.26^{fg}	2.14^{ef}	8.25^{a}	1.83^{h}	6.69^{a}	2.75^{ghij}
GN_NRP	3.81^{cde}	2.17^{j}	4.11^{bc}	2.78^{cdef}	2.18^{ijkl}	3.02^{defgh}	2.14^{i}	3.93^{cdefg}
GN_RP	1.95^{jkl}	3.06^{defghij}	3.08^{cdef}	2.95^{cdef}	3.31^{cdefgh}	2.85^{efgh}	3.41^{bcdefg}	3.77^{defgh}
GN_BP	2.31^{hijkl}	3.92^{abcde}	3.04^{cdef}	2.13^{ef}	3.04^{defghi}	3.48^{cdef}	3.46^{bcdef}	6.21^{a}
O_NRP	5.63^{b}	2.13^{j}	3.38^{cdef}	3.31^{abcde}	2.27^{ijkl}	2.51^{fgh}	2.23^{hi}	4.17^{bcdef}
O_RP	2.13^{ijkl}	4.12^{abc}	2.35^{efg}	3.64^{abc}	3.64^{cde}	2.84^{efgh}	4.28^{bc}	5.29^{abc}
O_BP	2.16^{ijkl}	2.93^{efghij}	1.85^{g}	2.31^{def}	2.78^{efghijk}	2.39^{fgh}	3.05^{defghi}	4.58^{bcde}
WK_NRP	2.76^{fghij}	2.79^{fghij}	2.49^{defg}	3.16^{bcdef}	2.36^{ijkl}	3.02^{defgh}	2.82^{defghi}	4.53^{bcdef}
WK_RP	2.99^{efghi}	3.59^{abcdefg}	2.47^{defg}	3.29^{abcde}	2.93^{defghij}	2.28^{fgh}	3.91^{bcd}	3.58^{efghi}
WK_BP	2.24^{ijkl}	3.39^{bcdefgh}	2.38^{efg}	3.21^{abcdef}	4.74^{b}	2.89^{efgh}	3.49^{bcdef}	5.28^{abc}
MN_NRP	3.28^{defg}	3.76^{abcdef}	2.91^{defg}	3.26^{abcdef}	2.72^{fghijk}	3.03^{defgh}	2.76^{efghi}	4.73^{bcde}
MN_RP	3.64^{cdef}	4.29^{ab}	3.1^{cdef}	3.34^{abcde}	3.55^{cdefg}	3.44^{cdef}	3.66^{bcde}	4.17^{bcdef}
MN_BP	2.01^{jkl}	3.7^{abcdef}	1.83^{g}	2.64^{cdef}	3.61^{cdef}	3.71^{cde}	3.06^{defghi}	5.13^{abcd}
MY_NRP	3.97^{cd}	2.36^{ij}	2.76^{defg}	3.51^{abcd}	2^{kl}	3.1^{defg}	2.43^{fghi}	5.37^{ab}
MY_RP	2.43^{ghijk}	3.44^{abcdefgh}	3.13^{cdef}	3.14^{cdef}	2.27^{ijkl}	2.36^{fgh}	2.96^{defghi}	3.62^{efghi}
MY_BP	1.47^{l}	4.07^{abcd}	2.28^{fg}	2.33^{def}	3.97^{bc}	4.17^{cd}	3.03^{defghi}	3.43^{efghij}

Modality: Aroma-by-mouth							
Sample	**Flavor Mushroom**	**Flavor Tofu**	**Flavor Vegetable**	**Flavor Kidney Bean**	**Flavor Chickpea**	**Flavor Pinto Bean**	**Flavor Great Northern Bean**
p-value	7.2E-10	2.9E-49	5.7E-11	5.5E-26	9.6E-56	2.6E-10	8.0E-09
LSD value	1.27	0.95	1.10	0.82	0.91	1.02	1.20
N_NRP	4.96^{abc}	3.67^{bc}	4.16^{ab}	2.14^{efgh}	3.01^{defg}	1.43^{gh}	4.3^{abc}
N_RP	3.56^{defghi}	2.57^{defghi}	2.43^{efgh}	1.67^{gh}	2.66^{efghi}	2.47^{cdef}	3.22^{cdefg}
N_BP	2.94^{ghi}	1.65^{ij}	1.67^{hi}	2.13^{efgh}	1.96^{ij}	1.65^{fgh}	3.41^{bcdef}
CHKP_NRP	3.49^{defghi}	8.58^{a}	1.8^{ghi}	1.54^{h}	4.66^{c}	1.23^{h}	2.07^{g}

Table 4.2 (cont'd)

CHKP_RP	2.99^{ghi}	9.12^{a}	1.31^{i}	2.09^{efgh}	6.32^{b}	2.34^{cdefg}	2.27^{fg}
CHKP_BP	3.46^{efghi}	3.65^{bc}	1.83^{ghi}	2.2^{efgh}	11.45^{a}	1.7^{fgh}	2.06^{g}
CR_NRP	5.43^{a}	2.75^{cdefgh}	4.14^{ab}	3.64^{bc}	2.58^{efghi}	2.24^{defgh}	4.72^{a}
CR_RP	5.08^{ab}	2.29^{efghi}	2.48^{efgh}	4.1^{b}	1.44^{j}	3.28^{bc}	2.99^{defg}
CR_BP	3.31^{fghi}	1.99^{ghij}	2.16^{fghi}	6.28^{a}	2.12^{ghij}	4.82^{a}	2.69^{efg}
GN_NRP	4.13^{bcdefg}	3.49^{cd}	3.27^{bcde}	2.06^{efgh}	2.79^{efghi}	1.55^{fgh}	3.92^{abcd}
GN_RP	3.79^{cdefgh}	2.32^{efghi}	2.58^{defgh}	2.49^{defg}	2.19^{ghij}	2.56^{bcdef}	4.11^{abcd}
GN_BP	2.36^{i}	1.86^{hij}	2.02^{ghi}	2.48^{defg}	2.9^{defgh}	2.34^{cdefg}	4.41^{abc}
O_NRP	4.38^{abcdef}	4.45^{b}	3.67^{abcd}	1.97^{efgh}	2.11^{ghij}	1.68^{fgh}	3.84^{abcde}
O_RP	3.39^{fghi}	2.94^{cdefg}	2.43^{efgh}	2.64^{def}	2.26^{ghij}	2.73^{bcde}	4.69^{a}
O_BP	2.37^{i}	1.87^{hij}	1.92^{ghi}	2.46^{defg}	2.27^{ghij}	2.44^{cdefg}	4.36^{abc}
WK_NRP	5.11^{ab}	3.08^{cdef}	4.23^{ab}	2.47^{defg}	2.57^{efghi}	2.24^{defg}	4.74^{a}
WK_RP	4.37^{abcdef}	2.76^{cdefgh}	2.79^{defg}	2.77^{de}	2.43^{fghi}	2.84^{bcd}	4.38^{abc}
WK_BP	2.62^{hi}	2.54^{defghi}	2.5^{efgh}	4.11^{b}	2.85^{defghi}	3.31^{bc}	3.99^{abcd}
MN_NRP	4.76^{abcd}	3.49^{cd}	3.95^{abc}	1.89^{fgh}	2.76^{efghi}	1.77^{efgh}	4.86^{a}
MN_RP	5.21^{ab}	3.37^{cd}	3.24^{bcdef}	3.84^{bc}	3.21^{def}	3.51^{b}	4.16^{abcd}
MN_BP	2.84^{hi}	2.16^{fghij}	2.32^{efghi}	3.23^{cd}	3.76^{cd}	1.81^{efgh}	4.63^{a}
MY_NRP	4.7^{abcde}	3.15^{cde}	4.37^{a}	2.17^{efgh}	2.86^{defghi}	1.82^{efgh}	4.69^{a}
MY_RP	5.38^{ab}	2.06^{ghij}	3.21^{bcdef}	2.73^{de}	2.06^{hij}	2.39^{cdefg}	4.61^{ab}
MY_BP	3.25^{fghi}	1.24^{j}	2.89^{cdefg}	3.03^{cd}	3.35^{de}	1.67^{fgh}	4.62^{a}

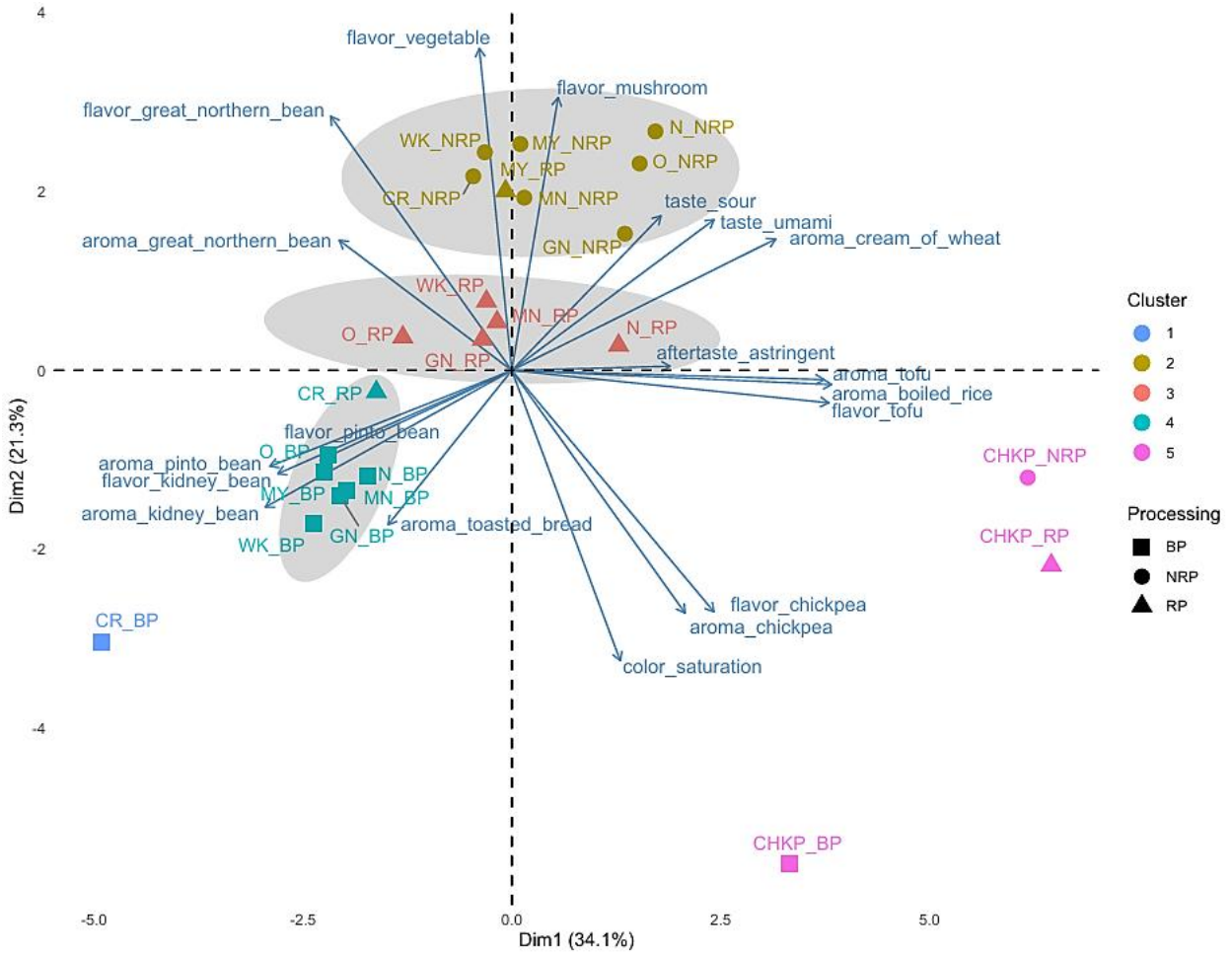

Figure 4.3: Principal component analysis biplot to visualize the effect of cultivar and processing treatments on significant sensory attributes ($p < 0.05$) of pulse samples in boiled pulse (BP), non-roasted porridge (NRP) and roasted porridge (RP) represented by squares (■), circles (●), and triangles (▲) respectively, across eight pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN). Hierarchical cluster analysis assigned colors and grouped samples into clusters with shared sensory profiles.

Effect of processing

Hierarchical cluster analysis (HCA) highlighted the distinct clustering of pulse samples based on processing treatments. PC1, PC2, and PC3 accounted for 31.4%, 21.3%, and 17% of the variance respectively in principal component analysis (PCA) (Figure 4.3). Boiled pulses (BP) were characterized by kidney and pinto bean-like odors and flavors, roasted porridge (RP) by great northern bean-like odors and flavors, and non-roasted porridge (NRP) by vegetative/green and mushroom/earthy/musty flavors. BP samples from white-colored beans (e.g., Navy, Great Northern, Otebo, White Kidney) and yellow-colored beans (e.g., Manteca, Mayacoba) (Figure 4.1)

formed cluster 4 in quadrant 3 associated with kidney- and pinto-bean-like odors and flavors. The panelists characterized the beany notes of great northern bean-like odor and flavor as sour beany while the pinto bean-like odor and flavor were described as sweet and beany. The "beany" odor and flavor ratings for these samples could have stemmed from their closer resemblance to canned bean references provided during the sensory evaluation. These references could have cued visual differences in panelists' perception, although, it also could be that boiling resulted in aroma profiles more similar to canned bean references. Previous literature has also characterized boiled beans with beany odor and flavor along with earthy, vegetative notes (Bassett et al., 2021; Koehler et al., 1987; Mkanda et al., 2007).

Interestingly, despite NRP and RP samples being visually indistinguishable, PCA revealed a distinct separation between them, confirming that roasting significantly altered the sensory profile of both white and yellow beans. In this study, PCA results revealed that NRP samples of all pulses except Chickpea were strongly associated with "known off-flavors" including vegetative/green (Troszyńska et al., 2011) and mushroom/earthy/musty flavors (Vara-Ubol et al., 2004). In contrast, RP samples of white-colored and Manteca beans were rated higher for "beany odor and flavor" attributes, such as canned great northern bean-like characteristics (Figure 4.3, Table 4.1). This suggests that roasting effectively reduces "known off-flavors" such as vegetative/green and mushroom/earthy/musty flavors but simultaneously increases some beany attributes. Previous research supports the potential of pre-treatment methods to mitigate off-flavors in pulses before their transformation into food ingredients. For example, Young et al., (2020) demonstrated that roasting peas prior to milling and incorporating the flour into bread reduced beany flavors. Similarly, Frohlich et al. (2019) showed that micronizing peas before milling improved bread formulations, while Der (2010) reported similar benefits when micronizing lentil seeds for low-fat beef burgers.

These findings highlight the importance of refining pre-treatment strategies such as roasting conditions, including time and temperature, tailored to the specific size and type of pulses, to enhance the flavor profiles of pulse-based products, making them more appealing for diverse food applications.

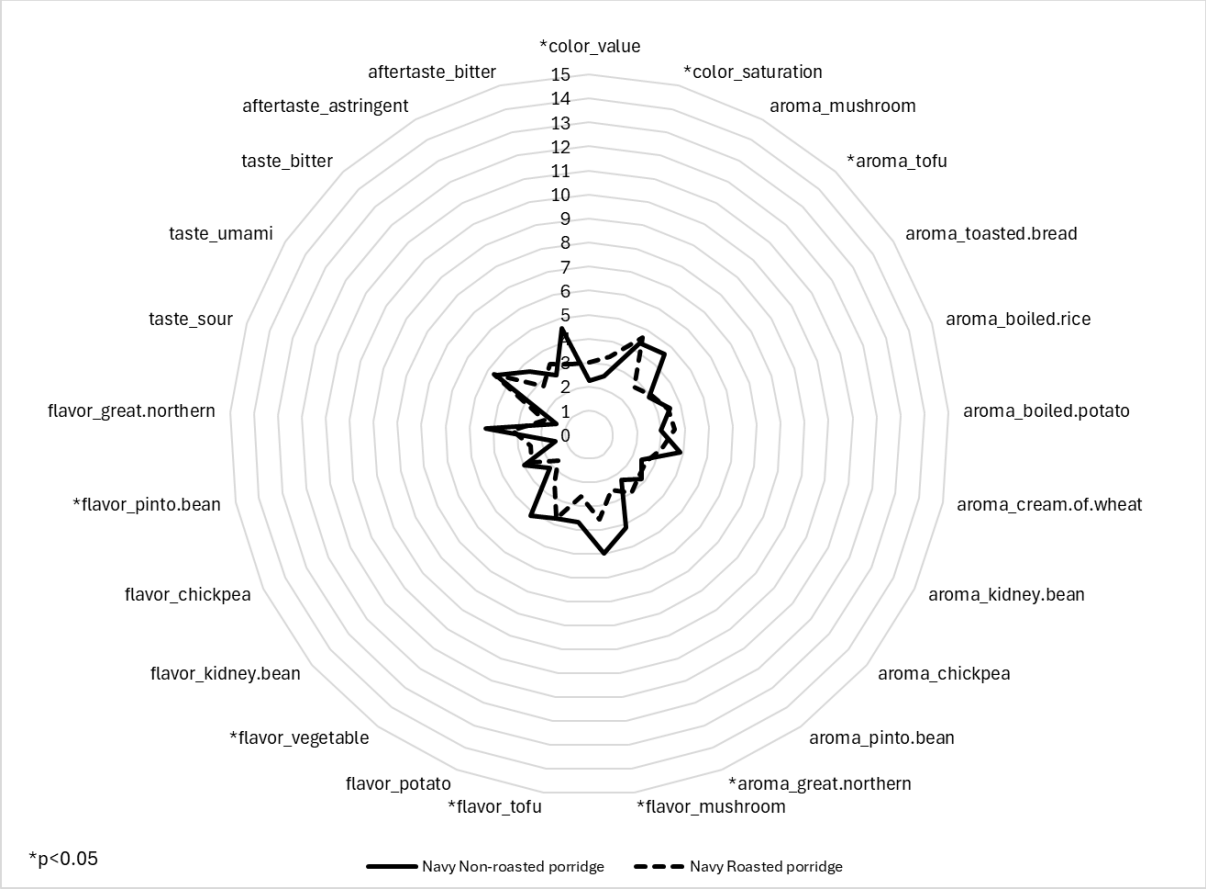

Figure 4.4: Radar plot displaying means of descriptive sensory analysis ratings of Navy non-roasted porridge (black) compared to Navy roasted porridge (dotted black). Asterisks refer to statistically significant change.

Effect of cultivar selection

Among the eight cultivars studied, Chickpea and Cranberry samples exhibited the most distinct sensory profiles, compared to the white and yellow-colored beans (Figure 4.1) (Figure 4.3). For chickpea, the differences could arise from its classification into a different genera from the rest of the samples—Chickpea *(Cicer arietinum)* and Common bean *(Phaseolus vulgaris),* respectively*,* which could explain their unique sensory characteristics. Panelists rated boiled Cranberry bean samples (cluster 1, quadrant 3) the highest for attributes like dark color (value), dull appearance (saturation), astringent aftertaste, and strong beany odors and flavors, including kidney- and pinto-bean-like notes. Chickpeas demonstrated distinct sensory characteristics across processing treatments (boiled, roasted, and non-roasted), consistently clustering separately from other pulses (Figure 4.4) and stood out for its tofu-like and canned chickpea-like odors and flavors, forming a cluster 5 in quadrant 4 of the PCA (Figure 4.4).

Both Chickpea and Cranberry NRP samples received the highest ratings for darkness of appearance and astringent aftertaste among all cultivars during sensory analysis. This astringency may be attributed to their biochemical composition. Non-volatile compounds–such as isoflavones, saponins, and phenolics have been associated with bitterness and astringency in soybeans and peas, respectively (Roland et al., 2017). Chickpeas contain phenolic isoflavones, including formononetin and biochanin A, which activate the same bitter receptors as other isoflavones like daidzein and genistein, suggesting they may also impart bitterness (Roland et al., 2011). Additionally, phosphatidylcholine, identified in defatted chickpea flour (Sánchez-Vioque et al., 1998), has been linked to bitterness in soybeans when oxidized (Sessa et al., 1974). This suggests that phosphatidylcholine oxidation in chickpeas may similarly contribute to bitterness. Additionally, dark-colored pigmented pulses, such as Cranberry beans, exhibited the highest total phenolic levels (19.12 mg/g DW) compared to non-pigmented, lighter-colored beans like Navy, Great Northern, Otebo, and White Kidney (Olumide O. Fashakin et al., n.d.) (Figure 4.1). This highlights the distinct flavor and odor profiles of Cranberry bean and Chickpea compared to white-colored beans as in the first row of Figure 4.1, particularly Navy and Great Northern beans, which exhibited milder sensory attributes (Table 4.2). This observation aligns with existing literature, which indicates that lighter-colored beans tend to have milder flavors, making them more versatile for use in food manufacturing. For instance, boiled white-colored beans were characterized as starchy and sweet with shorter cooking times, whereas dark-colored beans exhibited stronger vegetative and earthy intensities (Bassett et al., 2021). Studies further support the acceptability of light-colored beans for use in flour products; for example, a study conducted by Hooper et al. (2023) showed white kidney bean pasta received higher acceptability scores for overall liking and appearance on a 9-point hedonic scale than darker-colored Mayacoba and Black bean pasta prototypes. Winged bean seeds with lighter colors were also noted for their mild, nutty flavor, making them generally more acceptable compared to darker, bitter varieties (Ruberte & Martin, 1979).

An interesting finding in our study was observed in the Navy bean. Navy RP exhibited significantly reduced “known off-flavors”, such as mushroom/earthy/musty and vegetative/green/grassy flavors compared to Navy NRP (Chigwedere et al., 2022). Although the great northern bean-like odor was significantly reduced, a small but statistically significant increase in pinto bean-like flavor was also observed in Navy RP compared to Navy NRP (Figure 4.4). These findings highlight the

significant impact of cultivar selection on the sensory characteristics of pulse flour. Additionally, promoting the use of light-colored bean flours, such as Navy and Great Northern, due to their closer resemblance to the color of wheat flour and milder flavor intensity could increase their adoption in gluten-free pulse-based products as alternatives to the commonly used Chickpea flour (Sadohara et al., 2022).

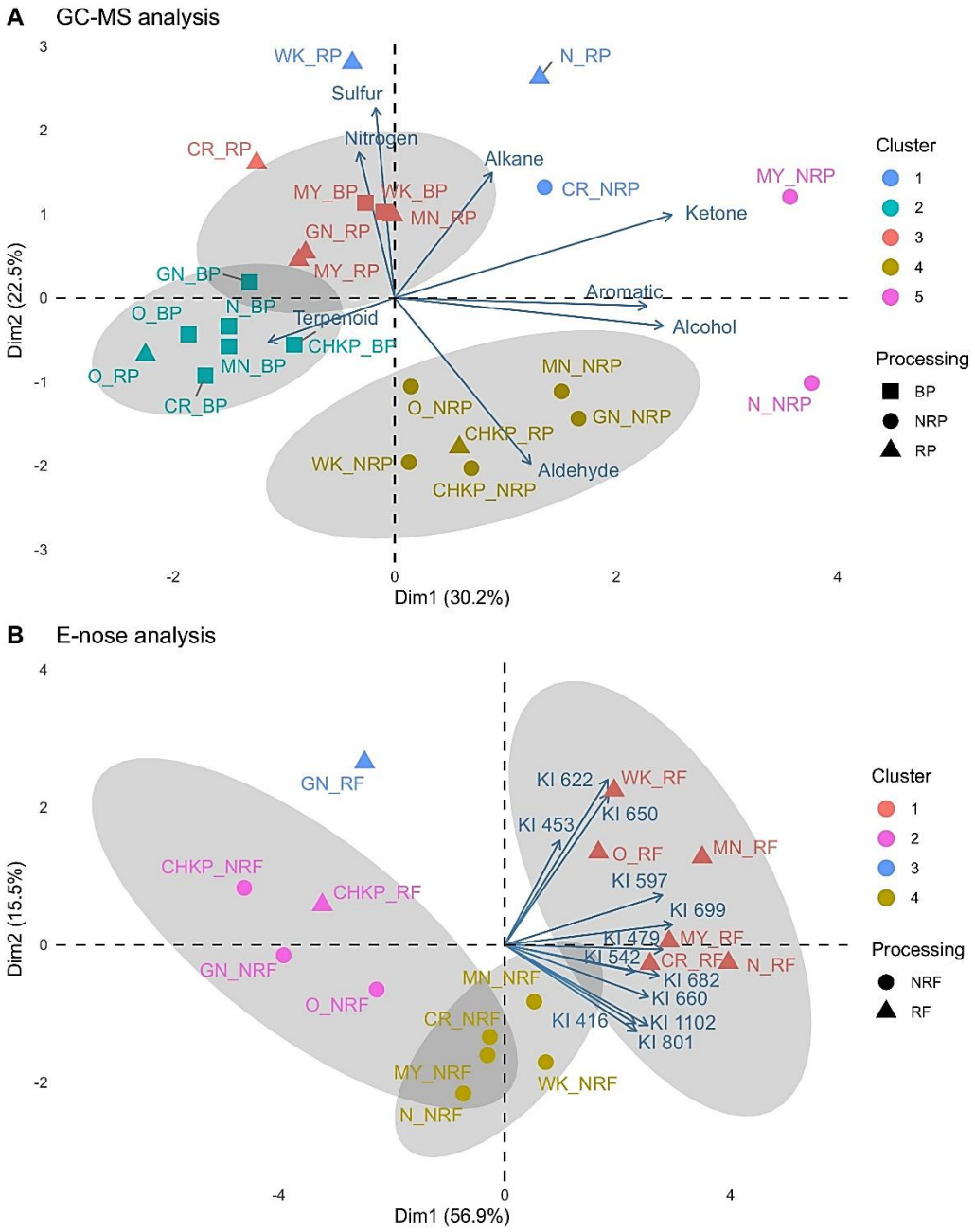

Figure 4.5: Characterization of pulse flavor via GC-MS and e-nose. A) Principal component analysis (PCA) biplot to visualize the relationship between area under the curve of volatiles

Figure 4.5 (cont'd)

analyzed by HS-SPME-GC-MS, grouped by chemical class, and pulse samples in boiled pulse (BP), non-roasted porridge (NRP) and roasted porridge (RP) represented by squares (■), circles (●), and triangles (▲) respectively, across eight pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN). Samples sharing similar volatile profiles are clustered together using hierarchical cluster analysis (HCA) and represented by distinct colored clusters. B) PCA biplot to visualize the relationship between peak areas of discriminant ions (DI>0.97), identified through PLS analysis of peak areas from e-nose analysis and mean panel attribute ratings from descriptive sensory analysis, for non-roasted flour (NRF) and roasted flour (RF) samples represented by circles (●) and triangles (▲) respectively, for eight pulse cultivars: N, O, CR, CHKP, MN, MY, WK, GN. HCA grouped samples with similar discriminant ion profiles into distinct colored clusters. Predictive compound identities associated with the discriminant ions are listed in Table S3.

Instrumental techniques applied to the study of off-flavors in pulses

Volatile compound analysis by HS-SPME-GC-MS

Targeted GC-MS analysis identified 32 volatile compounds, including aldehydes (8), alcohols (6), ketones (4), aromatics (6), terpenoids (1), alkanes (1), nitrogen-containing compounds (2), and sulfur-containing compounds (4). In total, 12 key volatile compounds were significantly correlated ($p < 0.05$) with odor and flavor intensities assessed by DA sensory analysis, were identified, highlighting their critical roles in shaping the sensory profiles of pulses through their associations with "known off-flavors" like vegetative/green, mushroom/ earthy and beany attributes. The identified compounds included (E)-2-hexenal, decanal, benzaldehyde, 1-hexanol, 1-octen-3-ol, 3-methyl butanol, styrene, L-limonene, 2-pentyl furan, naphthalene, 3,5-octadien-2-one, and 6-methyl-5-hepten-2-one.

To explore the relationships between volatile profiles of cooked pulse samples (NRP, RP, and BP) across eight cultivars, Principal Component Analysis (PCA) was conducted. Together, PC1 (30.2%), PC2 (22.5%), and PC3 (15%) explained 67.7% of the variance in the volatile peak areas. Processing treatment drove differences in volatile profiles of the cooked samples (NRP, RP, and BP) such that NRP samples clustered predominantly in quadrants I and IV. In contrast, the thermally processed RP and BP samples are clustered in quadrants II and III respectively (Figure 4.5A).

NRP samples from Mayacoba and Cranberry cultivars clustered in quadrant I, forming clusters 1 and 5 respectively exhibited higher concentrations of alkanes and ketones, while Chickpea, White Kidney, and Great Northern beans in quadrant IV represented by cluster 4 were associated with aldehydes, alcohols, and aromatics. The NRP samples were mainly characterized by higher

concentrations of aldehydes and alcohols. Alcohols such as 1-octen-3-ol (R=0.67), and 3-methyl butanol (R=0.41) were significantly correlated with mushroom/earthy/ musty flavors while 1-hexanol (R=0.61) was significantly correlated with vegetative/green flavor ($p<0.05$). Similarly, aldehydes including (E)-2-hexenal (R=0.67) and benzaldehyde (R=0.61) were significantly correlated to vegetative/green flavors while decanal (R=0.65), benzaldehyde (R=0.64) and (E)-2-hexenal (R=0.51) were significantly correlated with mushroom/earthy/ musty flavors as observed in descriptive sensory analysis (DA) data ($p < 0.05$). These findings align with previous studies. For instance, (Vara-Ubol et al., 2004) used descriptive sensory analysis and HS-SPME-GC-MS to demonstrate that low concentrations (1–10 ppm) of hexanol and 2-pentyl furan contributed to musty and earthy notes, while hexanal was strongly associated with green/pea pod aromas. Similarly, Xu et al. (2019) identified hexanal (grassy), (E, E)-2,4-nonadienal (rancid), 1-hexanol (green), 1-octen-3-ol (mushroom), and 2-pentyl furan (green bean) as key markers of beany flavors in germinated lentil flour using HS-SPME-GC-MS/olfactometry. In our study, although significant correlations ($p < 0.05$) were observed between individual volatiles and sensory attributes among chemical classes, alcohols uniquely exhibited significant correlations ($p < 0.05$) with both vegetative ($R = 0.62$) and mushroom/musty ($R = 0.50$) flavors, as determined by DA sensory analysis. Thus, in less thermally processed NRP samples, alcohol concentration could be the predictive indicator of known off-flavors in pulses. NRP samples across all pulses except Chickpea demonstrated elevated levels of hexanal, hexanol, 1-octen-3-ol, and 2-pentyl furan, which corresponded to stronger intensities of vegetative/green and mushroom/earthy off-flavors in descriptive sensory analysis (Figure 4.3). Roasting significantly ($p < 0.05$) reduced these volatiles in RP samples, particularly in the Navy cultivar, explaining the lower sensory intensities of vegetative/green and earthy/musty flavors in RP samples compared to NRP samples in Navy (Figure 4.4). Since the NRP samples were characterized by higher concentrations of aldehydes and alcohols, these results highlight the importance of roasting in mitigating known off-flavors by decreasing the concentrations of key volatiles responsible for vegetative/green and mushroom/earthy flavors. Additionally, roasting offers a more scalable, energy-efficient, and nutrient-preserving solution for pulse flour processing compared to boiling.

In contrast to NRP samples, the thermally treated RP and BP showed higher levels of terpenoids, sulfurous, and nitrogenous compounds. Specifically, quadrant II predominantly included RP samples from Manteca, Mayacoba, Cranberry, White Kidney, and Great Northern cultivars. These

samples exhibited elevated levels of sulfurous compounds such as dimethyl disulfide and methional as well as nitrogenous compounds, which were not detected in NRP samples. Following heat treatment, nitrogenous compounds like 3-butyl-2,5-dimethyl-pyrazine and 2,5-dimethyl-pyrazine increased significantly ($p<0.05$) in RF and RP samples of Cranberry, White Kidney, Manteca, and Mayacoba cultivars. Alkylpyrazines, which contribute a nutty flavor, are primarily formed through Maillard reactions between amino acids and carbohydrates Shibamoto & Bernhard, (1977) or by the pyrolysis of serine and threonine Baltes & Bochmann, (1987) during thermal treatments. Sulfur compounds and pyrazines, despite their low odor thresholds Landaud et al., (2008); Müller & Rappert, (2010), did not show significant correlations with sensory attributes from DA analysis in this study. This limitation may stem from the targeted approach for GC-MS analysis chosen in this study, which may not have encompassed a broader range of sulfurous and nitrogenous compounds that could potentially contribute to the beany odors observed in sensory evaluations. Expanding the scope of targeted compounds in future analyses or leveraging the untargeted profiling could provide a more comprehensive understanding of the volatile markers contributing to beany odors. Quadrant III, on the other hand, consisted mostly of BP samples from Otebo, Navy, Manteca, Chickpea, Cranberry, and Great Northern cultivars. These samples were primarily associated with terpenoid compounds. The presence of monoterpenes such as α-pinene, β-pinene, sabinene, 3-carene, myrcene, limonene, (Z)-β-ocimene, and (E)-β-ocimene may originate from endogenous isoprenoid biosynthesis or carotenoid degradation, potentially catalyzed by lipoxygenase (LOX) or hydroperoxides. Terpenoids showed significant positive correlations ($p<0.05$) with chickpea-like, kidney bean-like, and pinto bean-like beany odors and flavors from DA sensory analysis. Terpenoids have been reported to increase after roasting in flours of navy, red kidney bean, and yellow pea (Ma Zhen et al., 2016) and blanching in green peas (Barra et al., 2007; Jakobsen et al., 1998; Oomah et al., 2007). However, these compounds have not been directly linked to producing beany odors and flavors in prior research. In fact, (Y. Liu et al., 2023) reported "fragrant" sensory properties of egg white powder linked to high terpene content, and other studies have suggested that compounds like limonene and linalool could mask unpleasant odors (Ben Salha et al., 2021). This limitation highlights that targeted GC-MS was unable to identify volatiles or chemical classes responsible for beany odors and flavors.

In summary, targeted GC-MS analysis identified 12 key flavor compounds that were significantly correlated ($p<0.05$) with odor and flavor intensities based on DA sensory analysis. The analysis

also provided deeper insights into the role of roasting in mitigating aldehydes and alcohols associated with vegetative/green and mushroom/earthy/musty off-flavors, showcasing the method's capability for precise qualitative and quantitative profiling of volatile compounds.

Volatile compound analysis by e-nose

Flour samples were analyzed using an e-nose to determine whether volatile profiles from raw flour could predict the flavor attributes of cooked pulse products, aimed to streamline product development by identifying key markers directly from raw materials. The e-nose detected 64 major peaks, with 12 peaks identified as discriminant ions through partial least squares regression (PLS) analysis of e-nose data and DA sensory assessments. Retention times of these discriminant ions were converted to Kovats indices (KI), and potential compound profiles were suggested using the (AroChemBase) database.

E-nose distinguished the volatile profiles of NRF and RF samples from eight pulse cultivars, explaining 81% of the variance in discriminant ions across the first three principal components (Figure 4.5B). NRF samples clustered in quadrants III and IV (Cluster 4), predominantly representing White Kidney, Mayacoba, Manteca, and Cranberry cultivars. These samples were associated with discriminant ions KI-801, KI-1102, and KI-416, potentially linked to aldehydes and alcohols such as hexanal (leafy), nonanal (sweet), methanol (pungent), and butanol (cheese, sweet, oily, medicinal) odors (AroChemBase) (Table S3). KI-801 and KI-1102 were significantly positively correlated ($R = 0.5$, $p < 0.05$) with mushroom/musty flavors identified in DA sensory analysis. However, e-nose did not identify discriminant ions directly correlated with vegetative/green flavors observed in DA results.

Conversely, e-nose data aligned well with DA results in identifying markers associated with increased beany odors and flavors after roasting (Figure 4.2, Figure 4.3). RF samples clustered in quadrants I and IV (Cluster 1), primarily including White Kidney and Otebo cultivars. These samples were associated with discriminant ions KI-622, KI-650, and KI-453, tentatively identified as butanals (almond, toasted, malty), furans (beany, sweet, metallic, vegetable), and sulfurous compounds (rotten cabbage, onion) odors (AroChemBase) (Table S3). Similarly, RF samples from Mayacoba, Manteca, and Cranberry cultivars were linked to ions KI-479, KI-597, and KI-699, potentially linked to butanal (almond, toasted, malty), pentanal (nutty, almond), propanal (nutty, earthy), and sulfurous compounds such as propanethiol (rotten cabbage, onion) and dimethyl sulfide (rotten, sulfurous) (AroChemBase) (Table S3). Among these discriminant ions, KI-622,

KI-650, KI-479, KI-597, and KI-699 were significantly correlated with toasted odors (R = 0.7) and canned kidney bean- (R = 0.6) and pinto bean-like odors and flavors (R = 0.7) from DA sensory assessments ($p < 0.05$). These markers, likely linked to butanals (toasted, malty), furans (burnt, sweet), and sulfurous compounds (rotten cabbage, onion), provide insights into volatile compounds contributing to toasted and beany odors and flavors in pulses after roasting. Previous studies have highlighted the role of sulfurous and furan compounds in off-flavors. (Mishra et al., 2019) demonstrated correlation of volatile profile data with descriptive sensory analysis and odor activity values to establish the role of sulfurous compounds, such as methanethiol, diethyl sulfide, dimethyl disulfide, methional, and dimethyl trisulfide, contributing to "cooked kidney beany" aroma, while dimethyl sulfoxide and dimethyl sulfone were associated with sulfurous odors. Furans, commonly formed through Maillard reactions or the thermal degradation of sugars, amino acids, carotenoids, and polyunsaturated fatty acids (PUFAs) like linoleic acid (Izzotti & Pulliero, 2014; Min et al., 2003). (Sharan et al., 2022; Trindler, Annika Kopf-Bolanz, et al., 2022; C. Wang et al., 2021) identified 2-ethyl furan and 2-pentyl furan as key contributors to earthy, green, and beany notes in peas, faba beans, and soybeans.

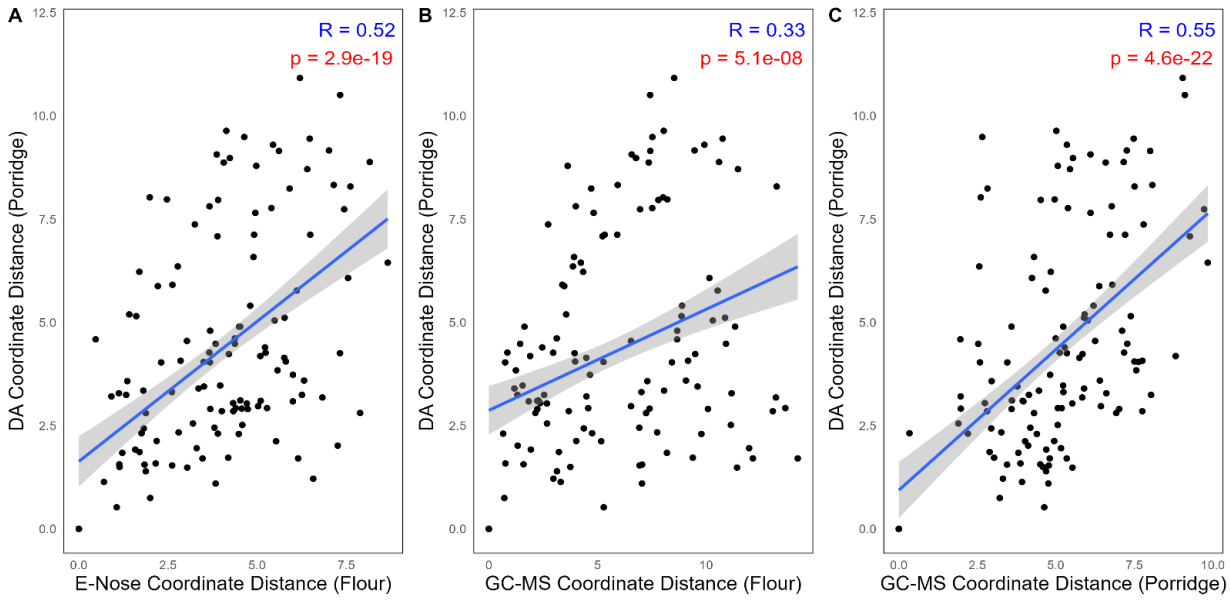

Figure 4.6: Scatter plot with linear trendline demonstrating the relationship between PCA coordinate distance matrices of descriptive sensory analysis mean ratings (DA) for non-roasted porridge (NRP) and roasted porridge (RP) porridges with PCA coordinate distance matrices of A) discriminant ions from e-nose analysis in non-roasted flour (NRF), roasted flour (RF); B) PCA coordinate distance matrices of volatiles analyzed by HS-SPME-GC-MS in NRF and RF; C) volatiles analyzed by HS-SPME-GC-MS in NRP and, RP. R-values indicate the Pearson's correlation coefficient between the two variables depicted in the scatter plot. P-value < 0.05 indicates statistical significance in predicting sensory attributes.

Comparing GC-MS and e-Nose for rapid off-flavor profiling in pulses

An objective of this study was to evaluate the effectiveness of GC-MS and E-nose in predicting off-flavors in pulses, determining which technique offers better potential for rapid profiling. We evaluated how well profile distances for e-nose or GC-MS predicted the degree of sensory difference (Figure 4.6). While descriptive analysis (DA) remains the benchmark for assessing sensory profiles, its reliance on trained panels, extensive sample preparation, and high costs makes it impractical for large-scale or high-throughput evaluations (Shurmer & Gardner, 1992). Instrumental techniques such as GC-MS and e-nose address these limitations by offering efficient, reproducible, and time-saving alternatives for off-flavor profiling. These methods can identify chemical compounds associated with sensory perception, complementing traditional DA approaches.

A significant correlation (p= 4.6e-22, R = 0.55) was observed between GC-MS volatile profiles and sensory attributes in cooked pulse products (NRP, RP) (Figure 4.6C). However, its ability to predict sensory characteristics from uncooked pulse flours (NRF, RF) was limited, as evidenced

by weaker correlations (p=5.1e-08, R = 0.33, Figure 4.6B). Since GC-MS relies on analyzing individual volatile compounds, it may overlook the complex interactions that contribute to sensory perception particularly, in diverse physical matrices and chemical constituents, further complicated by individual differences in human odor perception. Unlike this approach which relied on targeted GC-MS analysis, the e-nose uses an untargeted methodology, enabling the identification of a broader range of volatile compounds. As shown in Figure 4.6A, the e-nose demonstrated a significant correlation (p= 2.9e-19, R = 0.52) between discriminant ions in uncooked pulse flours (NRF, RF) and sensory data for cooked products (NRP, RP) (Figure 4.6A). The discriminatory ions KI-622, KI-650, KI-453, KI-479, KI-597, and KI-699 identified by e-nose, could serve as a digital fingerprint for beany odors and flavors. This ability to predict beany notes directly from raw pulse flour without cooking makes the e-nose a valuable tool for rapid screening. This can allow breeders and product developers to rapidly identify cultivars or formulations with reduced off-flavors, eliminating the need for extensive sample preparation and cooking. Additionally, e-nose has been reported to facilitate the optimization of processing parameters, such as roasting time and temperature, to minimize the formation of undesirable volatile compounds. Previously Cai et al., (2021) investigated the effects of various roasting time and temperature levels on the physicochemical, sensory, and volatile profiles of soybeans using both e-nose and HS-SPME-GC-MS techniques. Similarly, Asikin et al. (2018) compared the ripening stages of dogfruit *(Pithecellobium jiringa)* and stink bean *(Parkia speciosa)* using HS-SPME-GC-MS and an MS-based E-nose. The results from these studies concluded that HS-SPME-GC-MS identified specific marker compounds providing detailed chemical profiles and insights into the aroma changes. In contrast, the e-nose used discriminant ion masses to generate overall aroma profiles, enabling rapid differentiation between pre-treatment conditions or ripening stages through multivariate analysis. E-nose's ability to analyze overall aroma profiles highlights its strength in rapid screening and quality control, particularly for industrial applications. Key advantages of e-nose include high sensitivity, rapid analysis times, and ease of use, making it a practical tool for settings far removed from specialized chemical laboratories (Dymerski et al., 2011; Otles, 2016; Van Ruth, 2001). Despite these advantages, GC-MS remains an essential tool for quantifying specific volatile changes and understanding the effects of processing on pulse volatiles, such as those induced by roasting. These approaches offer a robust strategy for optimizing product development and quality

control in pulse-based foods, enabling both rapid screening and detailed characterization of volatile profiles.

Conclusion

This study investigated the sensory characteristics and volatile profiles of eight pulse cultivars to address challenges associated with off-flavors and processing in pulse-based products, while also evaluating the potential of instrumental approaches to predict flavor development. Sensory and volatile differences across cultivars and processing methods were observed using DA, GC-MS, and e-nose. Sensory analysis revealed that cultivars were differentiated primarily based on appearance and seed coat characteristics. The sensory and volatile profiles following processing pre-treatments, such as roasting and boiling, demonstrated shifts in the flavor profiles of treated pulse samples, with some flavors reducing and others intensifying as a result of heat treatment. E-nose successfully captured dynamic changes in key beany flavor markers, aligning with DA findings better than targeted GC-MS, demonstrating its potential as a predictive tool for flavor profiling in pulses. However, the untargeted approach of e-nose may have cast a wider net, detecting broader classes of discriminant ions potentially arising from furans or sulfurs that were underrepresented during targeted GC-MS analysis. Additionally, differences in column polarity between the two instruments could have influenced volatile separation and detection. Finally, since model products (roasted and non-roasted porridges) were not analyzed using e-nose, it is difficult to conclusively determine its superiority over GC-MS in predicting sensory characteristics of finished products.

The findings provide a foundational understanding of how cultivar selection, heat processing, and volatile composition influence the sensory quality of pulses. Future research should explore the impact of different milling techniques on flavor profiles. Investigating the effects of alternative pre-treatment methods, such as infrared radiation or optimized roasting, and leveraging e-nose as a rapid screening tool, can help identify processing conditions that enhance sensory quality. Identifying cultivars tailored for specific product applications could significantly improve consumer acceptance. Furthermore, consumer testing is needed to evaluate whether the sensory profile changes resulting from processing are perceived positively or negatively, particularly in the context of targeted food applications like snacks, pastas, or baked goods.

This study highlights the complementary roles of GC-MS and e-nose techniques in refining pulse flour flavor profiles. By providing actionable insights into optimizing processing parameters and

cultivar selection, these findings contribute to the integration of pulses into diverse food products, promoting their utilization in sustainable food systems and addressing global food security challenges.

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Chapter 5: Conclusion

Research Summary

This research examined how cultivar, processing, and harvest year influence the volatile composition of pulses and how cultivar and processing affect their sensory profiles. The findings provide critical insights into factors affecting off-flavor formation in pulses and offer strategies to improve sensory quality. Using sensory descriptive analysis (DA), headspace-solid phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS), and electronic nose (e-nose), this study demonstrated that cultivar and processing treatments significantly shape the composition of volatile organic compounds (VOCs), which directly impact sensory perception. Additionally, this research evaluated the potential of e-nose as a rapid screening tool for detecting off-flavors in pulses and compared its effectiveness to GC-MS in predicting sensory attributes.

Hierarchical clustering and principal component analysis revealed that seed coat color and harvest year drove differences in total volatile concentration and volatile composition. These findings highlight the role of cultivar and environmental conditions in shaping pulse flavor. Processing methods such as roasting and boiling altered VOC profiles, with boiling causing the greatest reduction in volatiles. However, roasting is a more practical pre-treatment strategy for pulse flour production due to its energy efficiency, ease in industrial adoption, and nutrient retention compared to boiling. Roasting significantly reduced the concentration of alcohols and aldehydes, but it also increased sulfurous and nitrogenous compounds in the roasted model product compared to non-roasted product (Chapter 3).

Studying the sensory profile of pulse flour in a simple matrix like porridge provided valuable insights for incorporating them into various food formulations. DA showed that roasting decreased vegetative/green and earthy/musty/mushroom flavors, which significantly correlated with alcohol and aldehyde volatile markers identified from GC-MS. Roasting increased beany odors and flavors, but GC-MS did not identify specific volatile compounds directly correlated to these sensory attributes. This suggests that either the volatiles responsible for beany notes were not included in the analytical targets, or that complex interactions between compounds contribute to the perceived beany flavor. Among cultivars, dark-colored pulses, such as cranberry beans, had stronger beany odor characteristics, whereas lighter-colored pulses, including navy and great northern beans, exhibited milder sensory profiles especially after roasting (Chapter 4).

Instrumental analysis revealed key differences between GC-MS and e-nose in detecting volatiles and predicting flavor. While GC-MS identified key VOCs associated with several key off-flavors, its capacity to predict the intensity of beany notes in samples based on flour or model products VOCs was limited. In contrast, e-nose analysis of flours significantly correlated discriminant ions (potentially associated with furans and sulfurous compounds) with sensory ratings of beany flavors in cooked product, suggesting it can serve as a high-throughput tool for rapid flavor screening without requiring the cooking of large sample sets (Chapter 4). These findings support the integration of multiple analytical techniques to improve the sensory quality of pulse-based products.

Future Directions

Future research should focus on optimizing roasting and exploring novel pre-treatment methods such as infrared radiation to mitigate the formation of undesirable aroma compounds while preserving the nutritional integrity of pulses. Additionally, developing calibrated models using e-nose to optimize processing conditions based on physical characteristics of pulses including seed coat color and size will help streamline process development. Further studies should also assess how different milling techniques impact the sensory and functional properties of pulses.

Breeding milder-flavored pulse cultivars presents an opportunity to enhance sensory quality, making them easier to formulate into various food products. Consumer acceptance studies can identify cultivars for targeted food applications based on their sensory profiles and determine whether the shift in aroma profile from vegetative/green and earthy/musty/mushroom to beany notes due to roasting is perceived positively or negatively.

By addressing both genetic factors and processing-related issues, this research can help increase pulse consumption and promote sustainable, plant-based food systems.

APPENDIX

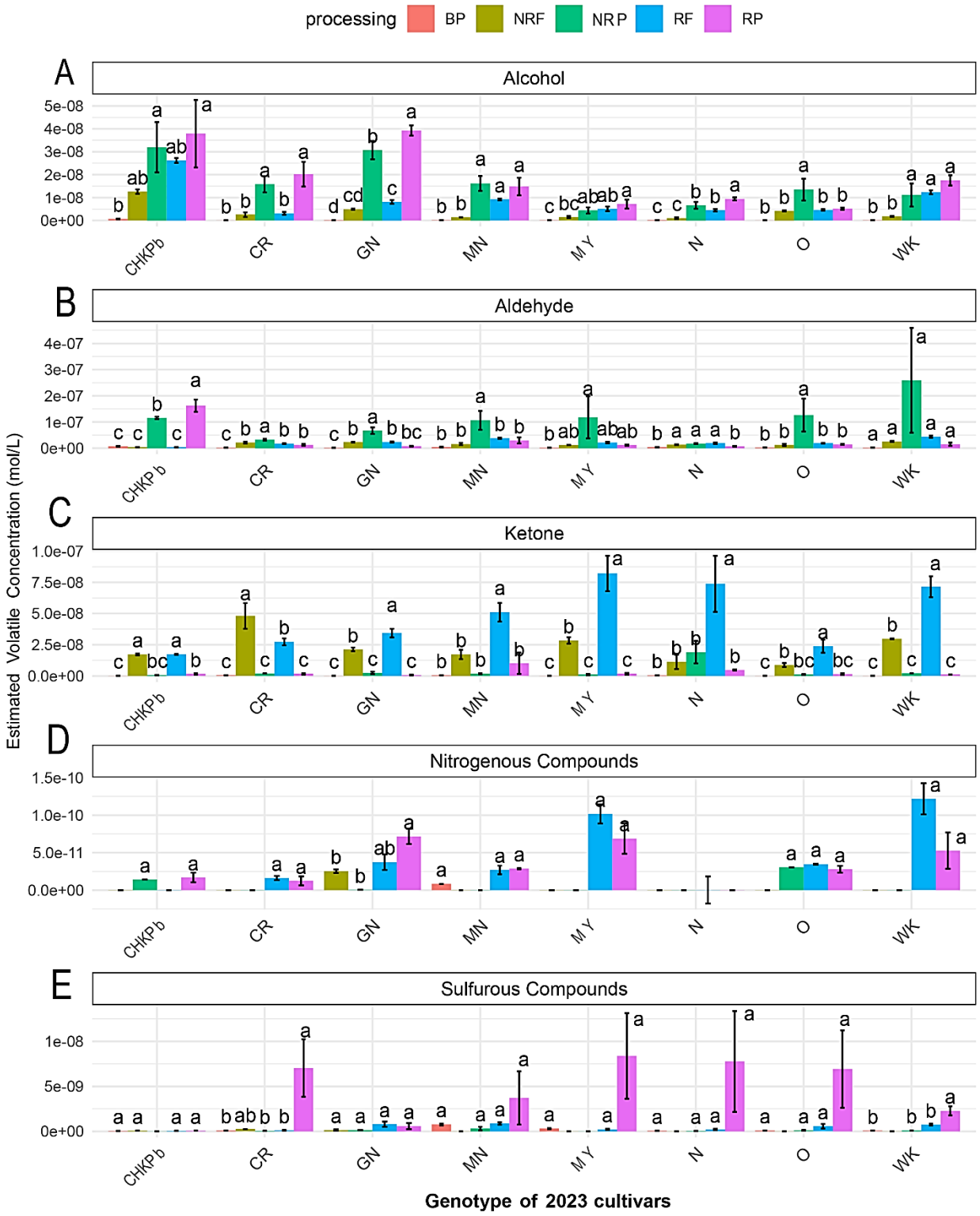

Figure S1: Effect of thermal processing (roasting; boiling) on the estimated volatile concentration of (A) alcohols; (B): aldehyde; (C): ketone; (D): nitrogenous compound; (E): sulfurous compound

Figure S1 (cont'd)

of eight cultivars grown in 2022: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), and Great Northern (GN) in non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP) and boiled pulses (BP). Results are the average value from triplicates. For each type of pulse, mean values that do not share a letter are significantly different ($p < 0.05$) as per the LSD post hoc comparison test. (Chapter 3).

Table S1: Estimated concentration in mol/L of volatiles quantified using authentic chemical standards across non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP), and boiled pulses (BP) from the pulse cultivars (Cranberry, Great Northern, Navy, Otebo, White Kidney, Manteca and Mayacoba) grown in harvest year 2023 from Michigan and a market sample of Chickpea obtained commercially (harvested in 2022). These samples were analyzed August through September 2024. Values represent the average of triplicate measurements grouped by chemical class. nd: not detected. Odor descriptions reflect the top three odor notes as reported by The Good Scents Company (2009) (Chapter 3).

White colored beans (estimated volatile concentration in mol/L)											
	Great northern beans					White Kidney beans					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	1.6E-09	2.8E-09	8.9E-09	1.1E-09	nd	3.2E-09	9.3E-09	9.8E-08	2.5E-09	2.4E-10	malty, musty, fermented
Hexanal	8.6E-09	7.6E-09	1.7E-08	1.3E-09	4.6E-10	8.0E-09	9.9E-09	1.1E-08	1.4E-09	2.7E-10	vegetable, aldehydic, clean
(E)-2-hexenal	2.1E-10	2.0E-10	5.5E-09	3.2E-10	nd	1.9E-10	2.8E-10	1.7E-08	1.3E-09	nd	sweet, vegetable, bitter almond
Heptanal	2.4E-10	3.2E-10	4.1E-10	4.8E-11	4.5E-11	3.7E-10	5.5E-10	3.2E-10	1.2E-10	4.6E-11	aldehydic, fatty, herbal
Benzaldehyde	2.0E-10	3.0E-10	1.2E-09	8.1E-10	6.0E-11	1.6E-10	4.5E-10	1.7E-09	1.4E-09	1.5E-10	sweet, cherry, nutty
Octanal	1.1E-10	5.7E-11	9.8E-11	4.6E-11	2.8E-11	1.5E-10	2.4E-10	1.9E-10	9.6E-11	4.9E-11	aldehydic, fatty, herbal
Nonanal	6.7E-10	4.4E-10	4.7E-10	2.3E-10	1.1E-10	6.7E-10	1.1E-09	1.1E-09	6.2E-10	2.7E-10	aldehydic, fatty, rose
Decanal	7.5E-11	4.9E-11	6.9E-11	5.7E-11	2.5E-11	9.9E-11	1.3E-10	1.5E-10	1.3E-10	2.7E-11	sweet, aldehydic, floral
ALCOHOL											
Butanol	4.3E-10	5.7E-10	1.6E-10	1.0E-10	nd	4.6E-10	1.5E-09	1.1E-10	9.3E-11	nd	sweet, fermented, oily
3-Methylbutanol	1.1E-09	2.8E-09	6.8E-09	1.6E-08	4.0E-11	7.5E-11	4.1E-09	1.5E-09	6.7E-09	nd	musty, vegetable, cocoa
1-Pentanol	3.3E-10	4.2E-10	2.0E-09	8.1E-10	1.1E-11	1.4E-10	2.8E-10	1.1E-09	3.4E-10	2.2E-11	sweet, fermented, yeasty
1-Hexanol	4.7E-10	1.8E-10	6.2E-09	2.7E-09	1.1E-11	1.3E-10	1.5E-10	4.0E-09	1.1E-09	1.2E-11	sweet, pungent, herbal
1-Octen-3-ol	1.1E-10	1.4E-10	1.6E-10	9.5E-11	6.6E-12	1.1E-10	1.8E-10	5.4E-10	5.5E-10	1.8E-11	vegetable, mushroom, chicken
KETONE											
2-Butanone	1.1E-08	1.7E-08	1.1E-09	2.7E-10	nd	1.5E-08	3.5E-08	1.0E-09	4.9E-10	nd	camphoreous, acetone, fruity
2-Heptanone	4.0E-11	8.1E-11	9.9E-11	5.7E-11	3.4E-12	3.2E-11	1.1E-10	7.2E-11	2.5E-11	5.4E-12	sweet, spicy, banana

Table S1 (cont'd)

6-Methyl-5-hepten-2-one	7.0E-12	5.9E-11	1.7E-11	1.9E-13	2.2E-12	2.3E-11	1.3E-10	1.8E-15	4.6E-11	5.7E-12	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	4.9E-10	4.1E-10	4.9E-10	5.2E-11	1.2E-10	4.5E-10	1.4E-09	3.5E-10	9.8E-11	1.5E-10	malty, cocoa, nutty
o-Xylene	6.4E-11	8.9E-11	1.5E-11	nd	5.7E-12	3.5E-11	5.1E-11	nd	nd	1.6E-11	geranium
Styrene	2.4E-11	4.4E-11	7.1E-12	8.1E-12	nd	2.6E-11	4.0E-11	nd	nd	nd	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	1.6E-11	9.7E-12	3.0E-12	1.7E-12	nd	1.2E-11	1.8E-10	2.4E-12	3.9E-12	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	2.2E-11	2.9E-11	8.1E-12	7.1E-12	5.5E-12	2.0E-11	2.6E-11	1.8E-11	5.7E-12	2.5E-12	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	6.7E-11	3.9E-10	6.5E-11	2.7E-10	nd	nd	3.7E-10	4.0E-11	1.1E-09	3.2E-11	vegetable, onion, cabbage
Methional	nd	1.8E-12	9.2E-13	2.2E-11	nd	nd	5.9E-12	nd	1.1E-11	1.6E-12	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	1.3E-11	1.9E-11	1.4E-13	3.6E-11	nd	nd	6.1E-11	nd	2.6E-11	nd	nutty, peanut, musty
White colored beans (estimated volatile concentration in mol/L)											
	Navy bean					**Otebo**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	1.3E-09	3.8E-09	2.3E-10	2.6E-10	6.7E-10	8.5E-10	1.8E-09	7.3E-08	2.0E-09	4.2E-10	malty, musty, fermented
Hexanal	4.1E-09	3.7E-09	3.6E-09	1.3E-09	9.2E-10	2.5E-09	5.7E-09	1.1E-08	2.9E-09	7.2E-10	vegetable, aldehydic, clean
(E)-2-hexenal	1.3E-10	1.8E-10	4.5E-09	1.4E-09	nd	1.9E-10	1.5E-10	2.6E-09	9.8E-10	nd	sweet, vegetable, bitter almond
Heptanal	2.2E-10	4.6E-10	5.4E-11	4.4E-11	2.8E-11	1.7E-10	4.6E-10	3.0E-10	1.0E-10	3.7E-11	aldehydic, fatty, herbal
Benzaldehyde	1.1E-10	3.1E-10	2.5E-10	3.7E-10	1.0E-10	1.2E-10	2.1E-10	7.3E-10	8.1E-10	5.2E-11	sweet, cherry, nutty
Octanal	8.0E-11	1.2E-10	3.6E-11	3.9E-11	1.9E-11	2.4E-10	1.5E-10	1.0E-10	6.6E-11	1.3E-11	aldehydic, fatty, herbal
Nonanal	7.6E-10	7.8E-10	2.1E-10	1.2E-10	1.2E-10	2.0E-09	1.0E-09	4.4E-10	4.3E-10	6.2E-11	aldehydic, fatty, rose
Decanal	1.3E-10	3.9E-11	2.0E-11	1.9E-11	2.8E-11	1.0E-10	1.3E-10	4.4E-11	4.4E-11	1.7E-11	sweet, aldehydic, floral
ALCOHOL											

Table S1 (cont'd)

Butanol	3.9E-10	3.3E-10	nd	2.0E-10	nd	3.8E-10	3.1E-10	2.2E-09	3.6E-10	4.1E-11	sweet, fermented, oily
3-Methylbutanol	9.5E-11	1.5E-09	1.5E-09	3.4E-09	1.9E-11	3.2E-10	1.6E-09	5.9E-10	6.3E-10	nd	musty, vegetable, cocoa
1-Pentanol	8.3E-11	2.4E-10	4.8E-10	3.2E-10	4.3E-11	4.6E-10	2.6E-10	7.6E-10	3.6E-10	nd	sweet, fermented, yeasty
1-Hexanol	7.3E-11	6.6E-11	1.1E-09	5.8E-10	2.3E-11	8.5E-10	1.6E-10	2.9E-09	1.1E-09	2.5E-11	sweet, pungent, herbal
1-Octen-3-ol	7.6E-11	1.7E-10	2.0E-10	2.2E-10	1.1E-11	6.9E-11	1.2E-10	2.7E-10	1.3E-10	6.6E-12	vegetable, mushroom, chicken
KETONE											
2-Butanone	8.5E-09	3.7E-08	9.5E-09	2.3E-09	1.9E-10	4.3E-09	1.2E-08	4.5E-10	1.0E-09	nd	camphoreous, acetone, fruity
2-Heptanone	1.5E-11	4.1E-11	1.0E-11	2.9E-11	5.4E-12	1.9E-11	6.2E-11	4.1E-11	3.3E-11	4.8E-12	sweet, spicy, banana
6-Methyl-5-hepten-2-one	2.1E-11	9.3E-11	1.3E-11	1.7E-11	1.0E-12	2.2E-11	1.2E-11	3.8E-11	2.1E-11	2.7E-12	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	1.2E-10	6.4E-10	3.6E-10	4.2E-10	1.6E-11	2.1E-10	4.5E-10	2.3E-10	1.5E-10	1.2E-11	malty, cocoa, nutty
o-Xylene	nd	2.3E-11	nd	nd	nd	5.5E-11	5.0E-11	1.3E-11	nd	3.4E-11	geranium
Styrene	nd	nd	nd	nd	nd	nd	2.4E-11	nd	nd	3.6E-12	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	6.2E-12	2.0E-11	nd	nd	nd	1.7E-11	4.0E-10	2.2E-12	2.8E-12	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	1.3E-11	1.6E-11	nd	nd	3.5E-12	8.0E-12	2.5E-11	3.8E-12	6.4E-12	6.0E-12	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	nd	9.8E-11	2.0E-11	3.9E-09	2.4E-11	nd	2.8E-10	5.1E-11	3.5E-09	4.0E-11	vegetable, onion, cabbage
Methional	nd	1.2E-12	nd	nd	1.1E-12	nd	2.9E-12	8.0E-13	8.6E-12	6.5E-13	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	2.6E-11	nd	nd	nd	nd	1.7E-11	1.5E-11	1.4E-11	nd	nutty, peanut, musty
Yellow colored beans (estimated volatile concentration in mol/L)											
	Manteca beans					**Mayacoba beans**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											

Table S1 (cont'd)

2-Methyl butanal	1.8E-09	5.7E-09	1.6E-08	6.2E-09	4.0E-10	1.0E-09	2.7E-09	4.5E-08	2.7E-09	1.3E-10	malty, musty, fermented
Hexanal	4.5E-09	1.1E-08	1.7E-08	2.6E-09	6.7E-10	4.0E-09	5.8E-09	5.3E-09	5.9E-10	2.9E-10	vegetable, aldehydic, clean
(E)-2-hexenal	2.6E-10	4.0E-10	1.8E-08	4.1E-09	1.7E-10	1.8E-10	2.0E-10	7.4E-09	1.2E-09	8.2E-11	sweet, vegetable, bitter almond
Heptanal	2.2E-10	6.0E-10	7.1E-10	2.3E-10	5.0E-11	1.3E-10	3.3E-10	1.3E-10	7.6E-11	2.7E-11	aldehydic, fatty, herbal
Benzaldehyde	1.3E-10	3.6E-10	1.0E-09	1.2E-09	4.2E-10	2.3E-10	4.1E-10	5.8E-10	7.4E-10	2.4E-10	sweet, cherry, nutty
Octanal	8.5E-11	6.5E-11	1.6E-10	7.6E-11	3.5E-11	5.7E-11	1.7E-10	6.5E-11	7.5E-11	1.6E-11	aldehydic, fatty, herbal
Nonanal	9.5E-10	6.6E-10	7.0E-10	4.9E-10	2.7E-10	3.7E-10	1.0E-09	3.5E-10	5.4E-10	1.0E-10	aldehydic, fatty, rose
Decanal	1.2E-10	4.3E-11	1.1E-10	5.1E-11	3.4E-11	2.1E-11	5.2E-11	5.8E-11	1.0E-10	2.8E-11	sweet, aldehydic, floral
ALCOHOL											
Butanol	1.2E-10	8.1E-10	7.2E-11	6.2E-11	nd	2.7E-10	5.8E-10	2.7E-12	1.8E-10	nd	sweet, fermented, oily
3-Methylbutanol	1.3E-10	2.9E-09	3.0E-09	4.8E-09	nd	3.9E-10	1.6E-09	4.2E-10	2.2E-09	nd	musty, vegetable, cocoa
1-Pentanol	1.1E-10	5.2E-10	1.1E-09	4.2E-10	nd	8.4E-11	1.9E-10	2.0E-10	1.9E-10	nd	sweet, fermented, yeasty
1-Hexanol	2.6E-10	1.7E-10	3.6E-09	1.9E-09	4.1E-11	1.0E-10	6.5E-11	1.2E-09	7.1E-10	1.6E-11	sweet, pungent, herbal
1-Octen-3-ol	6.3E-11	1.9E-10	3.5E-10	2.9E-10	2.9E-11	7.9E-11	1.4E-10	3.7E-10	3.0E-10	2.4E-11	vegetable, mushroom, chicken
KETONE											
2-Butanone	8.6E-09	2.5E-08	8.0E-10	5.0E-09	2.4E-10	1.4E-08	4.1E-08	4.2E-10	7.9E-10	nd	camphoreous, acetone, fruity
2-Heptanone	2.3E-11	7.6E-11	4.5E-11	2.8E-11	7.4E-12	1.6E-11	4.2E-11	2.4E-11	2.1E-11	5.6E-12	sweet, spicy, banana
6-Methyl-5-hepten-2-one	3.1E-11	3.9E-11	3.1E-11	2.7E-11	2.0E-11	1.3E-11	4.0E-10	1.0E-10	3.3E-11	6.9E-12	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	2.9E-10	1.4E-09	1.0E-09	2.7E-10	7.1E-11	2.7E-10	3.2E-10	2.7E-10	5.7E-11	4.0E-11	malty, cocoa, nutty
o-Xylene	4.2E-11	4.5E-11	nd	nd	9.8E-12	nd	2.2E-11	1.8E-11	nd	9.5E-12	geranium
Styrene	3.3E-11	2.8E-11	nd	nd	nd	1.5E-11	1.9E-11	6.0E-12	6.1E-12	nd	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	2.1E-11	1.2E-11	1.5E-12	1.2E-12	2.2E-12	1.0E-11	1.1E-10	6.8E-12	2.4E-12	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	2.6E-11	2.0E-11	7.2E-12	3.6E-12	3.5E-12	2.0E-11	2.6E-11	7.2E-12	5.7E-12	6.6E-12	unknown

Table S1 (cont'd)

SULFUR COMPOUNDS											
Dimethyl Disulfide	nd	4.3E-10	1.5E-10	1.8E-09	3.7E-10	nd	1.1E-10	nd	4.2E-09	1.5E-10	vegetable, onion, cabbage
Methional	nd	3.6E-12	1.3E-12	7.5E-12	5.4E-12	nd	nd	nd	7.2E-12	2.0E-12	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	1.4E-11	nd	1.4E-11	4.1E-12	nd	5.1E-11	nd	3.4E-11	nd	nutty, peanut, musty
Other pulses (estimated volatile concentration in mol/L)											
	Chickpea 2022[b]					**Cranberry beans**					
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor Description**
ALDEHYDE											
2-Methyl butanal	8.5E-10	1.3E-09	1.9E-11	1.1E-08	7.0E-10	2.1E-09	2.2E-09	3.0E-10	1.3E-09	1.9E-10	malty, musty, fermented
Hexanal	2.5E-10	5.3E-10	5.5E-08	6.4E-08	1.7E-09	7.9E-09	5.2E-09	6.3E-09	2.3E-09	4.9E-10	vegetable, aldehydic, clean
(E)-2-hexenal	6.5E-11	nd	6.7E-10	7.3E-10	nd	1.3E-10	1.7E-10	7.8E-09	8.7E-10	nd	sweet, vegetable, bitter almond
Heptanal	4.7E-10	4.8E-11	7.6E-10	1.4E-09	1.1E-10	1.6E-10	3.1E-10	1.8E-10	1.5E-10	4.9E-11	aldehydic, fatty, herbal
Benzaldehyde	1.3E-10	1.7E-10	4.3E-10	5.9E-10	2.2E-10	1.7E-10	2.4E-10	8.2E-10	8.1E-10	1.2E-10	sweet, cherry, nutty
Octanal	1.3E-11	3.7E-11	1.5E-10	4.0E-10	8.8E-11	3.3E-11	6.2E-11	1.0E-10	8.7E-11	3.7E-11	aldehydic, fatty, herbal
Nonanal	1.1E-10	2.1E-10	1.2E-09	2.6E-09	1.0E-09	2.5E-10	5.1E-10	4.9E-10	6.2E-10	1.9E-10	aldehydic, fatty, rose
Decanal	2.5E-11	7.0E-11	9.2E-11	1.5E-10	3.4E-11	nd	5.7E-11	1.3E-10	8.4E-11	2.6E-11	sweet, aldehydic, floral
ALCOHOL											
Butanol	5.1E-10	1.4E-09	4.5E-11	2.4E-10	nd	5.2E-10	4.4E-10	7.5E-11	1.2E-10	nd	sweet, fermented, oily
3-Methylbutanol	3.8E-10	9.8E-10	1.1E-08	1.3E-08	2.3E-10	5.6E-10	8.0E-10	5.2E-09	7.8E-09	nd	musty, vegetable, cocoa
1-Pentanol	1.6E-09	2.9E-09	5.8E-09	4.6E-09	3.7E-11	2.0E-10	2.3E-10	4.6E-10	7.2E-10	nd	sweet, fermented, yeasty
1-Hexanol	4.2E-09	7.8E-09	3.8E-09	4.7E-09	4.8E-11	5.0E-11	1.2E-10	1.8E-09	1.1E-09	1.2E-11	sweet, pungent, herbal
1-Octen-3-ol	1.3E-10	2.4E-11	6.3E-10	1.0E-09	2.2E-11	7.5E-11	9.9E-11	4.2E-10	3.6E-10	1.4E-11	vegetable, mushroom, chicken
KETONE											
2-Butanone	8.6E-09	8.5E-09	1.7E-10	5.5E-10	nd	2.4E-08	1.4E-08	9.0E-10	8.0E-10	2.7E-10	camphoreous, acetone, fruity
2-Heptanone	nd	5.8E-11	2.6E-10	3.8E-10	1.3E-11	1.4E-11	4.2E-11	3.1E-11	2.1E-11	6.1E-12	sweet, spicy, banana

Table S1 (cont'd)

6-Methyl-5-hepten-2-one	1.0E-11	3.1E-11	2.2E-11	2.3E-11	3.3E-12	1.1E-11	nd	4.1E-11	3.6E-11	7.6E-12	musty, banana, fruity
AROMATIC COMPOUNDS											
2-Ethylfuran	1.4E-10	2.5E-10	1.5E-10	6.9E-10	7.3E-11	7.0E-10	3.1E-10	3.5E-10	1.7E-10	1.1E-10	malty, cocoa, nutty
o-Xylene	nd	4.7E-11	1.9E-11	2.1E-11	nd	nd	4.2E-11	nd	nd	nd	geranium
Styrene	nd	2.0E-11	2.4E-11	1.7E-11	nd	nd	1.4E-11	nd	nd	nd	sweet, plastic, floral
Geosmin	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	musty, earthy, fresh
TERPENOIDS											
L-limonene	1.1E-11	3.1E-11	4.9E-12	6.8E-12	nd	5.7E-12	1.3E-11	2.9E-12	3.1E-12	nd	camphoreous, herbal, terpenic
ALKANES											
Decane	1.1E-11	2.6E-11	1.7E-11	3.8E-11	3.6E-12	4.0E-11	2.6E-11	4.0E-12	5.0E-12	3.8E-12	unknown
SULFUR COMPOUNDS											
Dimethyl Disulfide	2.9E-11	1.9E-11	nd	3.1E-11	1.5E-11	1.2E-10	5.0E-11	1.7E-11	3.5E-09	3.7E-11	vegetable, onion, cabbage
Methional	nd	nd	nd	nd	2.9E-13	nd	2.2E-12	5.3E-12	1.3E-11	6.5E-13	cabbage, pungent
NITROGEN COMPOUNDS											
2,5-Dimethyl pyrazine	nd	nd	7.1E-12	8.4E-12	nd	nd	8.1E-12	nd	6.2E-12	nd	nutty, peanut, musty

Table S2: Average peak areas of volatiles quantified using means of triplicate measurements from area under the curve and reported for a single m/z (mass-to-charge ratio) using the respective unique mass of volatiles grouped by chemical class across non-roasted flour (NRF), non-roasted porridge (NRP), roasted flour (RF), roasted porridge (RP), and boiled pulses (BP) from the pulse cultivars-Cranberry, Great Northern, Navy, Otebo, White Kidney, Manteca and Mayacoba grown in harvest years 2022 and 2023 from Michigan and a market sample of Chickpea obtained commercially (harvested in 2022). *2022[a]: analyzed in April 2024; *2022[b]: analyzed in September 2024. Volatiles annotated as MS, NIST: compared mass spectrum with National Institute of Standards and Technology (NIST) mass spectra library database (V.05); RT, STD: compared retention time and spectrum of identified compound with those of an authentic compound. by comparisons with the National Institute of Standards and Technology (NIST) mass spectra library database (V.05) and/or by matching retention times of authenticated standards, nd: not detected. Odor descriptions reflect the top three odor notes as reported by (The Good Scents Company 2009) (Chapter 3).

Chickpea cv. 'Sierra' (2022[a])								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	57980	414889	546041	nd	34004	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	687411	1428640	17152259	16002248	891104	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	nd	nd	88064	77540	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	nd	132085	126462	132464	62000	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	365744	1926040	396589	349750	852029	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	32511	256267	102541	102915	144297	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	140263	1143847	485943	501537	405945	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	28312	154494	51606	36514	64847	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	163276	358959	nd	nd	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	129553	264241	nd	nd	185233	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	1085834	2612451	1207651	1110644	119298	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	11044734	18362955	408313	451674	330037	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	436572	763191	1265637	846175	273829	vegetable, mushroom, chicken	57	MS,NIST,RT,STD

Table S2 (cont'd)

Maltol	12077	319546	nd	nd	40925	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	63489	510591	nd	nd	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	60496	262756	119953	163355	71242	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	1431	123043	nd	nd	7971	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	47960	166099	24386	24711	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	133628	832930	150063	133044	159925	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	76080	157882	nd	nd	nd	geranium	91	MS,NIST,RT,STD
Styrene	6527	27986	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Naphthalene	98919	155721	16911	21777	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	912195	1153821	1263940	1105033	883548	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	8189	13167	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	4125	nd	nd	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	35450	13910	nd	18890	32782	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	nd	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	79055	40563	36078	69970	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	67203	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	101979	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Navy cv. 'Alpena' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								

Table S2 (cont'd)

2-Methyl butanal	113106	267493	11348	4395	nd	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	1389407	3528105	2641011	355621	224302	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	nd	nd	4453950	587954	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	134124	299721	169401	20192	30116	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	318457	765632	1443147	842859	285756	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	304444	549158	107582	34686	42280	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	603167	1369214	444076	126541	181318	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	59057	132426	85007	30448	34987	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	117532	108082	nd	123260	36093	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	nd	155224	144508	1163442	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	41940	85353	521750	333857	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	124256	166731	6329960	2738191	81589	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	144811	487518	978103	525501	33071	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	30662	141453	nd	71275	25676	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	120068	276747	12191	171437	60887	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	37488	83037	85055	64895	nd	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	11116	38888	nd	nd	2688	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	74418	139122	268990	219101	20289	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	149402	357234	3966078	753359	124337	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	59977	71268	nd	615655	nd	geranium	91	MS,NIST,RT,STD
Styrene	27007	25698	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	28567	59148	40786	38695	55765	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	194374	151859	933425	475306	121657	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								

Table S2 (cont'd)

L-limonene	12687	3137	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	nd	nd	nd	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	21833	210415	10994809	15910	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	10449	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	63703	nd	1040960	243635	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	194028	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	nd	nd	50999	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Cranberry cv. 'CR1801-2-2' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	7366	605972	47990	85313	176145	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	3646	3889775	805634	394220	522771	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	6668	69343	921232	197656	72485	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	5034	187041	25166	18803	26136	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	4138	596593	1138636	1325034	670093	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	6173	554017	49373	46005	90007	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	5684	1795543	234609	240270	712138	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	4686	235197	44687	66588	61279	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	4475	242529	nd	nd	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	4455	392259	638756	631419	103455	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	4192	330206	639093	55356	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	4869	365127	634028	467811	168257	sweet, pungent, herbal	56	MS,NIST,RT,STD

Table S2 (cont'd)

1-Octen-3-ol	1993	246913	1510088	950002	304784	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	257260	25273	78275	29985	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	63978	716197	8974	6334	15579	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	nd	144973	158612	nd	55297	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	6969	485307	21805	6269	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	122924	100035	249504	66106	27714	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	3658	473033	918454	225732	409060	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	9248	181061	51782	nd	93453	geranium	91	MS,NIST,RT,STD
Styrene	2459	145276	nd	nd	32264	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	48645	57671	37872	34197	23163	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	233677	149113	614006	281804	556938	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	3048	84152	nd	nd	15951	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	nd	21315	3122	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	356675	7277465	2964252	120469	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	nd	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	308985	nd	152323	176395	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	617060	nd	123988	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	32931	nd	36962	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	57031	nd	47618	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Great Northern cv. 'Powderhorn' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**

Table S2 (cont'd)

ALDEHYDE								
2-Methyl butanal	107960	255189	152485	397480	nd	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	286932	1545905	5619434	310420	114120	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenals	27384	40069	1560337	310623	557763	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	38297	86449	102039	20071	nd	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	168272	475337	2596801	1020132	526200	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	140995	218361	91133	27252	nd	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	535384	549993	295342	108430	51410	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	55724	66589	73738	30725	27487	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	226002	187806	3712206	nd	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	95225	818890	1539601	955558	58845	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	161559	136501	742175	100868	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	934682	525992	5251450	1790015	272575	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	302679	381264	488263	138242	109850	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	190173	nd	34975	22650	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	15642	209978	6423	102178	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	31521	98735	53243	nd	nd	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	11900	nd	nd	nd	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	57375	50846	127339	43395	30326	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	70990	308425	395844	61564	433483	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	78154	84683	nd	nd	7023	geranium	91	MS,NIST,RT,STD
Styrene	56635	49280	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	25298	27943	14625	15851	164797	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	115889	163351	157412	97704	369884	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								

Table S2 (cont'd)

L-limonene	18159	1804	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	41332	nd	nd	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	122274	21397	7589305	585719	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	nd	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	89141	nd	nd	4722199	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	139308	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	nd	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Manteca cv. 'Y1608-07' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	641577	995256	175534	236384	65887	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	8152275	5720436	4406276	1957748	628207	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	192588	105363	2314312	1118826	93873	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	458260	324769	87698	85716	42888	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	2017294	2326193	1826027	2170174	980601	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	584212	635472	140761	162961	87930	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	1913750	2413253	506170	701670	315002	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	125114	314905	99989	145333	53855	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	341673	702868	1959916	nd	8630	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	72552	2792408	488632	757423	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	243126	694325	317468	102069	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	714820	1180427	2959073	1247426	169031	sweet, pungent, herbal	56	MS,NIST,RT,STD

Table S2 (cont'd)

1-Octen-3-ol	1797541	594486	1500354	1104172	215479	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	262435	928096	34242	60912	79463	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	773333	917975	9777	7672	15273	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	315825	405274	66874	70534	nd	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	nd	nd	37342	20012	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	480511	183886	184725	109142	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	1268046	3322132	681984	599096	313949	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	181182	94736	80397	65433	nd	geranium	91	MS,NIST,RT,STD
Styrene	155883	29529	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	73870	82094	49073	57742	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	799041	547490	301726	236278	216342	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	44591	7475	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	nd	13898	nd	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	84440	833995	15875	9873385	108515	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	8624	nd	nd	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	60758	687294	nd	117765	294419	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	222452	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	34574	nd	21276	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Mayacoba cv. 'Y 1802-9-1' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**

Table S2 (cont'd)

ALDEHYDE								
2-Methyl butanal	230630	1307858	36863	125937	26684	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	4529413	7708738	1848296	815824	255453	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	169767	338680	33770	179054	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	318562	739587	53215	61231	27795	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	613117	3590426	1717543	1263318	747102	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	446851	1107052	52429	87892	55971	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	2086547	3328626	239492	548963	193681	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	172584	352404	41280	123659	23689	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	231560	561931	36021	95326	91846	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	129003	1729344	970770	220270	111748	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	321763	493390	584087	69477	47191	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	805099	929969	3179344	749360	728408	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	482459	1149006	2021131	575402	280688	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	766650	19543	72544	37394	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	257447	1609235	19584	10437	92954	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	100681	421925	85759	52193	96645	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	16081	nd	nd	nd	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	364292	619023	570967	118622	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	605985	2488932	1776885	137328	328096	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	45247	161077	nd	1252	nd	geranium	91	MS,NIST,RT,STD
Styrene	4948	66396	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	97465	132576	46288	42867	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	197354	760406	391568	134081	558060	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								

Table S2 (cont'd)

L-limonene	65600	10667	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	6607	nd	7363	nd	4604	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	10171	439084	28862	322389	3498334	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	24639	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	353266	27468	362696	1729830	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	1147190	nd	70490	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	112765	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	221711	nd	39892	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Otebo cv. 'Samurai' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	136764	630763	552012	16013	nd	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	574644	5615175	4418144	1402058	161843	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	56430	229338	1989198	314557	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	53323	712577	161733	65019	6028	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	142817	2713296	1453781	1413045	177428	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	102533	690393	153462	118514	nd	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	286261	3935318	407815	449648	77595	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	46754	293342	53490	65732	22515	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	97961	795204	nd	88868	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	98269	1131637	36545	49735	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	102295	461710	318322	48799	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	253106	794733	2745521	821428	nd	sweet, pungent, herbal	56	MS,NIST,RT,STD

Table S2 (cont'd)

1-Octen-3-ol	135693	630554	326447	159584	nd	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	33921	904566	nd	47085	40810	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	23025	816949	nd	4174	3075	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	21462	412575	38879	nd	nd	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	nd	nd	nd	nd	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	48019	501769	160480	62965	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	104300	2183831	509727	105915	53023	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	33986	217909	nd	nd	nd	geranium	91	MS,NIST,RT,STD
Styrene	5463	122899	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	27706	105847	19158	20159	70899	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	94119	509603	187385	88493	106333	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	nd	9676	nd	18316	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	nd	41278	nd	nd	nd	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	48526	442293	5704	3899889	11780	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	11695	nd	nd	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	426476	nd	86511	222485	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	877153	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	199851	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
White kidney cv. 'WK 1601-1' (2022)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**

Table S2 (cont'd)

ALDEHYDE								
2-Methyl butanal	77558	722699	9204506	263943	69772	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	1607810	2390494	3210856	456766	86759	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	59637	72253	3874239	152127	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	113431	265367	116785	26173	nd	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	496110	867235	617729	1524460	513599	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	335186	666273	44742	71408	28835	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	1073351	1587980	188414	281497	125657	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	165507	227961	43141	60268	nd	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	288984	268827	1337687	235358	221446	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	54600	480609	165298	383615	116249	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	86307	106190	141015	34158	46531	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	427561	338580	1213484	942608	1123889	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	246232	193652	771812	1078474	297120	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	34596	237879	nd	54831	38362	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	97795	298842	6813	13440	61729	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	64393	138797	nd	67032	99634	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	22560	25790	nd	10165	nd	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	139121	54261	89535	62395	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	453941	1653719	436526	408338	270618	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	382658	128844	nd	52060	nd	geranium	91	MS,NIST,RT,STD
Styrene	151256	99248	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	51315	52696	nd	38453	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	189046	183585	105967	114361	360181	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								

Table S2 (cont'd)

L-limonene	2713	3216	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	4484	2055	nd	4540	8039	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	345558	28750	14386294	280892	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	39898	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	157162	nd	32161	199754	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	268098	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	33624	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	37863	nd	32016	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Chickpea cv. 'Sierra' (2023[b])								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	59419	387145	5659	3419779	210922	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	119250	895377	91852318	108170543	2862079	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	14852	nd	753187	814523	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	125978	62116	998023	1853835	146996	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	171963	884624	2201817	3000758	1141425	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	13490	146186	608859	1572733	347284	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	86657	645248	3656006	7880997	3013801	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	36547	328642	431750	698617	162417	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	207373	2250763	71753	379667	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	140286	1372602	16123719	17968514	328326	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	1459304	7789526	15477842	12323314	98760	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	10417620	58907473	29030667	35686466	360808	sweet, pungent, herbal	56	MS,NIST,RT,STD

Table S2 (cont'd)

1-Octen-3-ol	401120	378333	10077140	15981346	355819	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	nd	1413402	nd	57812	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	71591	452816	9244	29137	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	nd	482128	2191455	3181706	107716	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	4820	65250	46441	47810	6977	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	76714	224076	778643	645502	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	96714	754410	441728	2047561	217345	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	nd	214320	84182	94730	nd	geranium	91	MS,NIST,RT,STD
Styrene	nd	162664	192778	138832	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Naphthalene	23092	105110	62508	104647	22305	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	551366	1883562	3414641	15348415	913048	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	2182	28289	4530	6323	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	5452	92780	59372	134588	12885	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	16977	43645	nd	69357	34845	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	nd	1833	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	36153	85171	nd	55394	50009	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	nd	nd	nd	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	nd	50956	60826	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	nd	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD

Table S2 (cont'd)

Navy cv. 'Alpena' (2023)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	93920	268291	15849	18415	203053	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	1961877	1792488	1727300	647291	1555866	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	29476	41500	1028453	316016	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	59937	122543	14383	11740	36564	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	150669	412850	324497	483277	518842	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	83045	119506	37135	40181	76585	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	581674	593941	161203	89963	363440	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	184470	58031	28693	28199	132051	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	158613	133903	nd	80017	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	35157	561857	552651	1245662	26768	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	74345	217622	430769	287398	116362	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	182195	163773	2823254	1440020	171952	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	237986	520133	623070	673866	180020	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	94640	nd	28138	36052	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	70716	307757	79093	19579	10019	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	39417	104144	26180	73666	44724	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	10122	44365	5998	8090	2102	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	112400	218944	60748	60168	36336	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	84569	456487	256108	298970	48150	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	nd	40939	nd	nd	nd	geranium	91	MS,NIST,RT,STD
Styrene	nd	nd	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD

Table S2 (cont'd)

Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	19696	26053	nd	23733	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	164968	144049	134969	66664	321794	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	1201	3965	nd	nd	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	6171	7928	nd	nd	12347	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	57728	12053	2291747	54921	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	2158	nd	nd	7006	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	161751	nd	438757	45821	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	282490	nd	nd	4815	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	42106	nd	nd	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	33783	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Cranberry cv. 'CR 2111-1' (2023)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	146368	677176	90837	401006	56531	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	3815651	8743899	10630073	3868200	829517	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	28818	187542	8677973	968374	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	43625	398168	236081	196207	63767	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	226753	1238214	4209334	4154298	588656	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	34528	242935	404913	341814	145878	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	188076	1545982	1461520	1873293	564788	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	nd	268395	597140	394847	122713	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	209800	701367	119688	187992	nd	sweet, fermented, oily	31	MS,NIST,RT,STD

Table S2 (cont'd)

3-Methylbutanol	206235	1129021	7327834	10994293	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	179607	607290	1244030	1928231	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	123723	913088	13367836	8160509	93406	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	233650	1583822	6682980	5797704	222684	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	180655	nd	260243	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	200524	720971	47567	42443	14442	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	36355	350369	258833	174518	50638	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	5139	nd	86197	74472	15912	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	183351	1038233	513067	578645	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	496530	927825	1037369	514427	316492	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	nd	190419	nd	nd	nd	geranium	91	MS,NIST,RT,STD
Styrene	nd	113057	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	nd	25779	48889	57263	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	134637	920855	807391	607253	446810	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	1100	11680	2676	2869	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	19309	91701	14176	17767	13639	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	70483	112999	39092	7966765	84995	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	13584	33444	80181	4058	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	155654	28967	74849	202849	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	73902	380781	141181	1348363	93883	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	58387	nd	44759	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	nd	nd	38798	nd	nutty, peanut, musty	108	MS,NIST,RT,STD

Table S2 (cont'd)

Great Northern cv. 'Powderhorn' (2023)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	471245	856909	2698366	338557	nd	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	14510778	12726072	28372235	2108937	773718	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	231958	223509	6106354	360380	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	313024	414626	537339	62300	58219	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	1042122	1521356	5948839	4129106	304886	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	421006	224899	385601	180647	108720	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	2029467	1314958	1423558	690084	332458	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	355471	230282	327035	270104	118547	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	681161	911548	250785	164666	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	1571530	3933239	9518067	22441144	56043	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	871435	1117227	5340355	2170323	29647	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	3578848	1374352	47364251	20366093	85631	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	1761842	2265015	2644273	1530794	105891	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	215407	292340	293137	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	559994	903702	58728	14548	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	332439	678120	823503	473487	28378	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	14615	123291	36069	408	4631	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	1217585	1268645	966217	441728	11440	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	1452153	1216692	1455114	155988	355426	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	289964	403838	68835	nd	25890	geranium	91	MS,NIST,RT,STD
Styrene	192652	358001	57732	66003	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD

Table S2 (cont'd)

Azulene/Naphthalene	62076	29586	34015	51513	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	1171249	1225280	747533	365494	306606	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	14974	8939	2791	1617	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	80044	104754	28907	25333	19625	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	152782	896070	147972	621983	nd	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	11326	5736	135513	nd	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	55926	448821	26567	365823	64225	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	51908	830358	70967	457229	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	91380	134123	1012	257586	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	58342	15987	33775	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Manteca cv. 'Y 1608-14' (2023)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	553900	1737419	4819722	1876589	121495	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	7503150	18663458	28234895	4380401	1132061	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	288323	446471	19847479	4583497	191242	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	288429	777076	921136	303494	64634	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	647470	1820631	5319962	6326361	2126840	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	334780	258183	648039	297964	138816	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	2845788	1999023	2104420	1485481	807697	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	572010	204935	541346	241218	162140	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	187196	1295253	115071	98798	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	179686	4092564	4205484	6752947	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD

Table S2 (cont'd)

1-Pentanol	298121	1390146	3017103	1118826	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	1967307	1287103	27001678	14117593	310979	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	1009830	3053472	5592654	4577089	471570	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	43658	nd	57693	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	452934	1343313	42377	265107	12918	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	194910	632730	374301	231815	62034	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	64138	81141	65766	56159	42012	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	987203	2405194	2266421	1237785	82686	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	877423	4092299	3026965	815607	212755	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	190875	201995	nd	nd	44336	geranium	91	MS,NIST,RT,STD
Styrene	271230	226555	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	86537	48103	59690	67008	35443	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	997336	1417659	1114061	589801	226918	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	19609	10792	1369	1104	2059	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	92106	69487	25654	12700	12577	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	965076	337103	4190278	848147	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	22308	7924	46897	33858	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	86743	486943	75523	224705	299336	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	718180	148799	435672	196952	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	97217	nd	102882	29564	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	64583	nd	78010	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Mayacoba cv. 'Y 1802-11-2' (2023)								

Table S2 (cont'd)

	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	71951	190985	13731725	812304	38214	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	1943143	2797521	8861167	986339	490394	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	40978	46257	8281540	1350182	92038	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	34057	87322	163594	99760	34947	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	297265	533784	2940451	3788604	1222531	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	58854	174986	256636	295461	64573	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	280306	796893	1044066	1614121	312219	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	30215	76159	272549	484456	130924	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	107866	234054	4245	285744	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	144299	577059	589618	3066170	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	75604	172991	544845	506886	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	253589	160248	8953282	5345300	118152	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	246890	433550	5972118	4860514	391498	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	121347	nd	111626	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	118486	339317	22383	42067	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	40855	108415	204585	174899	46937	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	6283	192454	210247	69353	14413	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	224910	566611	900971	592496	37268	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	191283	229858	800368	169400	119035	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	nd	39758	82768	nd	42979	geranium	91	MS,NIST,RT,STD
Styrene	29902	39056	48946	50269	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	22208	35154	71850	70244	26197	dry, resinous, pungent	128	MS,NIST

Table S2 (cont'd)

2-Pentyl furan	161523	157842	346556	183045	122260	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	2031	22113	6339	2268	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	9655	12408	25623	20262	23470	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	62766	nd	9508711	335844	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	nd	nd	45278	12295	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	nd	149348	nd	137521	110307	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	279443	nd	434377	nd	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	81361	nd	247420	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	52167	nd	111878	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
Otebo cv. 'Samurai' (2023)								
	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	258228	533725	22000208	605448	127305	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	4167707	9645358	17800849	4877927	1217061	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	211011	172969	2939824	1098748	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	225706	597428	391220	134514	48633	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	611498	1078370	3723408	4150822	263969	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	926685	579625	395199	261727	51321	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	6086182	3003735	1323151	1297951	185327	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	475002	608148	205404	209592	81785	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	606196	491628	3474829	575816	65721	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	449193	2198475	831763	880104	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD

Table S2 (cont'd)

1-Pentanol	1237593	694181	2046180	961508	nd	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	6454520	1204137	22236466	8352552	189985	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	1111295	1847874	4268621	2095396	106381	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	472015	nd	nd	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	229230	625323	23871	54492	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	159773	517515	340146	272313	40046	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	46409	26210	79610	43319	5738	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	936322	868568	923978	479289	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	615429	1358395	696950	452988	36166	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	247329	224926	58119	nd	153405	geranium	91	MS,NIST,RT,STD
Styrene	nd	200154	nd	nd	29801	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	126409	37589	63314	62292	nd	dry, resinous, pungent	128	MS,NIST
2-Pentyl furan	714501	983032	476970	440364	285099	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	16114	366939	2062	2562	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	28643	88106	13625	22665	21270	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	631237	116518	7855031	91553	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	18115	4997	53961	4105	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	1367	224360	nd	240576	111164	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	762184	nd	269086	65327	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-butyl-3,5-dimethyl pyrazine	nd	124552	109596	100417	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	37303	nd	nd	nd	nutty, peanut, musty	108	MS,NIST,RT,STD
White kidney cv. 'WK 1601-1' (2023)								

Table S2 (cont'd)

	Average Area Counts							
Compound Name	**NRF**	**RF**	**NRP**	**RP**	**BP**	**Odor description**	**Unique Mass (m/z)**	**Annotation**
ALDEHYDE								
2-Methyl butanal	980101	2830556	29762620	764076	73372	malty, musty, fermented	57	MS,NIST,RT,STD
Hexanal	13507409	16622968	19030729	2363567	462365	vegetable, aldehydic, clean	57	MS,NIST,RT,STD
(E)-2-hexenal	214434	311744	18634031	1425902	nd	sweet, vegetable, bitter almond	55	MS,NIST,RT,STD
Heptanal	483883	711598	415142	161234	59951	aldehydic, fatty, herbal	70	MS,NIST,RT,STD
Benzaldehyde	792017	2287858	8809168	7037358	770733	sweet, cherry, nutty	77	MS,NIST,RT,STD
Octanal	590368	935210	761974	378704	192083	aldehydic, fatty, herbal	44	MS,NIST,RT,STD
Nonanal	2016933	3351046	3273328	1856843	818245	aldehydic, fatty, rose	57	MS,NIST,RT,STD
Decanal	468517	627321	691314	612755	126165	sweet, aldehydic, floral	41	MS,NIST,RT,STD
ALCOHOL								
Butanol	726045	2310032	172424	147230	nd	sweet, fermented, oily	31	MS,NIST,RT,STD
3-Methylbutanol	105150	5795043	2144094	9417954	nd	musty, vegetable, cocoa	42	MS,NIST,RT,STD
1-Pentanol	367084	740840	2851557	902191	57578	sweet, fermented, yeasty	31	MS,NIST,RT,STD
1-Hexanol	999790	1135970	30693176	8176701	89651	sweet, pungent, herbal	56	MS,NIST,RT,STD
1-Octen-3-ol	1706338	2892669	8618808	8901172	290539	vegetable, mushroom, chicken	57	MS,NIST,RT,STD
Maltol	nd	557840	nd	269580	nd	sweet, cotton candy, caramellic	71	MS,NIST
KETONE								
2-Butanone	783225	1878721	53263	26163	nd	camphoreous, acetone, fruity	72	MS,NIST,RT,STD
2-Heptanone	263549	880920	600186	207648	45385	sweet, spicy, banana	58	MS,NIST,RT,STD
6-Methyl-5-hepten-2-one	47903	272487	4	96223	11967	musty, banana, fruity	108	MS,NIST,RT,STD
3,5-Octadien-2-one	910734	1576192	2118573	800942	nd	fruity, green, grassy	95	MS,NIST
AROMATIC COMPOUNDS								
2-Ethylfuran	1353038	4161124	1047131	293805	434440	malty, cocoa, nutty	81	MS,NIST,RT,STD
o-Xylene	157287	232588	nd	nd	71014	geranium	91	MS,NIST,RT,STD
Styrene	209683	330352	nd	nd	nd	sweet, plastic, floral	104	MS,NIST,RT,STD
Geosmin	nd	nd	nd	nd	nd	musty, earthy, fresh	112	MS,NIST,RT,STD
Azulene/Naphthalene	47110	103987	77458	93382	nd	dry, resinous, pungent	128	MS,NIST

Table S2 (cont'd)

2-Pentyl furan	928363	971437	677011	444757	554267	Fruity, green, earthy beany	81	MS,NIST
TERPENOIDS								
L-limonene	10776	164140	2247	3598	nd	camphoreous, herbal, terpenic	136	MS,NIST,RT,STD
ALKANES								
Decane	70840	91904	65388	20317	8766	unknown	71	MS,NIST,RT,STD
SULFUR COMPOUNDS								
Dimethyl Disulfide	nd	837963	90758	2559976	73026	vegetable, onion, cabbage	94	MS,NIST,RT,STD
Methional	nd	37128	nd	66396	10267	cabbage, pungent	48	MS,NIST,RT,STD
Methanethiol	84519	602517	40087	407053	232405	vegetable, sulfurous, eggy	48	MS,NIST
1-(Methylthio)-propane	nd	2019627	182613	733109	65359	garlic, acidic	61	MS,NIST
NITROGEN COMPOUNDS								
2-Butyl-3,5-dimethyl pyrazine	nd	438465	nd	189835	nd	roasted, nut flavor	122	MS,NIST
2,5-Dimethyl pyrazine	nd	272947	nd	271301	nd	nutty, peanut, musty	108	MS,NIST,RT,STD

Table S3: Discriminant ions (DI) profiled in pulse flour using e-nose. The results shown are the average of triplicate measurements of peak areas from discriminant ions for non-roasted flour (NRF) and roasted flour (RF) of eight pulse cultivars: Navy (N), Otebo (O), Cranberry (CR), Chickpea (CHKP), Manteca (MN), Mayacoba (MY), White Kidney (WK), Great Northern (GN). Potential compound profiles and odors associated with the respective DI were identified using the AroChemBase database (Version 4.6, Toulouse, France) (Chapter 4).

DI	Area of discriminant peaks																Profiled compounds identified using AroChemBase V7 database
KI	N_ NRF	N_ RF	CHKP_ NRF	CHKP_ RF	CR_ NRF	CR_ RF	GN_ NRF	GN_ RF	O_ NRF	O_ RF	WK_ NRF	WK_ RF	MN_ NRF	MN_ RF	MY_ NRF	MY_ RF	Odor description
453	12278	19326	9550	19425	5394	15683	9926	13575	13022	14497	16353	67702	10487	16886	10666	16951	acetaldehyde (aldehydic, fruity…); methanethiol (sulfurous…)
478	112750	133015	42872	51490	90084	121512	83894	86030	82998	137414	107212	125410	128736	127389	95010	115969	propanal (nutty, earthy...); dimethyl sulfide;
542	11494	14390	8340	13269	9061	13344	8100	9031	9885	11855	15574	12358	12344	14190	11237	12390	2-methylpropanal (fruity, malty, toasted…); 1-propanol (alcoholic, ethereal…)
596	8186	17927	7681	7992	13450	16493	10171	10600	7718	16889	10829	13604	12225	19642	11209	19731	butanal (malty, malty, pungent...); 1-propanethiol (cabbage, onion...); 2-Butanone (chocolate, butter, fruity…)
609	6090	0	0	0	0	0	0	4674	0	1274	0	4237	0	0	0	0	ethyl acetate(apple, fruity...); butan-2-one (cheese, sharp…)
621	0	7902	4692	5858	2958	8063	1576	7929	3669	10107	4325	9556	2946	11058	2686	7729	2-methylfuran (chocolate, burnt, sweet...); but-2-enal (floral, pungent...)
650	0	8361	0	0	1470	6131	0	11865	0	7697	0	6646	2582	9403	0	6541	3-methylbutanal (almond, toasted, malty...);
659	8126	11405	5688	6879	6841	10614	3276	0	6804	8961	8996	9879	6936	10068	7737	10312	2-methylbutanal (almond, toasted, malty...); 1- butanol (cheese,strong, sweet, oily, medicinal…)
681	6584	9877	1431	1311	8900	8537	3044	3491	4117	7121	6668	10766	12142	11033	8898	9767	pent-1-en-3-ol (burnt...); 3-methyl-1-butanol
698	4921	9183	3894	3255	6520	7102	1908	3973	4260	7600	5094	7244	7266	9721	5627	8913	pentanal (nutty, almond...)
732	2687	7575	4905	6393	3264	7510	2613	7454	3959	7499	4291	8379	2469	9555	2890	8316	propanoic acid (soy, rancid, pungent…); pyrazine (roasted, nutty, pungent...); 2- ethyl furan (malty, sweet, burnt…)
800	17898	25758	10419	12102	24796	16261	5330	8713	14535	14709	17381	18531	21000	21332	23965	22591	hexanal (leafy, sharp...); 2-methylpropanoic acid
855	853	1874	703	947	941	984	526	308	653	598	765	1475	615	1201	1245	1589	acetate 2-pentanol (beany, fruity, vegetable...);
913	6549	12317	4029	7064	6797	6517	569	1381	4367	5186	4565	10632	4693	8567	10094	10994	2,5-dimethylpyrazine (nutty...); ethyl pyrazine; methylthio-propanol (vegetable, cooked potato,)
953	895	833	1050	1095	759	974	1193	1021	1200	858	789	967	1156	1157	989	1095	benzaldehyde (almond...); a-pinene
991	13030	16128	5744	8203	9721	16563	6522	6809	11905	12550	11956	11300	9907	14110	11226	16307	2-pentylfuran (beany, sweet, metallic, vegetable…); 1-Octen-3-ol (earthy, fatty, grassy…);
1046	4443	4491	1475	2193	4661	4749	2628	2796	4713	4301	4550	4370	4295	4384	4811	4616	acetophenone (almond, cheese, musty, sweet...); 2-octenal (walnut, earthy...); limonene
1102	8750	12455	1919	3636	7950	11614	5728	6391	6654	8923	11102	5369	6654	9382	8866	10460	2-isopropyl-3-methoxypyrazine (pea, beany...); tetramethylpyrazine (nutty, burnt...); n-nonanal (sweet...)