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Breeding for Taste: Sensory Characterization and Consumer Preferences for Lima Bean
Cultivars

By

YUKINA MURATA
THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Food Science and Technology

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Jean-Xavier Guinard, Chair

Christine H. Diepenbrock

Julien Delarue

Committee in Charge

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Abstract

Lima beans (*Phaseolus lunatus*), one of the five domesticated species within the *Phaseolus* genus, offer agroeconomic potential in the United States due to their production capacity and an increasing global demand for plant-based proteins. Although nutritionally comparable to more widely consumed legumes, lima beans remain one of the least consumed legumes in the U.S., and limited information exists on their sensory qualities and consumer acceptance across cultivars. Part of a nationwide study of lima bean genomics and germplasm resources funded by USDA NIFA SCRI, this research was a comprehensive investigation of the sensory properties and consumer acceptance of lima beans. This study specifically aimed to: 1) characterize the sensory profiles of succulent and dry cultivars, 2) identify positive and negative sensory drivers of consumer liking, and 3) explore perspectives and consumption behaviors among regular- and non-regular lima bean consumers.

Quantitative and qualitative sensory and consumer testing methodologies were implemented to bridge the knowledge gap between consumer behaviors and lima bean sensory and other characteristics. Quantitative descriptive analysis (QDA) was conducted to generate detailed sensory profiles, encompassing flavor, taste, texture/mouthfeel, and appearance attributes across 35 succulent and 43 dry lima bean cultivars. Trained panel evaluations enabled statistically robust characterization of human-perceived sensory differences. Central location tests (CLTs) were performed on select cultivars to collect hedonic responses and determine sensory attributes influencing consumer preferences. Additionally, focus groups (FG) were used to compare attitudes, beliefs, perceptions, and usage between regular and non-regular consumers, identifying triggers of and barriers to lima bean consumption.

QDA identified 30 significant attributes across succulent cultivars and 26 across dry lima beans. Flavor intensities, characteristics, and overall sensory profiles varied among different seed sizes and seed coat colors for both succulent and dry lima beans. Large succulent and dry cultivars exhibited stronger flavor intensities and greater sweetness, while phenolic-pigmented cultivars were associated with increased bitterness and earthy, kidney bean flavors, likely linked to phenolic compounds in the seed coat. Consumer testing indicated the highest liking for large, green succulent cultivars and large, white dry cultivars. Internal preference mapping further revealed three preference segments for the succulent lima beans and two preference segments for the dry lima beans. External preference mapping identified the consensual direction of acceptance for moist, soft, and sweet cultivars with corn, buttery, and some green flavor notes for both succulent and dry lima beans. These combinations may be achieved by large-seeded cultivars with minimized seed coat pigmentation by phenolics. Lastly, focus group findings highlighted key barriers among non-consumers, including long cooking time, perceived product unavailability, and media depiction with negative connotations. The differences observed between user groups could inform strategic marketing and communications that would advertise the desirable features of lima beans and clarify or dismiss some of their perceived limitations or drawbacks so that both US production and consumption of lima beans would increase.

Overall, this research identified critical sensory motivators and barriers shaping lima bean acceptance in the U.S. These insights provide valuable guidance for breeding programs aiming to develop cultivars aligned with U.S. consumer preferences, ultimately supporting broader adoption of lima beans as a nutritious, sustainable protein source.

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Thesis Introduction

Lima bean (*Phaseolus lunatus*) is one of the five domesticated species in the *Phaseolus* genus, alongside other legumes including common bean, year-long bean, scarlet runner bean, and tepary bean ([Aragao et al., 2010](#)). Lima beans underwent distinct domestications in Mesoamerica and in the Andes ([Garcia et al., 2021](#); [Chacon-Sanchez et al., 2017](#)). Andean domesticated types are characterized by large, flat seeds, whereas Mesoamerica domesticated types are characterized by small, round seeds ([Garcia et al., 2021](#)). Beyond morphological differences, distinctive gene pools were also found to be associated with agronomically relevant properties such as cultivated altitude and seed protein pattern ([Gutierrez Salgado et al., 1995](#)). Given this agronomic diversity across gene pools, evaluating germplasm sets of diverse and elite accessions (both large- and baby-seeded types) that have reasonable agronomics in the U.S. summer growing season may be a crucial driver for targeted breeding to holistically optimize sensory quality traits ([Pires et al., 2021](#); [Bria et al., 2019](#)). While literature on lima bean accessions and resulting variability in sensory attributes remains limited, studies on other *Phaseolus* legumes suggest that genetic variation may significantly influence chemical composition and resulting sensory qualities ([Florez et al., 2009](#); [Rivera et al., 2013](#)).

Lima beans hold extended significance in U.S. history, culture, and agro-economics. Culturally, their significance traces back to Mexican, tropical South American, and Peruvian cultures where the Mesoamerican and Andean domestications occurred, respectively, and extending to the U.S. continent where Native American populations appreciated it as one of their staple crops ([Park et al., 2016](#)). In the U.S., Native American populations have been growing and cooking lima beans together with corn and squash (i.e., the "three sisters") to offer a balanced diet and complete protein. Building on this cultural foundation, lima bean production has

persisted in the U.S., with an estimated total dry small seed production of 14.3 M lb accounting for 60% of the world's lima bean production ([USDA NASS, 2025](#); [Kleist, 2022](#)). While lima beans are harvested across continents, California alone contributes to 99% of domestic dry lima bean production — nearly 5 million pounds in 2020 — primarily due to the crop's adaptation to dry climates ([Dohle, 2017](#); [Kan-Rice, 2015](#)). Production from California alone is valued at approximately \$30 million, thus holding continuous significance as an agroeconomic resource ([Kan-Rice, 2015](#)). The lima bean production capacity and market share in the U.S. together suggest the potential agroeconomic benefits offered by continuing and supporting lima bean production.

The edible seeds are sold at two distinct growth stages. Fresh, succulent lima beans are harvested two and a half to three months after seeding, when seed pods are still green and seeds are still immature; these seeds are often distributed as frozen or canned products ([The New Crop Resource Online Program, 1999](#)). Dry seeds, on the other hand, are harvested four to five months after seeding and are sold as shelf-stable dry seeds or in canned form. Succulent lima beans are primarily produced in the Mid-Atlantic region, and dry lima beans are produced largely in California; the versatile product formats allow easy distribution to consumers across the U.S. and export to markets ([Sarah, 2017](#); [Long et al., 2014](#)). The nutritional profile of dry lima beans across baby- and large-seed entries is comparable to other dry legume grains that are commonly consumed (Table 1.1). With growing consumer awareness of shifting toward a plant-based diet as a preventative measure against chronic health conditions and in support of environmental sustainability, dry lima beans may serve as an additional ingredient option, further advancing healthy dietary patterns as one of the most affordable sources of protein and fiber ([Feher et al., 2020](#); [Viroli et al., 2023](#); [Drewnowski et al., 2024](#)). Also known as "butter beans" for their

buttery and starchy texture, lima beans allow versatile culinary application and easy incorporation into dishes.

Table 1.1 Proximate composition of cooked succulent and dry legume grains (per 100g)

<i>Succulent</i>						
	Energy (kcal)	Carbohydrate (g)	Protein (g)	Lipid (g)	Fiber (g)	Ash (g)
Lima (baby)	105 kcal	19.4 g	6.65 g	0.3 g	4.8 g	1.25 g
Lima (Fordhook)	103 kcal	19.3 g	6.07 g	0.34 g	5.3 g	1.3 g
Peas	84 kcal	15.6 g	5.36 g	0.22 g	5.5 g	0.92 g
Edamame (immature soybean)	121 kcal	8.91 g	11.9 g	5.2 g	5.2 g	1.21 g
Fava	88 kcal	17.6 g	7.92 g	0.73 g	7.5 g	1.12 g
<i>Dry</i>						
	Energy (kcal)	Carbohydrate (g)	Protein (g)	Lipid (g)	Fiber (g)	Ash (g)
Lima (baby)	126 kcal	23.3 g	8.04 g	0.38 g	7.7 g	1.12 g
Lima (large)	115 kcal	20.9 g	7.8 g	0.38 g	7 g	1.15 g
Soybeans	172 kcal	8.36 g	18.2 g	8.97 g	6 g	1.91 g
Black beans	132 kcal	23.7 g	8.86 g	0.54 g	8.7 g	1.15 g
Cowpeas	116 kcal	20.8 g	7.73 g	0.53 g	6.5 g	0.94 g
Lentil	116 kcal	20.1 g	9.02 g	0.38 g	7.9 g	0.83 g

*Per 100g cooked, mature seeds, boiled without salt, except that succulent fava bean only raw sample data available

*Sample compared in USDA Food Database (USDA, n.d.)

Despite their substantial production capacity across the U.S. and the nutritional value they offer amid increasing demand for plant-based protein, the crop remains underutilized by consumers. Lima bean is one of the least consumed legumes in the U.S., with per capita consumption of only 0.2 lb, which has been continuously declining since 1970 ([Bentley, 2019](#)). Some of the potential causes for this low consumption may include the lack of information on sensory profiles across cultivars, consumer awareness and liking on sensory profiles of lima

beans, as well as lack of consumer awareness on nutritional benefits, preparation methods, and general public information on lima beans. Breeders have made efforts in lima bean breeding to explore germplasm and improve agronomic performance. However, sensory quality and consumer liking are often neglected in breeding efforts, potentially creating a gap between production and consumption. Prior studies suggest that sensory characteristics may vary across lima bean accessions, but detailed sensory mapping and its linkage to consumer preference for breeding purposes remain largely unexplored ([Ibeabuchi et al., 2017](#)). Therefore, a solid understanding of the sensory and consumer qualities of lima beans would support both consumer- and farmer-focused breeding and contribute to increased consumption.

This thesis aims to explore a range of succulent and dry lima bean cultivars through the lens of sensory science and consumer evaluation to inform breeding decisions. Chapter 1 investigates the sensory profiles of 35 succulent lima bean cultivars and identifies sensory drivers of liking and disliking among selected samples. Chapter 2 follows the same approach applied to 43 dry lima bean cultivars. Chapter 3 explores qualitative consumer experiences through focus groups, with the objective of capturing the gap in perception between regular and non-regular lima bean consumers. Together, these three studies provide quantitative and qualitative insights to support consumer-centered lima bean breeding and future resource utilization.

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Chapter 1: Sensory Characterization and Consumer Liking of Succulent Lima Beans

1.1. Introduction

The first chapter aims to uncover the sensory qualities and consumer liking of succulent lima beans across a variety of cultivars to inform breeding efforts. Across 35 succulent lima bean cultivars provided by our breeding collaborators, we first characterize sensory profiles across cultivars using qualitative descriptive analysis to construct a sensory map. Second, representative cultivars from the sensory map were presented in a consumer test at a centralized location, aiming to identify sensory drivers of liking and disliking for each consumer segment. Collectively, this research may provide sensory-focused phenotypic information on succulent lima bean cultivars, clarifying target sensory qualities and offering tailored guidelines for breeding.

1.2. Material and Methods

1.2.1. Succulent Lima Bean Samples

Thirty-five entries of lima beans were harvested at the succulent stage for evaluation. Among those, thirty-one entries were grown in Georgetown, Delaware, USA, and four entries were grown in Clemson, South Carolina, USA. Samples were harvested between August and October 2024. Fresh lima bean seeds were dehulled, cleaned, blanched, and kept frozen in Ziploc bags during storage and transportation to the testing location (Davis, California, USA). The seeds were available in various combinations of size, seed coat pattern, and seed coat color (Table 1.2).

Table 1.2 Categories of Appearance of Succulent Lima Beans

Appearance Categories	Specification
Size (3)	Small/baby, medium/Fordhook, large
Seed coat pattern (5)	Self (no pattern), Jackson Wonder, Florida Butter, Restricted Christmas, Christmas
Seed coat color (9)	Black, Buff/purple, Pink, Red/green, Red/white, White green, White, Green, Yellowish green

1.2.2. Cooking and Preparation

A two-quart pot was filled halfway with distilled water and heated to boiling on a gas stove. Each sample was cooked for 20 minutes, with timing initiated once the water returned to a boil after the frozen samples were added. The cooking water was then drained, and the cooked samples were transferred to a metal pan and kept in a food warmer maintaining a sample temperature of 68–70°C until ready for evaluation. Cooked samples were served no later than one hour after cooking. Each sample was weighed (6.5–28 g) and served in a disposable paper cup with a lid. Serving size varied depending on availability per variety.

1.2.3. Qualitative Descriptive Analysis (QDA)

Participants (n = 10) from the University of California, Davis, were recruited as dedicated panelists for QDA. Recruitment screened participants based on the following criteria: age of 18–60, regular legume consumption (at least once a month), absence of any food allergies or sensitivities, and availability. Panelists were introduced to the scope of the project and an overview of descriptive analysis and signed the consent form (IRB 2269161-1).

Panelists committed to eight one-hour training sessions. The majority of the succulent samples were provided under a three-digit blind code as training samples and for establishing the texture scale. The first four training sessions consisted of introducing panelists to the tasting

experience, discussing sensory attributes of each sample, developing a list of objective sensory lexicons, and using unstructured line scales for mock evaluation as a group. The last four training sessions focused on familiarization with the online survey platform, evaluating samples individually, and revisiting descriptors and their definitions as a group.

After finalizing a set of objective sensory lexicons and their definitions, formal evaluations were conducted to characterize a complete sensory profile for each sample. Panelists were seated in individual booths partitioned by dividers. A total of 14 evaluation sessions were conducted, during which five samples were evaluated per session. Each sample was evaluated in duplicate due to time limitations and sample availability. Panelists used unstructured line scales to indicate the numerical intensities of given attributes on the online survey system (Red Jade).

1.2.4. Consumer Test

A total of 12 succulent samples were selected based on clustering from descriptive analysis, potential in agronomic performance, and commercial relevance, in order to identify sensory drivers of consumer liking and disliking of lima beans. Hierarchical cluster analysis (HCA) was conducted on the mean table of significant sensory attributes from descriptive analysis to identify sample clusters. Data were standardized and scaled (mean = 0, SD = 1) across all samples prior to clustering. Silhouette score analysis identified two as the statistically optimal number of clusters. However, a six-cluster solution was selected to maximize phenotypic and sensory diversity represented in the descriptive analysis. Samples at the centroids of six clusters were chosen as cluster representatives and included in the consumer test. An additional six samples were selected based on their potential in breeding and agronomic performance.

Participants ($n = 114$) reported to the central testing location (Sensory Theater, UC Davis, CA) to taste 12 lima bean samples over two days, with six samples served per day. Samples were prepared using the same methodology as described in Section 2.2. Approximately 15 g of cooked sample was portioned into a 4-oz paper cup with a plastic lid, and each cup was kept insulated in a Styrofoam box until ready to be served. Each sample cup was labeled with a three-digit blind code. The order of sample presentation per day was randomized, and individual serving order was determined using a Latin square design.

Participants were asked to taste each sample in their individually assigned serving order and to answer a series of questions about each sample. The questionnaire addressed overall liking, attribute-specific liking, adequacy of attribute intensity (JAR), check-all-that-apply (CATA), and open comments on likes and dislikes of the product. Liking questions were presented in the following order: appearance liking, size liking, color liking, overall liking, flavor liking, and texture liking. While external preference mapping (EPM, explained in the following section) identifies the sensory drivers of liking and disliking across consumer segments, JAR provides directional guidance for attribute optimization by quantifying how specific attribute intensities deviate from consumers' ideal levels for each product. CATA allows consumers to describe product sensory profiles using attributes developed by the trained panel, thus capturing the perception by untrained consumers and offering a consumer-relevant sensory profile of each product. Between samples, participants were asked to cleanse their palate with water and crackers during 60-second intervals. Upon completion of all samples, participants also completed an exit survey addressing participant demographics (age, gender, ethnicity, diet, income, and highest level of education completed or in progress) as well as behaviors and perceptions related to legume consumption.

1.2.5. Data Analysis

1.2.5.1. Descriptive Analysis

The global product differences across 35 succulent lima bean cultivars were assessed using multiple Analysis of Variance (MANOVA) with Wilks' lambda distribution at $p < 0.05$. Three-way Analysis of Variance (ANOVA) with two-way interactions was conducted to identify sensory attributes that differed significantly across lima bean samples at $p < 0.05$. A fixed-effects model was first applied to confirm product significance. Attributes with significant interaction terms in the fixed-effects model were rerun in a pseudo-mixed model; those with product significance in both the fixed-effects and pseudo-mixed models were deemed significantly different across products. Fisher's least significant difference (LSD) test was then conducted to identify specific statistical differences among samples.

Principal component analysis (PCA) using correlation matrix was conducted to interpret product variation and its association with sensory attributes. Separate PCAs were run for (1) flavor and taste, (2) texture and mouthfeel, and (3) appearance to prevent principal components from being dominated by differences between attribute categories rather than differences among cultivars.

Within-modality PCA was selected as the primary mode of analysis for descriptive data to improve resolution within each sensory modality. Multiple Factor Analysis (MFA) treating the three sensory modalities as separate blocks is provided in Supplementary Material 1 for confirmation of the overall sensory structure. The MFA explained 31.2% and 17.3% of total variance in Dimensions 1 and 2, respectively. Dimension 1 was strongly driven by texture and mouthfeel attributes, while Dimension 2 was structured by both flavor/taste and appearance

attributes, indicating differential contributions of sensory modalities across dimensions. RV coefficients among modalities were consistently low (~ 0.35), reflecting unique and non-redundant variation captured by each block and supporting within-modality interpretation for better resolution. Nevertheless, high RV coefficients between each modality and the overall MFA solution (~ 0.71 – 0.77) confirm that all three modalities are essential and balanced contributors to the overall sensory variation observed across cultivars.

Full mean intensities and LSD groupings are provided as a supplementary material (ST. 1). Boxplots showing attribute intensities by size and seed coat color categories were also constructed to supplement the LSD results. All statistical analyses were conducted in R.

1.2.5.2. Consumer Tests (overall liking, JAR, CATA, internal and external preference mapping with consumer clusters, demography)

ANOVA was performed on overall liking and attribute-specific liking scores to determine whether products differed significantly at $p < 0.05$. When a significant sample effect was detected, Fisher's Least Significant Difference (LSD) test was applied to identify pairwise differences among products. A Pearson correlation matrix was also constructed to examine associations among hedonic variables. A hedonic PCA biplot was constructed using a correlation matrix of mean consumer liking scores for overall liking and attribute-specific likings. Liking attributes were represented as vectors and products as scores, providing a visual summary of the hedonic dimensions along which products were most differentiated. This biplot complements internal preference mapping by summarizing overall hedonic structure across liking attributes prior to consumer segmentation analysis.

JAR responses were recoded into three adequacy categories: "too low" (ratings 1–2), "just-about-right" (rating 3), and "too high" (ratings 4–5). For each sensory attribute (moistness, firmness, seed-coat thickness, flavor, and sweetness), a Chi-square test or Monte Carlo Fisher's exact test was used to assess whether the distribution of adequacy categories differed significantly across products, given the large number of samples and very small counts for some attribute-by-JAR combinations.

Penalties were calculated as the difference between mean overall liking of consumers who rated the attribute as 'just about right' and mean overall liking of consumers who rated the attribute as 'too low' or 'too high'. Penalties were calculated as the difference between the mean liking of consumers in each non-JAR category and the overall mean liking of all consumers. Student's t-tests were used to evaluate whether these liking decreases were statistically significant.

Check-All-That-Apply (CATA) attributes and consumer counts were subject to Cochran's Q test to assess significant difference in proportion of consumers selecting an attribute across samples. Any attributes with maximum selection frequency of less than 10% were dropped out of the CATA analysis. Separate analyses were run for each attribute. It was followed by the McNemar post-hoc analysis with Bonferroni correction to identify pairwise significant difference in the number of consumers checking a specific attribute across samples. Lastly, penalty lift analysis was conducted to compare the difference in mean liking of consumers who checked the attribute and those who did not check the attribute using Student's t-test.

Internal preference mapping was performed by conducting PCA on a consumer $\times$ product matrix of overall liking scores using a covariance matrix. PCA automatically centered the data prior to constructing the internal preference mapping. Products and consumers were visualized as

scores and vectors respectively in the resulting biplot. To identify the optimal number of consumer segments, hierarchical clustering was applied on the centered data using Euclidean distance and Ward's linkage method. Cluster solutions were evaluated using both the Silhouette criterion and visual inspection of the dendrogram. Subsequently, mean overall liking scores for each consumer cluster were calculated from the raw data, followed by an LSD post-hoc test to assess differences among clusters.

External preference mapping (EPM) was conducted to identify sensory drivers of consumer liking and disliking within each segment. While JAR and CATA provide directional guidance for optimizing specific attribute intensities and capturing consumer sensory perception, EPM regresses consumer liking scores onto the sensory profiles from descriptive analysis. This linkage between sensory and hedonic spaces identifies which quantifiable sensory characteristics drive consumer acceptance across segments, providing actionable targets for breeding applications. Principal component regression (PCR) was selected as the modeling approach to address multicollinearity among sensory attributes, reduce dimensionality, and facilitate visualization of cluster-wise preference patterns in a shared sensory space. The first two principal components (PCs), derived from PCA of the descriptive analysis data, were retained as they captured the majority of variance in the sensory space. For each individual consumer, overall liking scores were regressed onto the two PC scores using a quadratic model. Each consumer's predicted liking surface was then discretized at their personal mean liking score as the preference threshold — grid points with predicted liking above the threshold were coded as 1 (preference), and below as 0 (rejection). The discretized surfaces were stacked within each consumer segment identified from the internal preference mapping, and summed to obtain the aggregated response surface. The resulting map shows the percentage of consumers in each segment whose predicted

liking exceeded their personal mean at each point in the sensory space. The 25%, 50%, and 75% contour lines were used to separate the majority preference zone from the rejection zone.

Table 1.3 Significant Succulent Flavor and Taste Descriptors, Definitions, and References (p<0.05)

Descriptors	Definitions	Reference
<u>Flavor (13)</u>		
Grassy	Mowing, fresh-cut grass	Freshly picked 2-3 strings of grass, teared in 3 parts
Hay	Hay	2-3 strings of hay
Sweet green	Sweet and fresh green vegetable	1 T peas + 1 T hot water in 2 oz cup, MW 20 sec
Bitter green	Bitter, savory, green vegetable	2 g asparagus + 4 g broccoli + 2 g green bean + 1 T water in mug, MW 20 sec
Maple syrup	Sweet, sugary	1.25 mL maple syrup
Edamame	Edamame green	1 T edamame + 1 T hot water in 2 oz cup, MW 20 sec
Kidney bean	Kidney bean	1 T kidney beans 1 T water in 2 oz cup, MW 20 sec, gently crush
Potato/starchy	Potato, cooked starchy	1:1 rehydrated mashed potato and starch solution (1:1 rice flour and water)
Buttery	Butter, creamy, dairy	7-8 g butter cube
Corn	Sweet, creamy, corn	1 T creamed corn, bring to room temperature
Earthy	Soil	1:1 soil and hot water
Curry	Spicy, savory, curry	1 g Japanese curry cube
Savory/brothy	Chicken stock, brothy	1 boiled egg in 600 mL boiled water for 10 min, ½ egg yolk per reference
<u>Taste (2)</u>		
Sweet	Sweetness	Low: 1 g sucrose/500 mL water High: 10 g sucrose/500 mL water
Bitter	Bitterness	Low: 0.05 g caffeine/500 mL water High: 0.2 g caffeine/500 mL water
<u>Texture/Mouthfeel</u>		
Wrinkle	The roughness of the seed coat surface on tongue in terms of wrinkliness	Min. and max. selected during training
Firmness	Force required to break the bean all the way down in a single bite	Min. and max. selected during training

Moistness	The moistness of single bean	Min. and max. selected during training
Initial Flow	The amount of cotyledon/contents that flows out of the bean at initial bite	Min. and max. selected during training
Seedcoat thickness	Force required to break/bite-off the seed coat at the beginning/end of a bite	Min. and max. selected during training
Seedcoat toughness	The relative distance between top and bottom teeth while breaking through the seed coat	Min. and max. selected during training
Flowability	The flowability of bean slurry (pasty/solid vs. flowing/creamy)	Min. and max. selected during training
Graininess	The mouthfeel of sandy/mealy particulates on tongue or in between teeth	Min. and max. selected during training
Chewiness	The number of mastication required to be able to swallow the slurry	Min. and max. selected during training
Easiness swallowing	The relative easiness to swallow the slurry	Min. and max. selected during training
Astringency	Overall dryness inside mouth after swallowing	Low: 0.2g sucrose/500ml water High: 0.6g sucrose/500ml water
<u>Appearance</u>		
Wrinkle/vein	The amount of wrinkles/vein occupying the surface of beans	Min. and max. selected during training
Damage	The amount of broken beans including fracture and seed coat peeling	Min. and max. selected during training
Individual size	The overall impression on the size of a single bean	Min. and max. selected during training
Size variation in a cup	The relative % difference in longitudinal and latitudinal length of individual beans	Low: no size variation High: size variation

*Panelists were exposed to majority of product set during training, generating texture scale in consensus and operational definitions were established prior to evaluation

1.3. Results and Discussion

1.3.1. Descriptive Analysis

1.3.1.1. Sensory Attributes

MANOVA confirmed the product differences at significance level of 0.05 (Wilks' $\lambda = 1.08 \times 10^{-5}$, $p = 8.3 \times 10^{-205}$). The 35 succulent lima bean entries were significantly different across 30 out of 35 sensory attributes developed through descriptive panels ($p < 0.05$) (Table 1.3). Significant attributes included flavor and taste across a wide range of categories (i.e. green, vegetable-associated, other unique descriptors), texture/mouthfeel, and appearance attributes.

Succulent lima beans were significantly different across entries of green flavors, including “grassy” and “hay,” represented by fresh-cut grasses and hay strings, respectively, and vegetable-like notes resembling boiled peas (“sweet green”) and mixed dark vegetables (“bitter green”). “Grassy” is one of the common descriptors for legumes across maturation stages. Descriptive studies on processed soymilk and young-maturing soybean and pea sprouts found significant product effects on “grassy” flavor ([Torres-Penaranda et al., 2001](#); Troszyńska et al., 2007). These beany or grassy flavors are often attributed to hexanal and butanol, the lipid oxidation products of unsaturated fatty acids in seeds. Lipoxigenase-free soymilk and processed tofu contained reduced concentrations of hexanal and butanol, as well as significantly lower scores for cooked beany flavor, resulting in higher hedonic scores by traditional consumers from Asia ([Torres-Penaranda et al., 1998](#); [Yang et al., 2015](#)). Together, these findings indicate that grassy flavor is chemically and perceptually meaningful, which may suggest the underlying biochemical signatures for breeding control for better product performance.

Legume sensory panels often report “beany,” a multifaceted term collectively referring to combinations of descriptors including grassy, earthy, cooked potato, and specific pulse-named

flavors ([Chigwedere et al., 2021](#)). Beany flavor is one of the most dominant and persistent attributes in legumes even after processing ([Byarugaba et al., 2020](#)). In this study, descriptive panelists were able to identify and segregate incremental terminologies for “beany” into multiple facets such as “earthy,” “potato/starchy,” and “kidney bean” flavors.

While the majority of the flavor attributes show consistency with findings in other legume sensory studies, “maple syrup” and “curry” were not explicitly found in other literature. However, panels in other cooked legume studies reported similar flavors such as sweet brown and caramelized ([Forster et al., 2024](#); [Mishra et al., 2017](#)). These compounds are produced by thermal reactions between reducing sugars and amino acids such as lysine, glycine, and proline in food, resulting in characteristic roasted and caramelized notes ([Tharuka et al., 2025](#)). Increased contents of aldehydes, alcohols, terpene alcohols, and ketones may be formed as a result of Maillard browning reactions in legumes ([Mishra et al., 2017](#)). In addition, pre- and post-fermented pea protein isolate (PI) were characterized as having roast flavor, which matched with furaneol and acetylpyridine aroma pens, the former being the primary contributor to maple flavor in maple syrup ([Arteaga et al., 2021](#); [Belford et al., 1991](#)). These observations suggest that maple-like and roasted flavors can be observed in legumes despite the variety of terminologies coined by panelists. Likewise, although the curry flavor may not be explicitly reported in other studies, the term “spicy aroma” was used in a sensory study comparing cooked whole and dehulled cowpeas, referring to “the smell of a spice” ([Penicela, 2010](#)).

Texture/mouthfeel attributes cover a wide range of sensory experiences, including initial food contact in the oral cavity, mastication, swallowing, and aftertaste. Attributes such as wrinkles, firmness, moistness, initial flow, flowability, graininess, chewiness, and difficulty swallowing describe the overall eating experience of the whole seed. Succulent legumes are also

known to be subject to textural variation due to genetic variations, environmental factors (i.e., soil irrigated with CaCl_2 producing harder shell), fertilizers (phosphate in nutrient solution producing soft shell), and storage conditions ([Shehata, 1992](#)). “Seed coat thickness” and “seed coat toughness” were also significant, specifically relating to the legume seed coat. The seed coat provides the controlling measure for water exchange between the cotyledon and the external environment, which may affect cotyledon hydration during cooking and resulting texture. The astringency/drying sensation after swallowing was also found to be significantly different.

Appearance provides the initial product information during evaluation. Attributes including wrinkle/vein, individual size, damage, and size variation in a cup were significant across products. Descriptive panelists in other legume studies have also found significant differences in appearance attributes such as color uniformity, size uniformity, splitting, and seed-coat peeling across products ([Nascimento et al., 2022](#); [Mkanda et al., 2007](#)), aligning with the appearance differences observed in this study.

1.3.1.2. Principal Component Analysis

Fig. 1.1 and Fig. 1.2 show the PCA biplot for flavor and taste attributes, with individual scores colored by three bean size categories (small, medium/Fordhook, and large). The first three PCs explained 73.5% of the total variance. PC1 (35.2%) was positively correlated with several green-related flavors ("sweet green," "hay," and "corn") and "sweetness," while "bitterness" showed the strongest negative correlation. PC2 (16.8%) captured variation in attributes including "curry," "maple syrup," "buttery," "savory brothy," and "kidney bean," with strong loadings by "curry" and "savory brothy." PC3 (12.1%) was driven primarily by "bitter green," "buttery," "potato starchy," and "earthy." PC4 (9.4%) was driven also by “bitter green.”

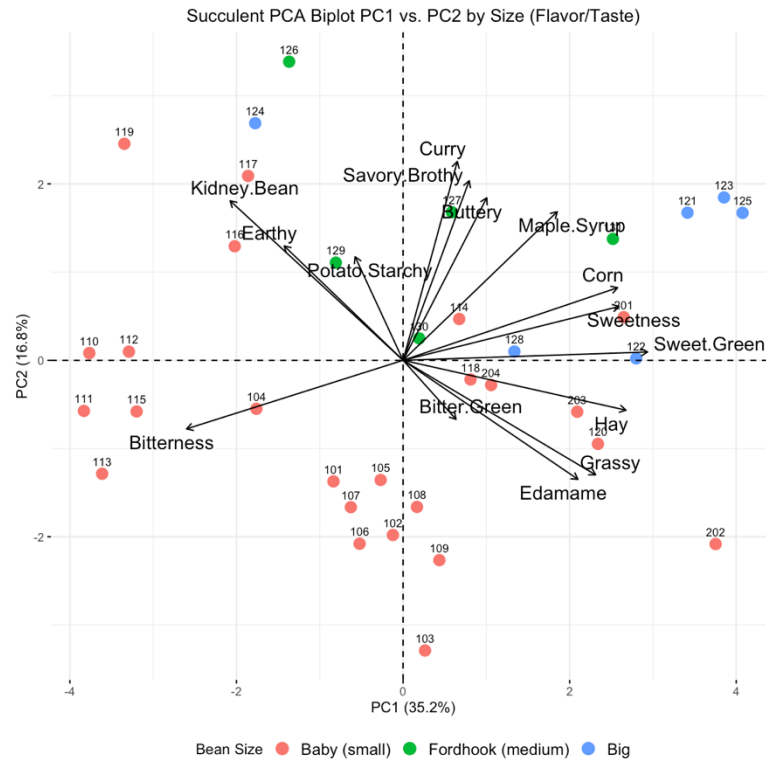


Fig. 1.1 PCA Flavor and Taste Attributes: PC1 (36.3%) vs. PC2 (17.5%), scores colored by bean size

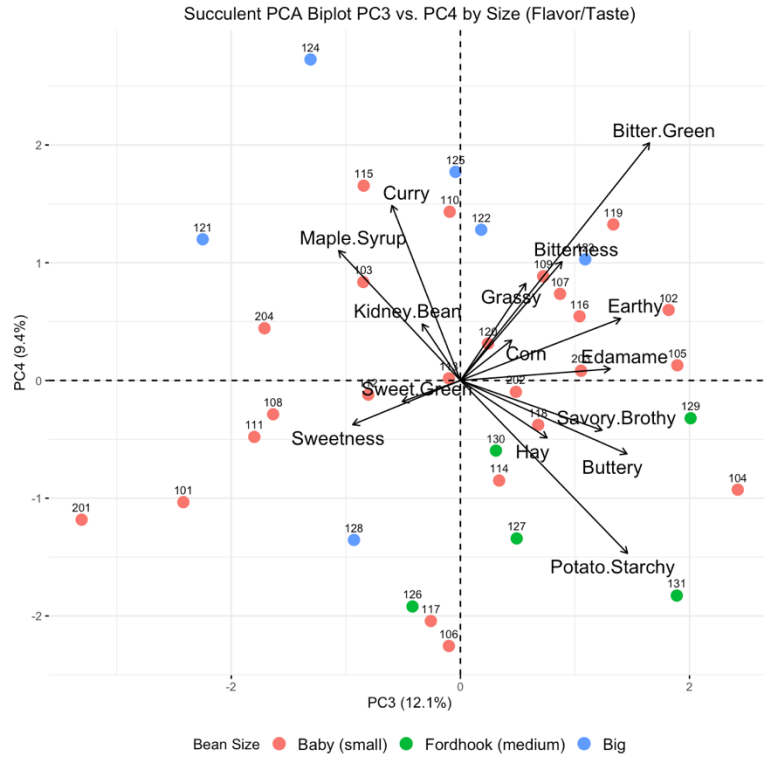


Fig. 1.2 PCA Flavor and Taste Attributes: PC3 (12.1%) vs. PC4 (9.4%), scores colored by bean size

In Fig. 1.1, succulent lima beans may be separated based on size, as baby lima beans were spread across the left and bottom-right quadrants, whereas medium and large lima beans were concentrated in the upper-right quadrant. Medium and large beans tended to exhibit stronger sweetness and lower bitterness compared to baby lima beans, as indicated by PCA, mean intensities (ST. 1), and the seed size-wise boxplot (Fig. 1.3). However, small lima beans could still exhibit sweetness and low bitterness comparable to some larger cultivars; four small samples grown in Clemson (i.e., Samples 201 through 204) scored relatively high sweetness intensities ranging from 40.8 to 53.85 and low bitterness ranging from 22.5 to 30.45. The remaining 20 baby lima beans from Delaware had lower sweetness (20.5–38.85) and higher bitterness (24.7–39.75) compared to the four Clemson samples.

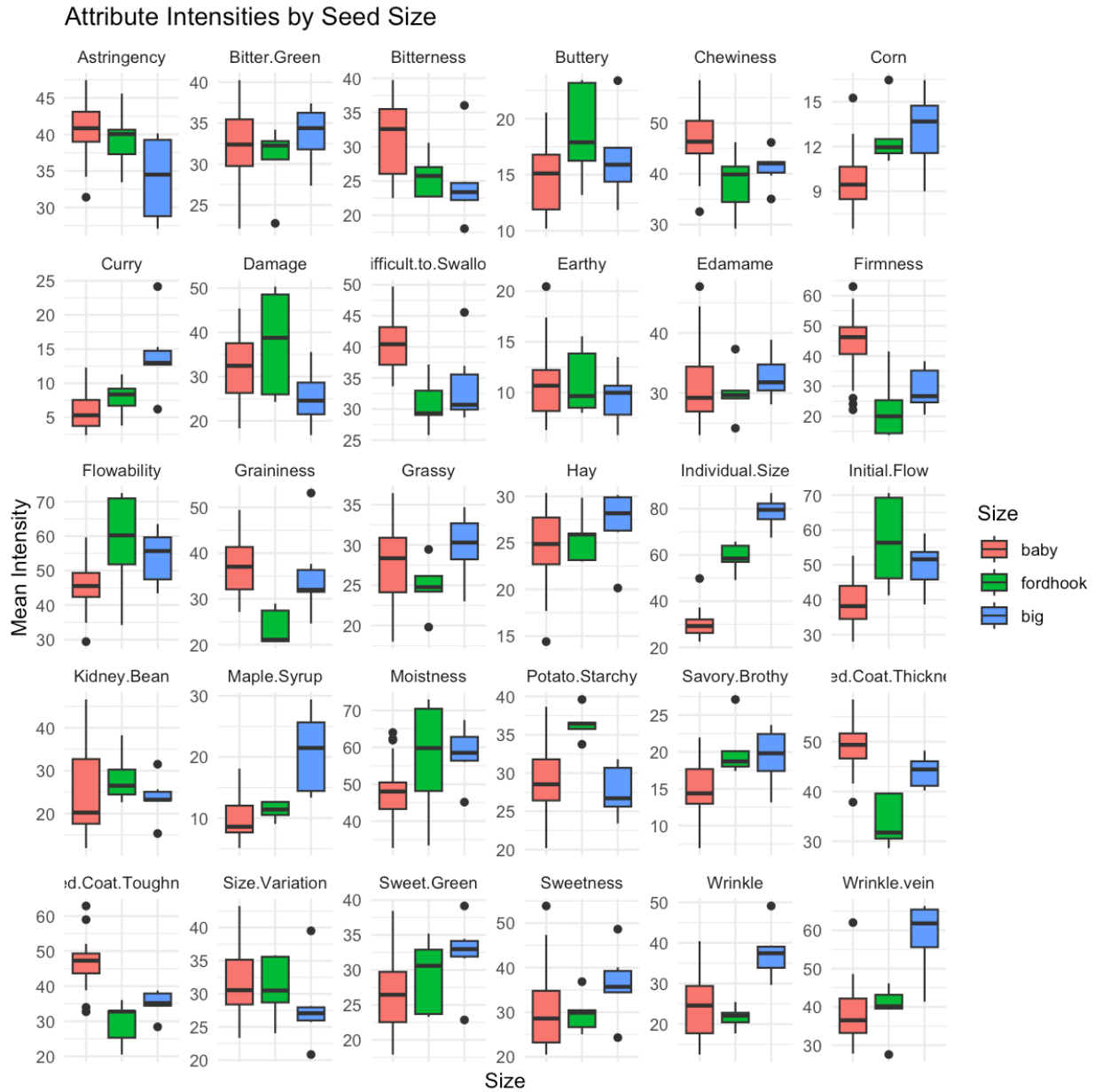


Fig. 1.3 Boxplot of mean intensities of all significant attributes by bean size

While literature on succulent lima beans in relation to seed size is limited, studies on other legume grains have explored the relationship between seed size and physicochemical properties. Among six dry common bean entries (*Phaseolus vulgaris*), a strong negative correlation between cooked bean size and bitterness was observed on PCA, and smaller samples

were the least preferred in consumer testing ([Mkanda et al., 2007](#)). Additionally, stronger bitterness in small-seeded legumes may be associated with higher phenolic contents. Large-seeded brown chickpeas were found to have lower phenolic contents than small-seeded chickpeas of the same color, suggesting a potential phenolic contribution to stronger bitterness in small-seeded entries ([Marathe et al., 2011](#)). A multi-omic study on five chickpea genotypes of various seed sizes further found that small-seeded genotypes had higher antioxidant capacity than other genotypes, with over-accumulated endogenous polyphenols including vanillin, L-phenylalanine, salicylic acid, and protocatechuic acid, which may be linked to higher bitterness and astringency in baby-seeded lima beans ([Quiroz-Figueroa et al., 2022](#)).

Medium and large succulent lima beans, located in the upper-right quadrants, may be characterized by stronger, more complex flavor combinations — including "corn," "sweet green," "hay," and "grassy" — relative to small lima beans. The boxplot (Fig. 1.3) further demonstrated that the median and middle 50% of large and medium samples were relatively higher than those of baby beans for "corn," "sweet green," and "savory brothy." Medium samples tended to be relatively stronger in "buttery" and "potato starchy" than the other size categories, while large samples tended to be stronger in "hay" and "grassy." Additionally, "maple syrup" and "curry" flavors were more pronounced in large and medium samples than in baby samples, as indicated by both the boxplots and mean intensities.

The PCA biplot for texture and mouthfeel attributes revealed additional associations between product size and sensory perception (Fig. 1.4). PC1 (69.7%) showed strong positive correlations with "seed coat thickness," "seed coat toughness," "graininess," "astringency," "difficulty swallowing," "firmness," and "chewiness," and negative correlations with "moistness," "initial flow," and "flowability." PC2 (12.9%) was primarily driven by "wrinkle"

and "astringency." Sample separation along PC1 indicated that medium and large samples tended to be more moist, soft, and creamy, with greater cotyledon flow, while baby beans tended to be dry, firm, and grainy. Their seed coats differ accordingly: medium and large beans had soft, thin seed coats that wrinkle more, whereas baby beans had tough, thick seed coats that contribute to longer chewing, difficulty swallowing, and higher astringent aftertaste. The boxplot confirmed that baby samples score higher in "firmness," "graininess," "seed coat thickness," "seed coat toughness," and "difficulty to swallow," and lower in "moistness," "flowability," and "initial flow."

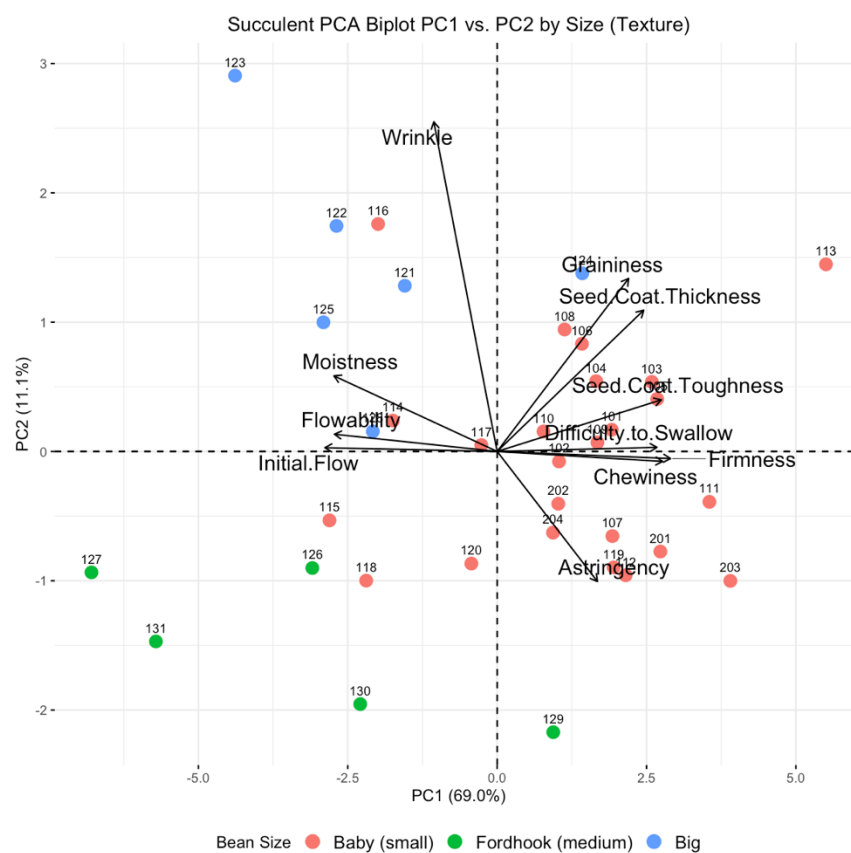


Fig 1.4 PCA Flavor and Taste Attributes: PC1 (36.3%) vs. PC2 (17.5%), scores colored by bean color

Seed coat structure may affect hydration and subsequent textural properties in legumes. While proximate composition data on succulent lima beans are limited, the seed coats across four dry lima bean accessions were composed of approximately 14.53–15.93% protein, 47.11–48.62% carbohydrate, 2.43–3.88% ash, and 33% crude fiber on a dry weight basis ([Seidu et al., 2015](#)). Undehulled (whole seed) lima bean flour was found to have significantly greater protein, crude fiber, and ash content than dehulled flour, potentially contributing to grainy and mealy mouthfeel in legumes ([Ibeabuchi et al., 2019](#)). Furthermore, seed coat structure may affect legume hydration. Small openings called micropyles are distributed across the seed coat and control moisture exchange and imbibition during cooking ([Perera et al., 2023](#)). Water imbibition and hydration rate may vary depending on seed coat thickness and color; however, these factors may not be directly correlated, such that seeds with thicker seed coats do not always exhibit the highest imbibition rates ([Mandizvo et al., 2019](#); [Chibarabada et al., 2014](#)).

Proximate composition may further affect the texture and mouthfeel of cooked legumes. Sensory and chemical evaluation of common beans has found that cultivars with higher perceived creaminess had higher protein content and amylose-to-amylopectin ratio, and lower overall starch, amylose, and amylopectin content ([Casanas et al., 2006](#)). Additionally, increasing hydrothermal processing time significantly decreased hardness and fracturability across legume species while increasing starch digestibility, indicating that water imbibition through the starch matrix in the cotyledon drives textural transformation ([Krisanapant et al., 2021](#)). Adequate hydration and thermal processing lead to starch gelatinization, in which amylose granules swell upon hydration and disrupt the crystalline structure supported by amylopectin ([Mohamed, 2021](#)). Collectively, these findings suggest that sensory differences across succulent lima bean cultivars

may arise from variation in seed coat structure and macronutrient composition, supporting the need for further proximate analysis.

The perceived thicker seed coat in baby beans not only reflects greater structural material but may also result in slower hydration compared to thinner seed coats, leading to more difficult consumption experiences. In dry legumes, the seed coat may become the limiting factor for moisture uptake ([Kinyanjui et al., 2014](#)). While succulent legumes do not require soaking prior to cooking, a thick seed coat around succulent seeds may potentially impede moisture transfer from cooking water to the cotyledon, resulting in dry, grainy texture in small-seeded cultivars.

By appearance (Fig. 1.5), large samples tended to exhibit greater wrinkling and more visible veins than the other two size categories, presumably due to their thin, soft seed coats producing more visually apparent wrinkles. Despite being more frequently categorized as soft and moist, large samples exhibited less physical damage than medium or baby beans. Medium beans may be more prone to breakage, as their seed coats were the thinnest and softest among the three sizes examined. Baby beans, on the other hand, may also be susceptible to damage due to their dryness contributing to greater brittleness. Large beans also exhibited the least size variation among the three categories.

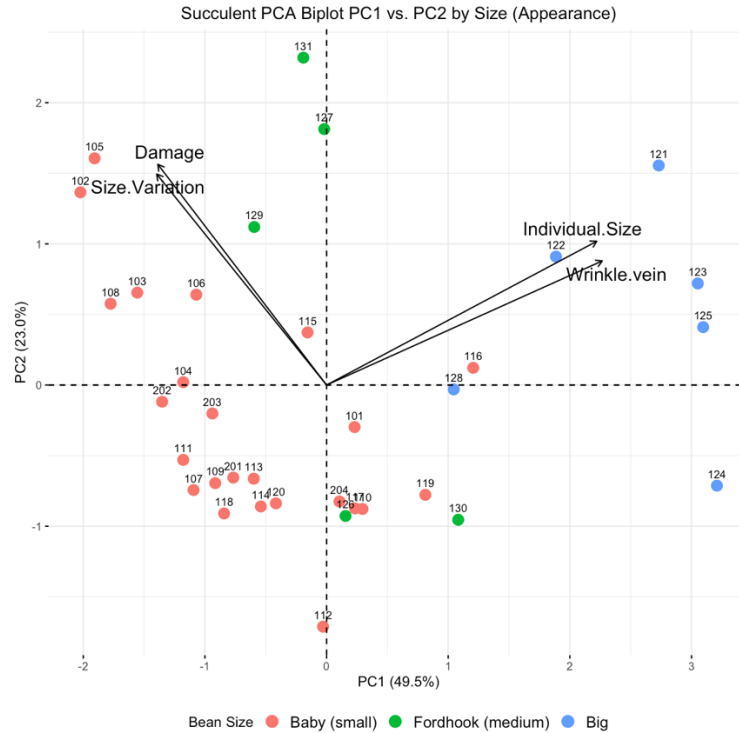


Fig 1.5 PCA Appearance Attributes: PC1 (50.8%) vs. PC2 (24.8%), scores colored by bean color

Succulent lima beans displayed a variety of seed coat colors, which may represent an additional source of variation in flavor and taste (Fig. 1.6). Fig. 1.6 mirrors Fig. 1.1 in terms of flavor and taste attributes, with sample scores colored according to actual seed coat color. Samples with darker seed coat colors (i.e., dark, pink, purple, and red/green) were located in the left quadrants, suggesting stronger "bitterness," "earthy," and "kidney bean" flavor profiles. Samples with lighter seed coat colors (i.e., green, yellowish green, and white-containing colors) were located in the right quadrants, indicating stronger and more complex flavor profiles characterized by "sweetness," "corn," and green-related flavors. The boxplot further consolidated these seed coat categories into green, non-phenolic (white), phenolic (divided into two groups for purple/black and red/pink) (Fig. 1.7). Phenolic-containing and red/pink samples tended to exhibit

higher mean intensities of "astringency," "kidney bean," and "earthy," whereas non-phenolic and green samples tended to be stronger in "grassy," "sweet green," "hay," and "edamame."

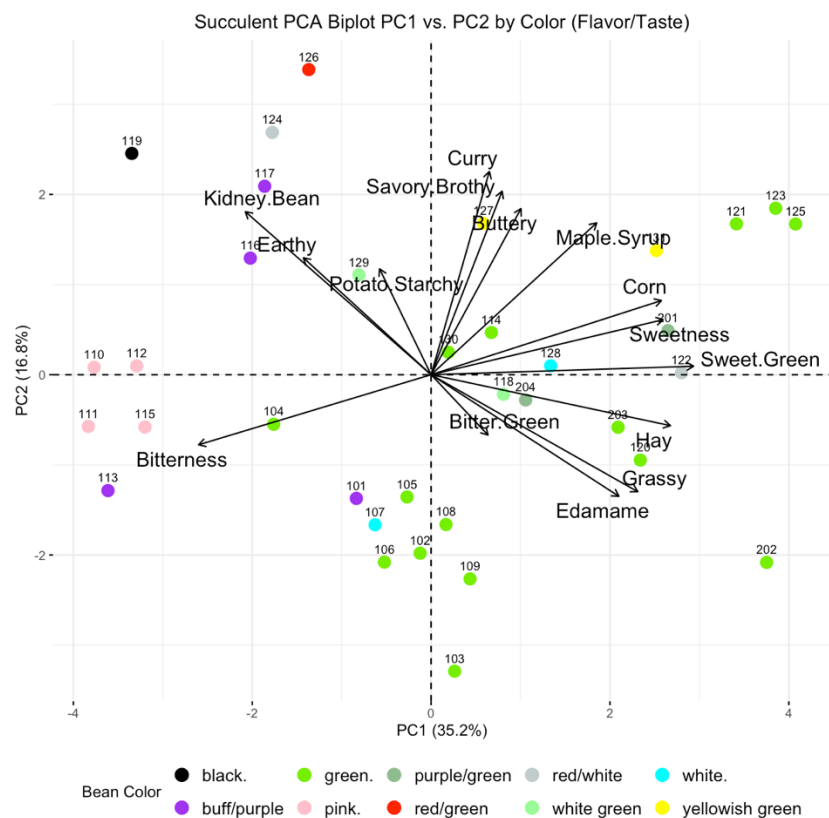


Fig. 1.6 PCA Flavor and Taste Attributes: PC1 (36.3%) vs. PC2 (17.5%), scores colored by bean color

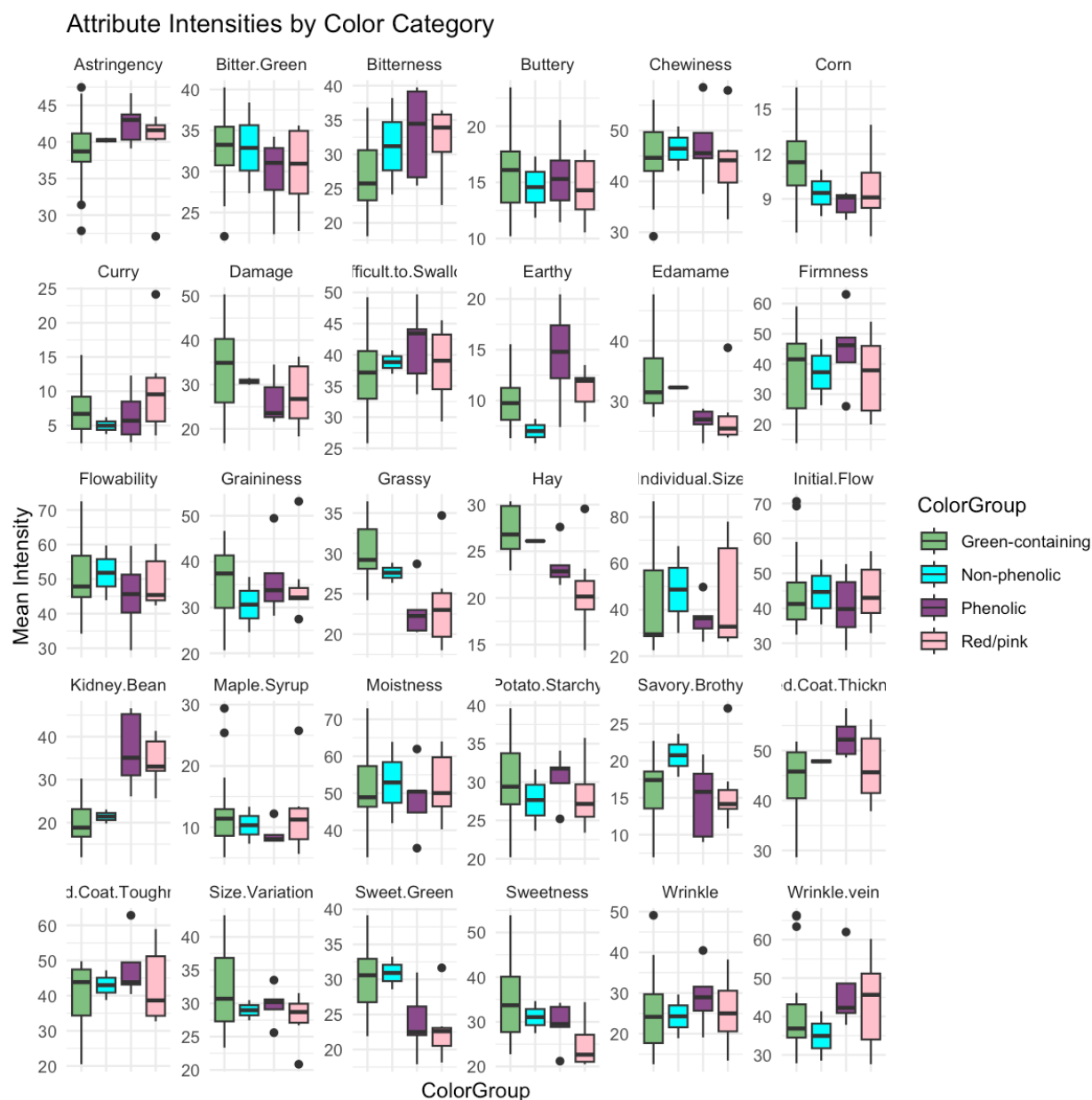


Fig. 1.7 Boxplot of mean intensities of all significant attributes by bean color

Polyphenolic components including flavonoids are thought to be responsible for the variety of seed coat colors observed among common bean entries. Among dry lima bean accessions, white-seeded samples were clustered into groups with low to medium phenolic content, whereas seeds of all other coat colors — including black, pink, red, and brown —

clustered together with the highest phenolic contents ([Agostini-Costa et al., 2015](#)). In other legumes, cultivars with darker seed coat colors have been associated with higher astringency and bitterness ([Madrera et al., 2021](#)). The higher astringency observed in phenolic-pigmented and red/pink samples may be attributed to their polyphenol content. Similarly, a panel evaluation of 15 pea accessions (*Pisum sativum* L.) found that darker seed coat colors were associated with earthy odor, chewiness, and shell thickness, while light-colored samples were associated with sweetness and juiciness ([Dueholm et al., 2025](#)). The same study also reported higher DDMP saponin content in dark-colored samples, which may degrade at cooking temperatures around 40°C and contribute to bitterness ([Heng et al., 2006](#)).

1.3.2. Consumer Test

1.3.2.1. Overall Liking and Attribute-Specific Likings

Participants (n = 114) tasted 12 succulent lima bean samples and rated their degree of liking or disliking on a 9-point hedonic scale. Among the 12 samples, 6 of them were representatives of the 6 clusters found in descriptive means (Fig. 1.8). Table 1.4 presents the mean and standard error of the mean for each product. Overall liking, appearance, size, color, flavor, and texture liking scores differed significantly across products (ANOVA, $p < 0.05$), with post-hoc LSD comparisons also shown in Table 1.4.

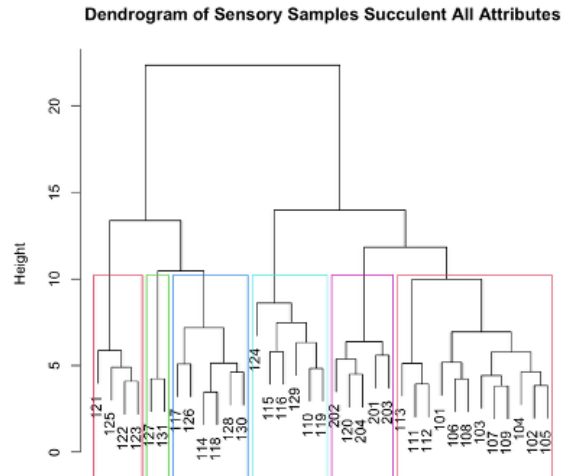


Fig. 1.8 Hierarchical clustering analysis of 35 succulent lima bean entries based on mean sensory attribute intensities from descriptive analysis, used to identify six representative entries for consumer testing.

Prior to tasting, participants visually evaluated their liking of overall appearance, size, and color of the samples. For overall appearance, green baby samples such as samples 202 and 109 were liked the most. In contrast, non-green samples such as sample 126 (purple Fordhook) and sample 204 (pale-white baby bean) were the least liked among the evaluated samples. For size liking, the large sample (sample 125) received the highest liking, followed by the Fordhook samples (samples 126 and 131). For color liking, green and yellowish-green samples tended to be rated more favorably than purple and black lima beans, although liking varied among green samples depending on the specific cultivar.

Participants were then asked to taste the samples and evaluate their overall liking, flavor liking, and texture liking. Overall, sample 125 (large, green), sample 114 (small, light green), and sample 131 (Fordhook, yellowish green) were the most liked, with mean overall liking scores of 6.37, 6.10, and 6.05, respectively. These three samples were liked at levels similar to or

significantly higher than the commercial baby (5.79) and commercial Fordhook (5.69) reference samples. They were also among the most preferred for flavor and texture liking. On the other hand, sample 204 was the least liked overall (mean = 4.42), as well as for flavor (4.48) and texture (4.71). Sample 110 was additionally among the least liked for texture (5.02).

The hedonic biplot (Fig. 1.9) indicated that color and overall appearance were the major drivers of variance in liking across products along PC1 (71%). Pearson correlation analysis ($p < 0.05$) revealed that overall liking was significantly and positively correlated with appearance, color, flavor, and texture liking (Table 1.5). Despite the generally higher liking scores associated with larger samples, a significant negative correlation was observed between appearance liking and size liking.

Table 1.4 Mean and SEM of overall liking, likings of appearance, texture, flavor, color and size with LSD post-hoc comparison

Sample	Overall	Appearance	Texture	Flavor	Color	Size
109 DE16040410B	5.18 (0.16) ^{ef}	6.14 (0.14) ^{ab}	5.45 (0.16) ^{de}	5.03 (0.17) ^d	5.89 (0.15) ^{bc}	2.87 (0.04) ^e
110 DE1720505D	4.96 (0.16) ^f	5.11 (0.17) ^c	5.02 (0.16) ^{ef}	5.22 (0.16) ^{cd}	5.24 (0.19) ^d	2.97 (0.04) ^{de}
114 DE1201101A	6.10 (0.16) ^{ab}	5.18 (0.17) ^c	6.11 (0.18) ^{ab}	6.21 (0.17) ^{ab}	5.50 (0.18) ^{cd}	3.04 (0.04) ^d
119 DE1820405B	5.52 (0.16) ^{de}	4.35 (0.17) ^d	5.99 (0.16) ^{abc}	5.50 (0.15) ^c	4.70 (0.20) ^e	3.22 (0.06) ^c
125 DP1100101A	6.37 (0.18) ^a	5.13 (0.20) ^c	6.43 (0.17) ^a	6.56 (0.17) ^a	6.62 (0.15) ^a	4.41 (0.07) ^a
126 DP16005 18B	4.96 (0.19) ^f	2.88 (0.16) ^f	5.44 (0.19) ^{de}	5.17 (0.18) ^{cd}	3.24 (0.17) ^f	4.26 (0.07) ^a
129 DE1710601E	5.61 (0.14) ^{cde}	5.25 (0.15) ^c	5.84 (0.15) ^{bcd}	5.46 (0.15) ^{cd}	5.78 (0.16) ^{bc}	3.32 (0.06) ^c
131 Fordhook 242	6.05 (0.16) ^{abc}	5.24 (0.16) ^c	6.08 (0.18) ^{abc}	6.28 (0.15) ^{ab}	5.86 (0.15) ^{bc}	3.49 (0.06) ^b
202 Thorogreen	5.53 (0.15) ^{de}	6.23 (0.15) ^a	5.51 (0.17) ^d	5.49 (0.15) ^c	6.19 (0.15) ^{ab}	2.54 (0.05) ^f
204 Jackson Wonder	4.42 (0.16) ^g	3.48 (0.15) ^e	4.71 (0.17) ^f	4.48 (0.16) ^e	3.15 (0.16) ^f	2.53 (0.06) ^f
Commercial baby	5.79 (0.15) ^{bcd}	5.75 (0.16) ^b	5.63 (0.18) ^{cd}	5.96 (0.15) ^b	5.97 (0.15) ^b	2.99 (0.04) ^{de}
Commercial Fordhook	5.69 (0.16) ^{bcd}	4.04 (0.16) ^d	5.66 (0.17) ^{bcd}	5.98 (0.16) ^b	4.68 (0.15) ^e	3.60 (0.06) ^b

* Values are means $\pm$ SEM. Means within a column followed by different letters are significantly different (LSD post-hoc test, $p < 0.05$).

Table 1.5 The Pearson correlation matrix ($P < 0.05$)

	Appearance	Overall	Color	Flavor	Texture	Size
Appearance	1.00	0.42***	0.79***	0.35***	0.31***	-0.26***
Overall		1.00	0.43***	0.87***	0.75***	-0.01
Color			1.00	0.40***	0.31***	-0.08**
Flavor				1.00	0.64***	0.02
Texture					1.00	0.01
Size						1.00

*Significant correlations are indicated by * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

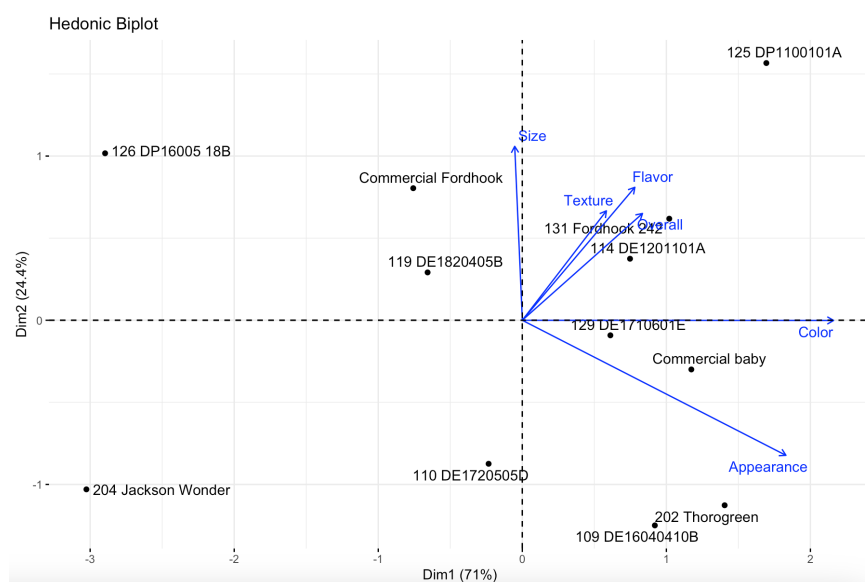


Fig. 1.9 Hedonic biplot of overall and attribute-specific likings

1.3.2.2. Just-About-Right (JAR) and Penalty Lift

Consumers rated the adequacy of five sensory attributes — firmness, moistness, seed coat thickness, flavor, and sweetness — on a three-level scale: too little, just-about-right (JAR), and too much. ST. 1.2 summarizes the percentage of consumers in each adequacy category per

attribute. Fig. 1.10 also shows the distribution of JAR scales per product across each JAR term. Chi-square or Fisher's exact tests indicated the significant difference in JAR distribution across samples for all attributes. At least 50% of consumers rated firmness as JAR for all samples. Similarly, at least 50% of consumers rated moistness and seed coat thickness as JAR for all samples except sample 110 (small, pink/red). For flavor adequacy, at least 50% of consumers rated JAR for all samples except samples 109 (small, green) and 204 (small, color not provided). The percentage of consumers rating sweetness as JAR varied among samples, ranging from 30.70% for sample 204 to 71.05% for sample 125 (large, green).

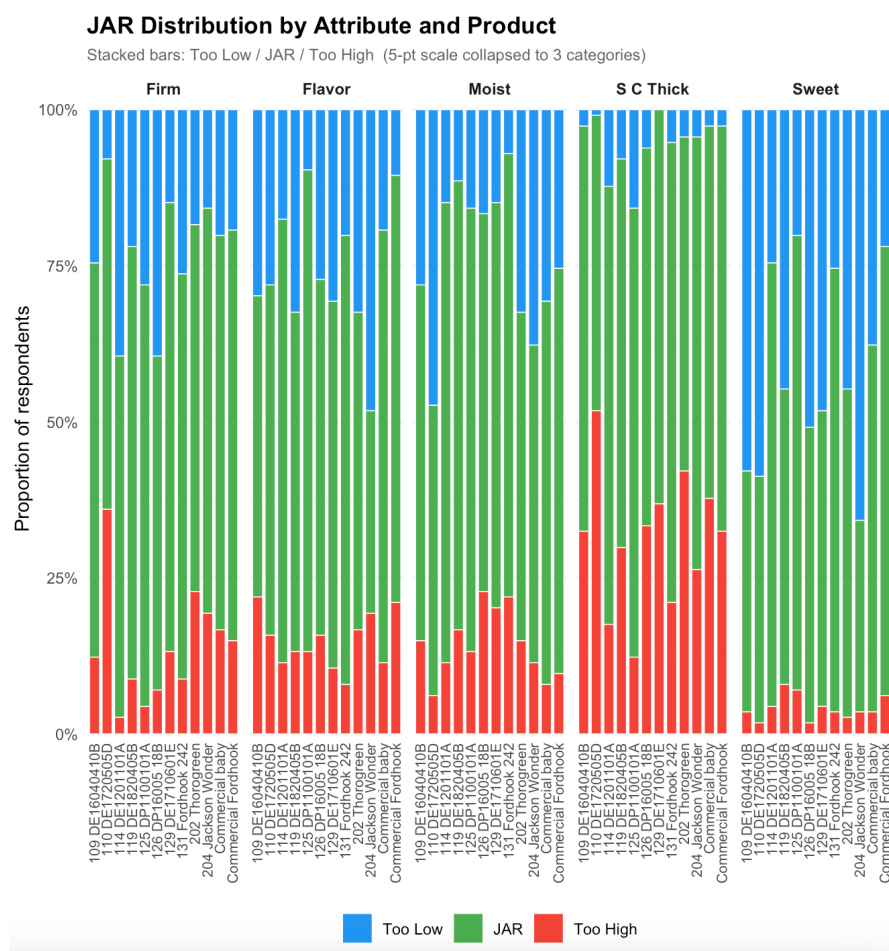


Fig. 1.10 Distribution of consumer responses (%) on the Just About Right (JAR) scale for attribute liking of succulent lima bean cultivars

Penalty analysis was conducted to assess which attributes were critical in reducing mean overall liking. Based on Student's t-tests, the drops in mean liking from the JAR category to either the "too low" or "too high" category were statistically significant ($p < 0.05$) in all attributes. Attributes falling in the "critical corner" — defined as a drop in mean liking greater than 1.0 point with more than 20% of consumers in the non-JAR category — were considered penalizing attributes (Fig. 1.11). Samples perceived as too dry, too weak in flavor, or too weak in sweetness were associated with significant penalties to overall liking. Outside the critical corner, approximately 15% of consumers contributed to a drop in overall liking of more than 2 points due to flavor being rated too strong. Additionally, approximately 30% of consumers contributed to a drop in overall liking of slightly less than 1 point due to seed coat thickness being rated too thick.

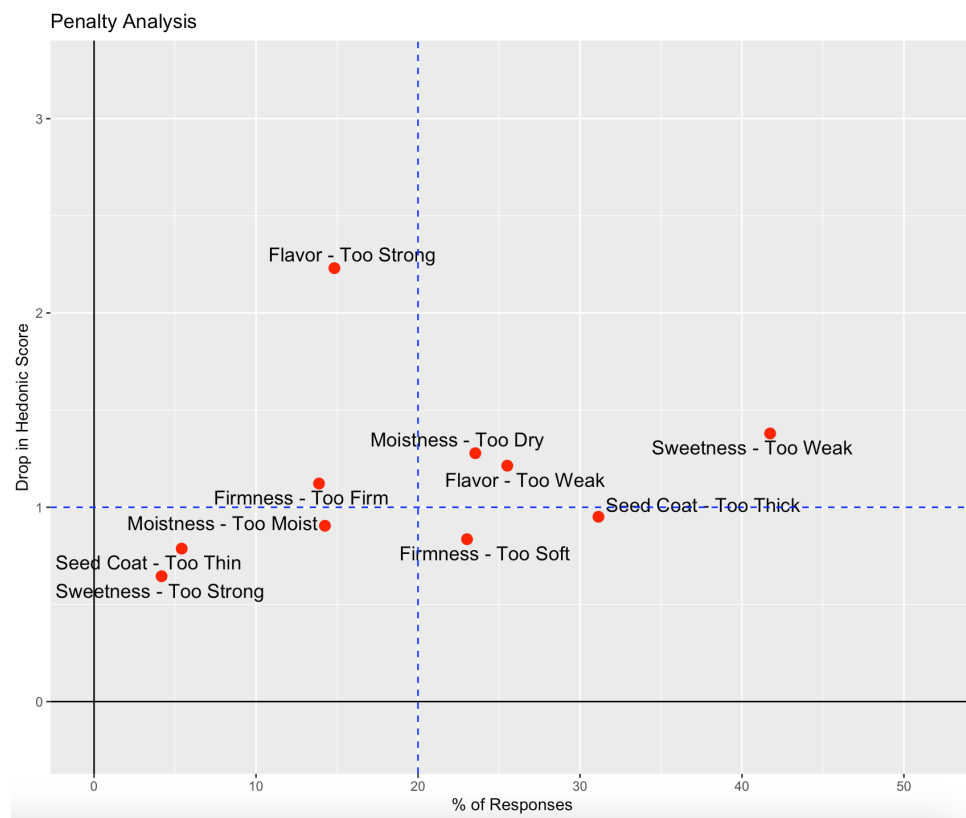


Fig. 1.11 Mean drop in overall liking associated with non-JAR responses for sensory attributes of succulent lima bean cultivars (penalty analysis)

1.3.2.3. Check-All-That-Apply

Correspondence analysis was conducted on the check-all-that-apply (CATA) data comprising 29 descriptors (Fig. 1.12). “Maple syrup” and “curry” had the maximum frequency less than 10% of the total, thus dropped for further CATA analysis. Based on Cochran's Q test, the proportion of consumers selecting each attribute differed significantly across samples for all attributes except "hay" ($p < 0.05$). McNemar pairwise comparisons with Bonferroni correction further revealed significant pairwise differences among samples across all attributes.

The first and second dimensions explained 48.1% and 21.6% of total variance (Fig. 1.12). Samples with the significantly highest overall liking — samples 114, 125, and 131 — were associated with the descriptors "moist," "buttery," "creamy," and "sweet." Among these top-rated samples, associations with additional descriptors varied by cultivar: sample 114 was also associated with "edamame," "corn," and "sweet green," while sample 125 had additional associations with "big," "maple syrup," "damaged," and "savory brothy." In contrast, sample 204, which received the lowest mean overall liking, was associated with "tough seed coat," "thick seed coat," "difficult to swallow," and "bitter."

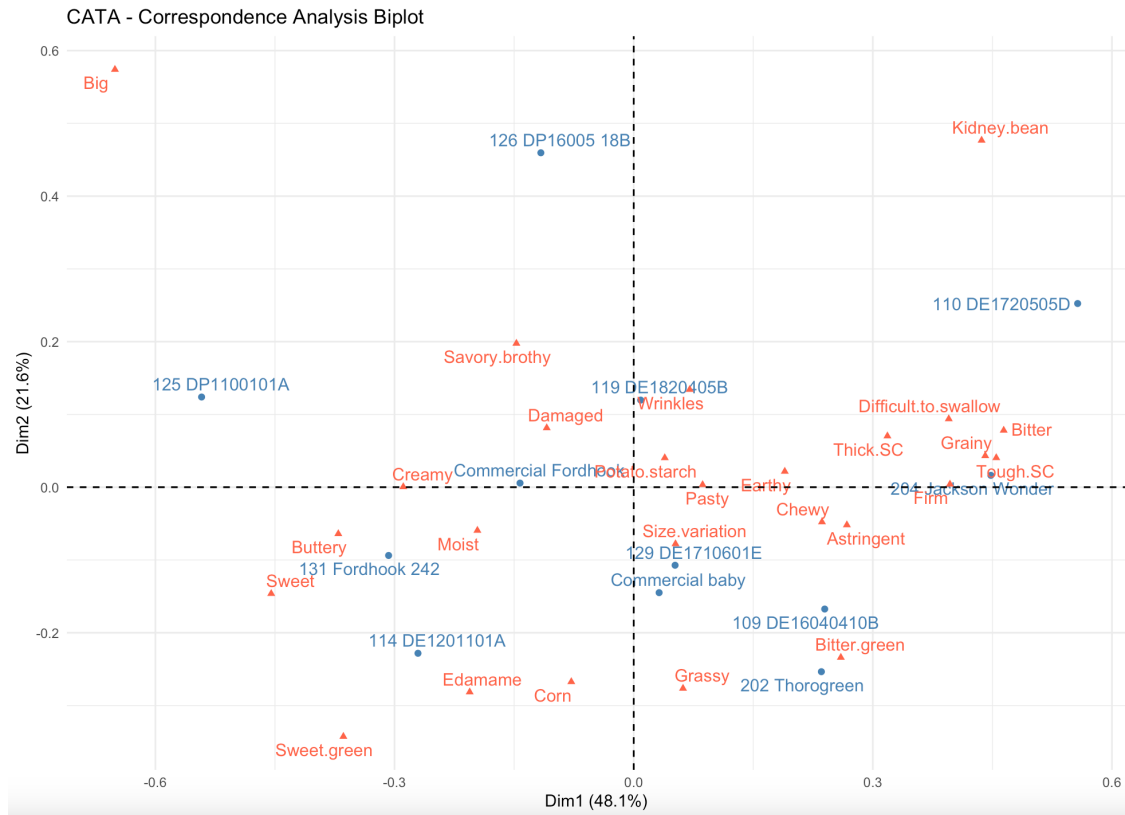


Fig. 1.12 Correspondence analysis on check-all-that-apply attributes

Penalty-lift analysis was also conducted for each CATA attribute (Fig. 1.13). Overall, consumer selection of "sweet," "sweet green," "buttery," "creamy," and "maple syrup" was associated with an increase in mean liking of approximately 1 point. Conversely, selection of "difficult to swallow," "bitter," and "astringent" was associated with a decrease in mean liking of approximately 1 point. Significant differences in mean overall liking between consumers who selected a given attribute and those who did not were found for all attributes except "corn," "firm," "size variation," and "grassy."

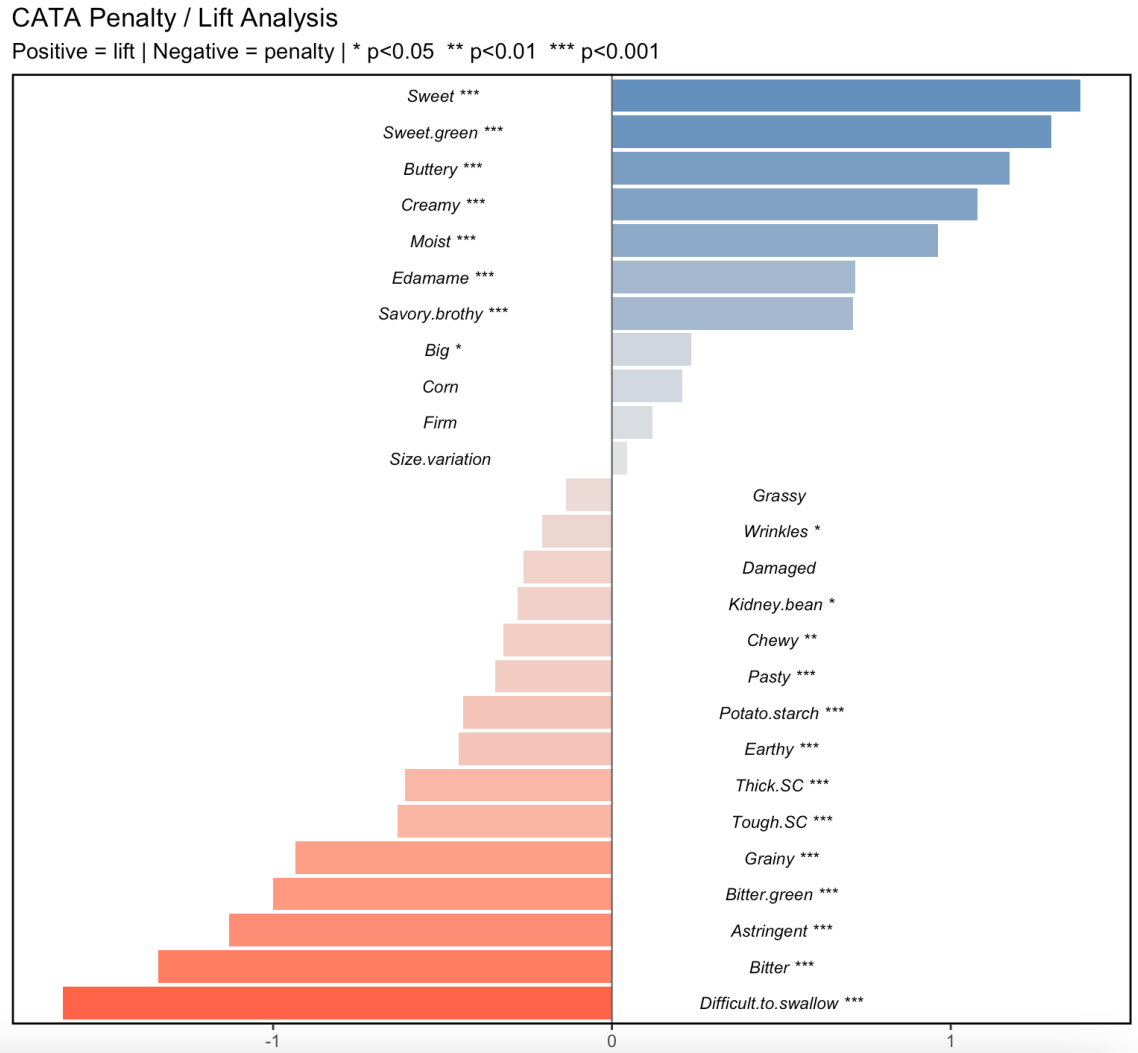


Fig. 1.13 CATA penalty/lift analysis

1.3.2.4. Internal Preference Mapping

Internal preference mapping and hierarchical clustering analysis on consumer liking scores identified three consumer segmentations (Fig. 1.14). The mean overall liking scores for each product per consumer segment is also shown in Fig. 1.15. Consumers in cluster 1 (n = 18) showed strong preference loadings toward the right side of the coordinate space, with preference concentrated on larger lima beans, including samples 131 and 125. Cluster 2 was the largest consumer group (n = 50), with significantly strong preference distributed across a variety of

The figure consists of two side-by-side PCA plots. The left plot is titled 'Consumers, plotted as loadings in the consumer-liking space (centered)'. The x-axis is 'Dimension 1, 23.66% of variance' and the y-axis is 'Dimension 2, 13.66% of variance'. Data points are colored by cluster: red for cluster 1, green for cluster 2, and blue for cluster 3. The right plot is titled 'Succulent Lima Beans, plotted in consumer-liking space'. The axes are the same as the left plot. Data points are labeled with variety names and codes, such as '202 Thorogreen', 'Commercial baby', '129 DE1710601E', '119 DE1820405B', '204 Jackson Wonder', '109 DE16040410B', '114 DE1201101A', '131 Fordhook 242', 'Commercial Fordhook', '125 DP1100101A', '110 DE1720505D', '126 DP16005 18B', '1001', '1030', '1009', '1005', '1008', '1002', '1004', '1003', '1012', '1028', '1024', '1026', '1025', '1027', '1029', '1031', '1033', '1034', '1035', '1036', '1037', '1038', '1039', '1040', '1041', '1042', '1043', '1044', '1045', '1046', '1047', '1048', '1049', '1050', '1051', '1052', '1053', '1054', '1055', '1056', '1057', '1058', '1059', '1060', '1061', '1062', '1063', '1064', '1065', '1066', '1067', '1068', '1069', '1070', '1071', '1072', '1073', '1074', '1075', '1076', '1077', '1078', '1079', '1080', '1081', '1082', '1083', '1084', '1085', '1086', '1087', '1088', '1089', '1090', '1091', '1092', '1093', '1094', '1095', '1096', '1097', '1098', '1099', '1100', '1101', '1102', '1103', '1104', '1105', '1106', '1107', '1108', '1109', '1110', '1111', '1112', '1113', '1114', '1115', '1116', '1117', '1118', '1119', '1120', '1121', '1122', '1123', '1124', '1125', '1126', '1127', '1128', '1129', '1130', '1131', '1132', '1133', '1134', '1135', '1136', '1137', '1138', '1139', '1140', '1141', '1142', '1143', '1144', '1145', '1146', '1147', '1148', '1149', '1150', '1151', '1152', '1153', '1154', '1155', '1156', '1157', '1158', '1159', '1160', '1161', '1162', '1163', '1164', '1165', '1166', '1167', '1168', '1169', '1170', '1171', '1172', '1173', '1174', '1175', '1176', '1177', '1178', '1179', '1180', '1181', '1182', '1183', '1184', '1185', '1186', '1187', '1188', '1189', '1190', '1191', '1192', '1193', '1194', '1195', '1196', '1197', '1198', '1199', '1200', '1201', '1202', '1203', '1204', '1205', '1206', '1207', '1208', '1209', '1210', '1211', '1212', '1213', '1214', '1215', '1216', '1217', '1218', '1219', '1220', '1221', '1222', '1223', '1224', '1225', '1226', '1227', '1228', '1229', '1230', '1231', '1232', '1233', '1234', '1235', '1236', '1237', '1238', '1239', '1240', '1241', '1242', '1243', '1244', '1245', '1246', '1247', '1248', '1249', '1250', '1251', '1252', '1253', '1254', '1255', '1256', '1257', '1258', '1259', '1260', '1261', '1262', '1263', '1264', '1265', '1266', '1267', '1268', '1269', '1270', '1271', '1272', '1273', '1274', '1275', '1276', '1277', '1278', '1279', '1280', '1281', '1282', '1283', '1284', '1285', '1286', '1287', '1288', '1289', '1290', '1291', '1292', '1293', '1294', '1295', '1296', '1297', '1298', '1299', '1300', '1301', '1302', '1303', '1304', '1305', '1306', '1307', '1308', '1309', '1310', '1311', '1312', '1313', '1314', '1315', '1316', '1317', '1318', '1319', '1320', '1321', '1322', '1323', '1324', '1325', '1326', '1327', '1328', '1329', '1330', '1331', '1332', '1333', '1334', '1335', '1336', '1337', '1338', '1339', '1340', '1341', '1342', '1343', '1344', '1345', '1346', '1347', '1348', '1349', '1350', '1351', '1352', '1353', '1354', '1355', '1356', '1357', '1358', '1359', '1360', '1361', '1362', '1363', '1364', '1365', '1366', '1367', '1368', '1369', '1370', '1371', '1372', '1373', '1374', '1375', '1376', '1377', '1378', '1379', '1380', '1381', '1382', '1383', '1384', '1385', '1386', '1387', '1388', '1389', '1390', '1391', '1392', '1393', '1394', '1395', '1396', '1397', '1398', '1399', '1400', '1401', '1402', '1403', '1404', '1405', '1406', '1407', '1408', '1409', '1410', '1411', '1412', '1413', '1414', '1415', '1416', '1417', '1418', '1419', '1420', '1421', '1422', '1423', '1424', '1425', '1426', '1427', '1428', '1429', '1430', '1431', '1432', '1433', '1434', '1435', '1436', '1437', '1438', '1439', '1440', '1441', '1442', '1443', '1444', '1445', '1446', '1447', '1448', '1449', '1450', '1451', '1452', '1453', '1454', '1455', '1456', '1457', '1458', '1459', '1460', '1461', '1462', '1463', '1464', '1465', '1466', '1467', '1468', '1469', '1470', '1471', '1472', '1473', '1474', '1475', '1476', '1477', '1478', '1479', '1480', '1481', '1482', '1483', '1484', '1485', '1486', '1487', '1488', '1489', '1490', '1491', '1492', '1493', '1494', '1495', '1496', '1497', '1498', '1499', '1500'. A legend at the bottom indicates 'Cluster' with red for 1, green for 2, and blue for 3.

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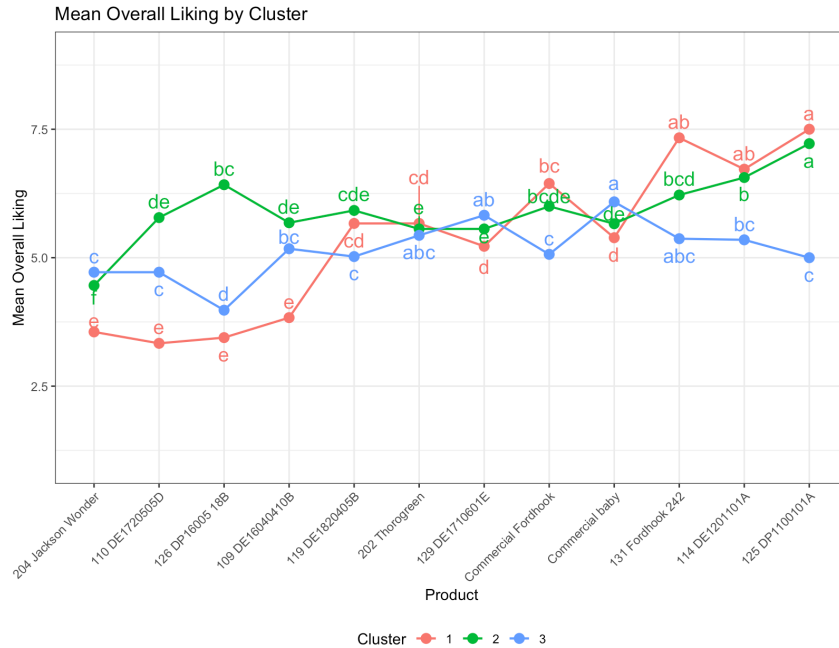


Fig. 1.15 Cluster-wise mean overall liking across products

1.3.2.5. External Preference Mapping

The external preference mapping shows the sensory drivers of liking and disliking per consumer cluster. The PCA across all attributes explained 38% and 23% of total variance in the first two dimensions of sensory space, respectively (Fig. 1.16). On the loading plot including all significant sensory attributes, PC1 (38%) was mainly driven by textural variation, with positive associations with firmness, seed coat thickness, and difficulty swallowing, and negative associations with moistness, flowability, and initial flow. PC1 was also associated with flavor and taste attributes, with bitterness in the positive direction and buttery, sweet green, and corn in the negative direction. PC2 (23%) was positively driven by flavors such as grassy, edamame, and sweetness, and negatively associated with earthy, bitter, potato starchy, kidney bean, and savory brothy.

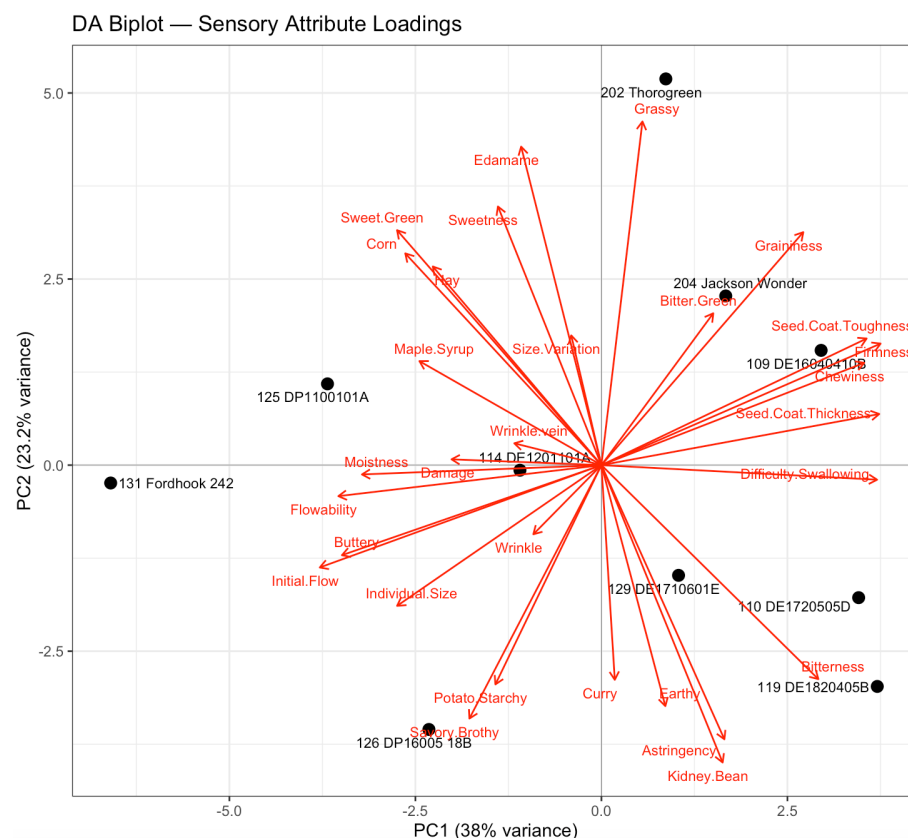


Fig. 1.16 PCA biplot: sensory attribute loadings and product scores in consumer test

Cluster 1 ($n = 18$) showed the best model fit among the three clusters (mean $R^2 = 0.71$) (Fig. 1.17). The strong color contrast between red and blue regions indicates high consensus within this segment regarding both preference and rejection directions. The 75% preference region was located in the upper left corner of the map, capturing samples 125 DP1100101A, 131 Fordhook 242, and 202 Thorogreen. This region corresponded to sensory attributes such as sweet green, corn, buttery, sweetness, and edamame flavor notes (Fig. 1.16), and was further associated with higher moistness, flowability, softness, and ease of swallowing. Two rejection regions ($\leq 25\%$ preference) were observed in distinct areas of the map. The lower left region, where sample 126 DP16005 18B is located, represented cultivars that may still be relatively moist but are characterized by strong potato starchy, savory brothy, kidney bean, and astringent flavor

notes. The rejection region on the right side of the map was associated with cultivars that are difficult to eat, driven by high firmness, dryness, chewiness, and graininess. Overall, Cluster 1 consumers preferred moist and soft cultivars with a specific flavor profile centered on sweet, buttery, corn, sweet green, and edamame notes. Their disliking was driven by multiple factors including dark and astringent flavor profiles on one end and dry, firm textural characteristics on the other.

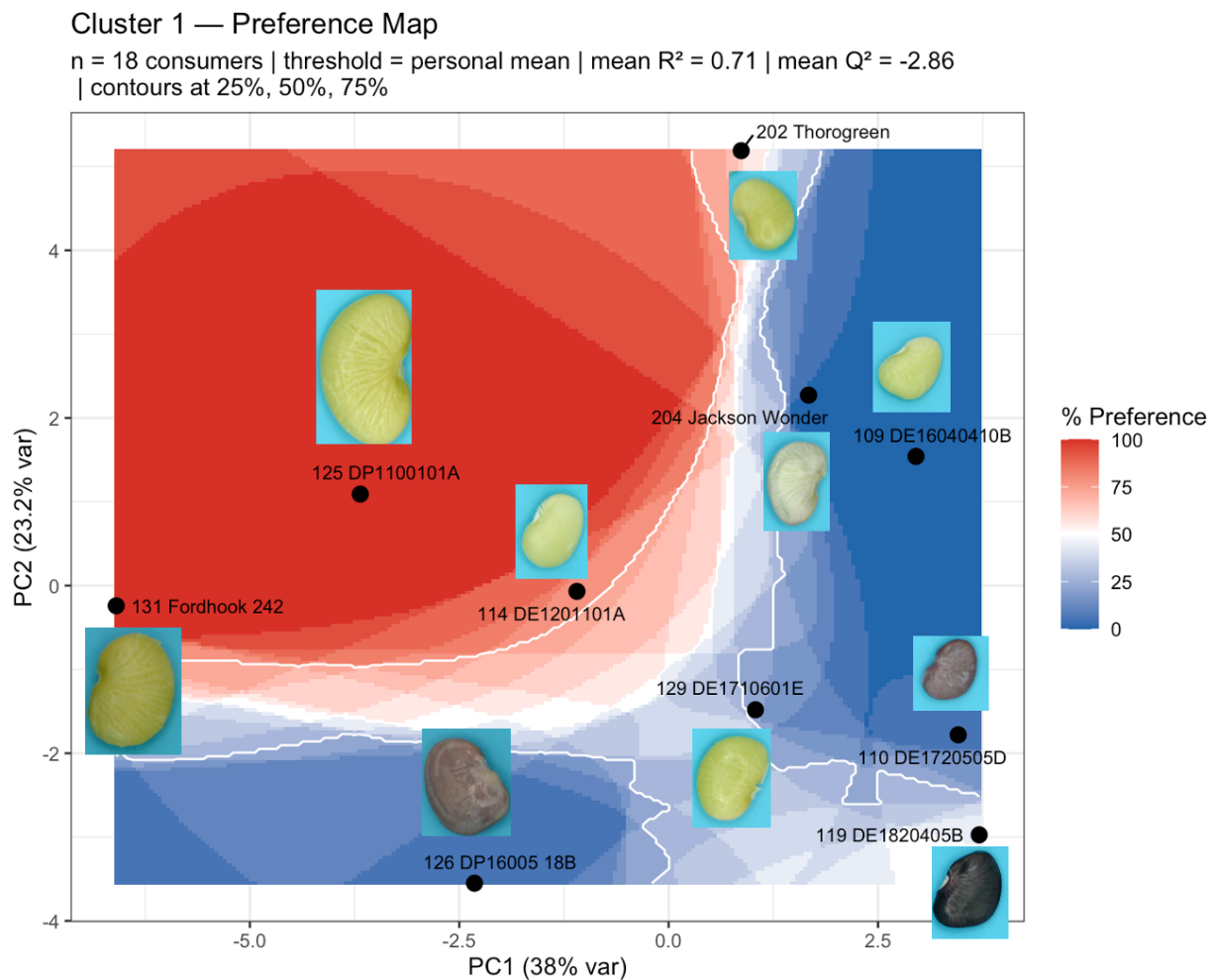


Fig. 1.17 External preference map for Cluster 1 (n = 18)

Cluster 2 ($n = 50$) showed moderate model fit (mean $R^2 = 0.55$) (Fig. 1.18). This cluster shared some preference patterns with Cluster 1, including an acceptance region in the upper left corner and a rejection region on the right side of the map. However, two notable differences were observed. First, the lower color contrast across the map indicates less consensus among consumers in Cluster 2 compared to Cluster 1, consistent with greater within-cluster heterogeneity in preference direction. Second, the acceptance region in Cluster 2 extended more broadly from the upper left to the lower right corner of the map, rather than being concentrated in the upper left as in Cluster 1. While no additional samples fell within the 75% preference contour, a wider range of samples fell within the higher preference region, including 129 DE1710601E, 126 DP16005 18B, and 119 DE1820405B — cultivars characterized by astringency, kidney bean, and earthy flavor notes. These findings suggest that the preference of Cluster 2 is still primarily driven by moistness, softness, buttery, and sweetness, similar to Cluster 1. However, Cluster 2 consumers show greater tolerance toward darker flavor profiles, including kidney bean, earthiness, and astringency. The disliking direction remained consistent with Cluster 1, where firm, dry, chewy, and grainy cultivars were associated with lower preference.

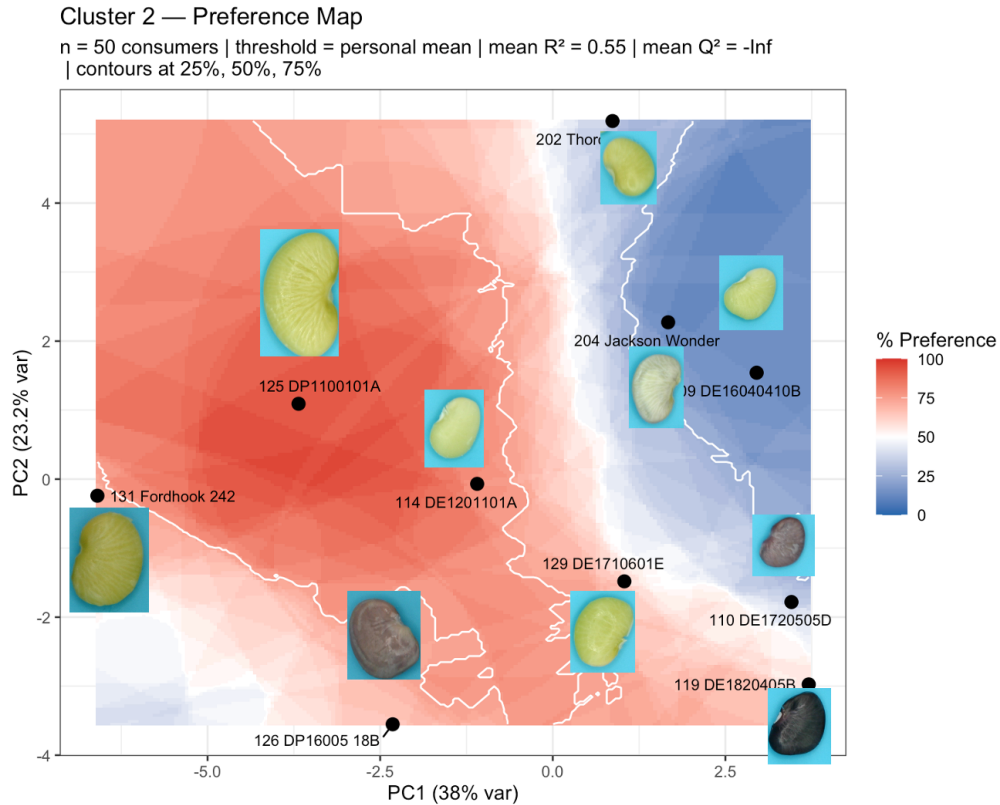


Fig. 1.18 External preference map for Cluster 2 (n = 50)

Cluster 3 (n = 46) showed moderate model fit (mean $R^2 = 0.62$) (Fig. 1.19). The color contrast across the map was the most faint among the three clusters, indicating the highest within-cluster heterogeneity in preference direction. The overall preference structure of Cluster 3 most closely resembled that of Cluster 1, with an acceptance region in the upper left corner and two rejection zones in the lower left and right sides of the map. However, the acceptance region appeared to extend more broadly toward the right and lower right portions of the map compared to Cluster 1, with samples 204 Jackson Wonder and 129 DE1710601E falling within the higher preference area. No distinctive contour lines were visible, reflecting the low consensus within this cluster. Overall, Cluster 3 consumers appeared to share a similar liking direction with

Cluster 1 toward moist, sweet, corn, and buttery flavor profiles, but with considerably less agreement among consumers within the segment.

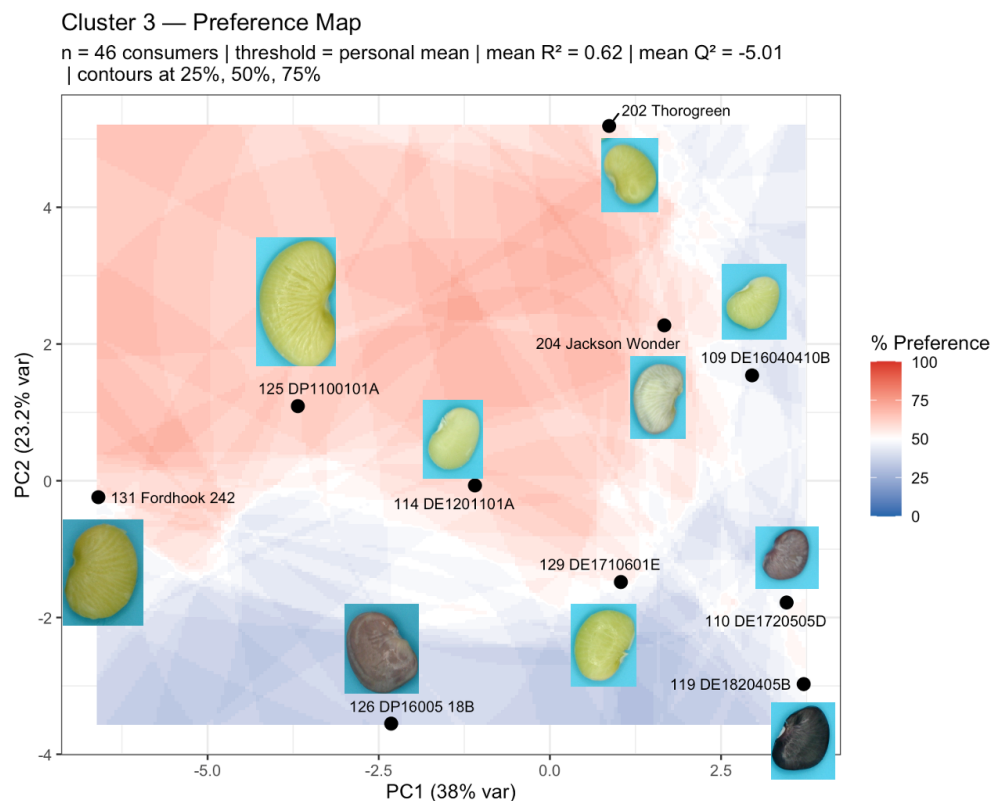


Fig. 1.19 External preference map for Cluster 3 (n = 46)

The consumer demographic summary by cluster showed the demographic distributions per consumer cluster including gender, age, ethnicity, income, education, and diet (Table 1.6). Cluster 1 may be characterized with higher proportion of female (83.3%) and higher proportion of consumers ages above 35 years old (33.3%) compared to cluster 2 and cluster 3. However, the small cluster size of 18 relative to other two clusters may require interpretation with caution. About half of the cluster 1 was comprised by White consumers whereas cluster 2 and 3 were about half Asian. Lastly, the income distribution showed that cluster 3 tended to have higher proportion of consumers with income between \$150,000-\$250,000 than the other two clusters.

Table 1.6 Consumer Demographic Summary by Cluster (succulent)

Variable	Category	Cluster_1 (18)	Cluster_2 (50)	Cluster_3 (46)
Gender	Male	3 (16.7%)	20 (40%)	19 (41.3%)
	Female	15 (83.3%)	30 (60%)	26 (56.5%)
	Nonbinary			1 (2.2%)
Age	18-24	7 (38.9%)	12 (24%)	20 (43.5%)
	25-34	5 (27.8%)	28 (56%)	20 (43.5%)
	35-44	4 (22.2%)	4 (8%)	5 (10.9%)
	45-54	2 (11.1%)	5 (10%)	1 (2.2%)
	55-60		1 (2%)	
Ethnicity	White/Caucasian	10 (55.6%)	14 (28%)	14 (30.4%)
	Hispanic/Latino	2 (11.1%)	6 (12%)	7 (15.2%)
	Asian	6 (33.3%)	22 (44%)	20 (43.5%)
	Black/African American		1 (2%)	2 (4.3%)
	Native American/American Indian		1 (2%)	
	Other		5 (10%)	2 (4.3%)
	Pacific Islander		1 (2%)	
	Prefer not to answer			1 (2.2%)
Income	<\$35,000	4 (22.2%)	11 (22%)	12 (26.1%)
	\$35,000-\$50,000	2 (11.1%)	11 (22%)	9 (19.6%)
	\$50,000-\$80,000	5 (27.8%)	12 (24%)	6 (13%)
	\$80,000-\$150,000	4 (22.2%)	10 (20%)	7 (15.2%)
	\$150,000-\$250,000	3 (16.7%)	5 (10%)	11 (23.9%)
	>\$250,000		1 (2%)	1 (2.2%)

Variable	Category	Cluster_1 (18)	Cluster_2 (50)	Cluster_3 (46)
Education	High school diploma	1 (5.6%)	1 (2%)	5 (10.9%)
	Bachelor's degree	9 (50%)	19 (38%)	20 (43.5%)
	Graduate/Professional degree	8 (44.4%)	30 (60%)	21 (45.7%)
Diet	Omnivore	17 (94.4%)	45 (90%)	42 (91.3%)
	Vegetarian	1 (5.6%)	2 (4%)	1 (2.2%)
	Pescatarian		1 (2%)	2 (4.3%)
	I don't know		2 (4%)	1 (2.2%)

1.4. Chapter Conclusion

This chapter investigated sensory characteristics across 35 succulent lima bean cultivars and identified consumer segmentations and their sensory drivers of liking and disliking. Sensory profiles of succulent lima beans may significantly differ across accessions. Seed size and seed coat colors may be associated with certain sensory attributes, such as large and medium seeds being more sweet, soft, and moist with thin seed coat. Effects of seed coat colors on sensory experience may be mainly attributed to the phenolic pigments. Consumer test identified that green-colored samples scored the highest overall liking regardless of seed size. Lastly, preference mappings identified three major consumer clusters. All three clusters had the consensual direction of liking toward products with sweetness, moistness, softness, corn, edamame, and buttery flavors. Distinctively, Cluster 2 showed more lenience toward dark flavors and astringency whereas Cluster 1 and 3 were generally rejecting those samples. The combinations of preferred attributes may be generally achieved by medium or large-seeded products with green to yellow seed coats. Sensory qualities for individual cultivars may be useful markers for germplasm identifications and promoting farmer- and consumer-focused lima bean

breeding to accelerate national consumption. Future scope of the study may include in-depth proximate analysis and chemical analysis to connect sensory attributes and responsible compounds.

1.5. Reference

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Chapter 2: Sensory Characterization and Consumer Liking of Dry Lima Beans

2.1. Introduction

The second chapter transitions from the succulent lima beans to exploration of the sensory profiles and consumer liking of dry lima beans. Following the same flow of analysis, the sensory profiles were first characterized across 43 dry lima bean entries. Second, representative samples from the sensory map will be presented in a consumer test at a centralized location, aiming to identify sensory drivers of liking and disliking for each consumer segment.

Collectively, this chapter may provide sensory-focused phenotypic information on dry lima bean entries, clarifying target sensory qualities and offering tailored guidelines for breeding.

2.2. Material and Methods

2.2.1. Dry Lima Bean Samples

Forty-three entries of lima beans were harvested at the dry stage for evaluation. Among those, thirty-nine entries were grown in Davis, California, USA, and four entries were obtained from commercial market. Upon harvest, the seeds were emptied from destemmed pods. Large debris such as remaining stems, dirt, stones, and defective samples were removed. Cleaned samples were kept in a dark, ambient condition during storage and transportation. The seeds were available in varieties of combinations of size, bean shapes, and seed colors in its appearance (Table 2.1).

Table 2.1 Categories of Appearance of Dry Lima Beans

Appearance Categories	Specification
Size (2)	Small/baby, large
Seed shape (2)	Flat, Round
Seed coat color (9)	White, White/green, Purple, White/purple, Yellow with speckles, Cream/tan with speckles, Cream with red hilum, Red/red with speckles, White with gold speckles

2.2.2. Sample Preparation for Training and Evaluation

Samples were cleaned by gently washing them in clean tap water and agitating by hand to remove any debris. The cleaned seeds were soaked in distilled water for 10 hours prior to cooking, gently covered with aluminum foil, and left at ambient temperature. After soaking, the soaking water was drained, and a half-quart of fresh distilled water was placed in the two-quart pot on a gas stove. Each sample was cooked for various amounts of time, ranging from 13 to 28 minutes, to achieve consistent doneness. The optimum cooking time for consistent doneness for each individual sample was determined using the Mattson cooker method after 12 hours of soaking in distilled water ([Wood, 2017](#)). The cooking water was drained, and the cooked samples were transferred into a metal pan and kept in a food warmer, maintaining a sample temperature of 68–70 °C until ready for the panel or consumer sessions. The cooked samples were served no later than one hour after cooking. Drained samples were served at a consistent portion size of 28.0 g each.

2.2.3. Qualitative Descriptive Analysis (QDA)

Participants (n = 11) from the University of California, Davis, were recruited as dedicated panelists for QDA. Recruitment screened participants based on the following criteria: age of 18–60, regular legume consumption (at least once a month), absence of any food allergies or sensitivities, and availability. Panelists were introduced to the scope of the project and an overview of descriptive analysis and signed the consent form (IRB 2269161-1).

Panelists committed to eight one-hour training sessions. The majority of the succulent samples were provided under a three-digit blind code as training samples and for establishing the texture scale. The first four training sessions consisted of introducing panelists to the tasting

experience, discussing sensory attributes of each sample, developing a list of objective sensory lexicons, and using unstructured line scales for mock evaluation as a group. The last four training sessions focused on familiarization with the online survey platform, evaluating samples individually, and revisiting descriptors and their definitions as a group.

After finalizing a set of objective sensory lexicons and their definitions, formal evaluations were conducted to characterize a complete sensory profile for each sample. Panelists were seated in individual booths partitioned by dividers. A total of 14 evaluation sessions were conducted, during which six samples were evaluated per session, except for the last session where two samples were evaluated. Each sample was evaluated in duplicate due to time limitations and sample availability. Panelists used unstructured line scales to indicate the numerical intensities of given attributes on the online survey system (Red Jade).

2.2.4. Consumer Test

A total of 12 dry lima samples were selected based on clustering from descriptive analysis, potential in agronomic performance, and commercial relevance, in order to identify sensory drivers of consumer liking and disliking of lima beans. Hierarchical cluster analysis (HCA) was conducted on the mean table of significant sensory attributes from descriptive analysis to identify sample clusters. Data were standardized and scaled (mean = 0, SD = 1) across all samples prior to clustering. Silhouette score analysis identified two as the statistically optimal number of clusters. However, a six-cluster solution was selected to maximize phenotypic and sensory diversity represented in the descriptive analysis. Samples at the centroids of six clusters were chosen as cluster representatives and included in the consumer test. An additional six samples were selected based on their potential in breeding and agronomic performance.

Participants ($n = 108$) reported to the central testing location (Sensory Theater, UC Davis, CA) to taste 12 lima bean samples over two days, with six samples served per day. Samples were prepared using the same methodology as described in Section 2.2. Approximately 15 g of cooked sample was portioned into a 4-oz paper cup with a plastic lid, and each cup was kept insulated in a Styrofoam box until ready to be served. Each sample cup was labeled with a three-digit blind code. The order of sample presentation per day was randomized, and individual serving order was determined using a Latin square design.

Participants were asked to taste each sample in their individually assigned serving order and to answer a series of questions about each sample. The questionnaire addressed overall liking, attribute-specific liking, adequacy of attribute intensity (JAR), check-all-that-apply (CATA), and open comments on likes and dislikes of the product. While external preference mapping (EPM, explained in the following section) identifies the sensory drivers of liking and disliking across consumer segments, JAR provides directional guidance for attribute optimization by quantifying how specific attribute intensities deviate from consumers' ideal levels for each product. CATA allows consumers to describe product sensory profiles using attributes developed by the trained panel, thus capturing the perception by untrained consumers and offering a consumer-relevant sensory profile of each product. Liking questions were presented in the following order: appearance liking, size liking, color liking, overall liking, flavor liking, and texture liking. Between samples, participants were asked to cleanse their palate with water and crackers during 60-second intervals. Upon completion of all samples, participants also completed an exit survey addressing participant demographics (age, gender, ethnicity, diet, income, and highest level of education completed or in progress) as well as behaviors and perceptions related to legume consumption.

2.2.6. Data Analysis

2.2.6.1. Descriptive Analysis

The global product differences across 43 dry lima bean cultivars were assessed using multiple Analysis of Variance (MANOVA) with Wilks' lambda distribution at $p < 0.05$. Three-way Analysis of Variance (ANOVA) with two-way interactions was conducted to identify sensory attributes that differed significantly across lima bean samples at $p < 0.05$. A fixed-effects model was first applied to confirm product significance. Attributes with significant interaction terms in the fixed-effects model were rerun in a pseudo-mixed model; those with product significance in both the fixed-effects and pseudo-mixed models were deemed significantly different across products. Fisher's least significant difference (LSD) test was then conducted to identify specific statistical differences among samples.

Principal component analysis (PCA) using correlation matrix was used to interpret product variation and its association with sensory attributes. Separate PCAs were run for (1) flavor and taste, (2) texture and mouthfeel, and (3) appearance to prevent the principal components from being dominated by differences between attribute categories rather than differences among cultivars.

Within-modality PCA was selected as the primary mode of analysis for descriptive data to improve resolution within each sensory domain. Multiple Factor Analysis (MFA) treating the three sensory modalities as separate blocks is provided in Supplementary Material 2 for confirmation of the overall sensory structure. The MFA explained 38.1% and 19.0% of total variance in Dimensions 1 and 2, respectively. Dimension 1 was driven by both flavor/taste and texture and mouthfeel attributes. Dimension 2 was structured primarily by appearance and texture and mouthfeel attributes. RV coefficients among sensory modalities were low to moderate, with flavor/taste and appearance having the moderate correlations ($RV = 0.58$), while

the remaining modality pairs showed low RV values (~ 0.34 – 0.36), indicating largely non-redundant variation across blocks and supporting within-modality interpretation for finer resolution. Nevertheless, high RV coefficients between each modality and the overall MFA solution (RV above 0.71) confirm that all three modalities are essential and balanced contributors to the overall sensory variation observed across cultivars.

Full mean intensities and LSD groupings are provided in Supplementary Table 2.1. Boxplots showing attribute intensities by size and seed coat color categories were also constructed to supplement the LSD results. All statistical analyses were conducted in R.

2.2.6.2. Consumer Tests (overall liking, JAR, CATA, internal and external preference mapping with consumer clusters, demography)

ANOVA was performed on overall liking and attribute-specific liking scores to determine whether products differed significantly at $p < 0.05$. When a significant sample effect was detected, Fisher's Least Significant Difference (LSD) test was applied to identify pairwise differences among products. A Pearson correlation matrix was also constructed to examine associations among hedonic variables. A hedonic PCA biplot was constructed using a correlation matrix of mean consumer liking scores for overall liking and attribute-specific likings. Liking attributes were represented as vectors and products as scores, providing a visual summary of the hedonic dimensions along which products were most differentiated. This biplot complements internal preference mapping by summarizing overall hedonic structure across liking attributes prior to consumer segmentation analysis.

JAR responses were recoded into three adequacy categories: "too low" (ratings 1–2), "just-about-right" (rating 3), and "too high" (ratings 4–5). For each sensory attribute (moistness, firmness, seed-coat thickness, flavor, and sweetness), a Chi-square test or Monte Carlo Fisher's

exact test was used to assess whether the distribution of adequacy categories differed significantly across products, given the large number of samples and very small counts for some attribute-by-JAR combinations.

Penalties were calculated as the difference between mean overall liking of consumers who rated the attribute as 'just about right' and mean overall liking of consumers who rated the attribute as 'too low' or 'too high'. Penalties were calculated as the difference between the mean liking of consumers in each non-JAR category and the overall mean liking of all consumers. Student's t-tests were used to evaluate whether these liking decreases were statistically significant.

Check-All-That-Apply (CATA) attribute endorsement counts were subjected to Cochran's Q test to assess significant differences in the proportion of consumers selecting each attribute across samples, with separate analyses run for each attribute. Any attributes with maximum selection frequency of less than 10% were dropped out of the CATA analysis. Separate analyses were run for each attribute. McNemar post-hoc analysis with Bonferroni correction was then applied to identify pairwise differences in the number of consumers endorsing a specific attribute across samples. CATA frequencies for each attribute and samples were plotted using correspondence analysis. Lastly, penalty-lift analysis was conducted to compare mean liking scores between consumers who endorsed a given attribute and those who did not, using Student's t-test.

Internal preference mapping was performed by conducting PCA on a consumer $\times$ product matrix of overall liking scores using a covariance matrix. PCA automatically centered the data prior to constructing the internal preference mapping. Products and consumers were visualized as scores and vectors respectively in the resulting biplot. To identify the optimal number of

consumer segments, hierarchical clustering was applied on the centered data using Euclidean distance and Ward's linkage method. Cluster solutions were evaluated using both the Silhouette criterion and visual inspection of the dendrogram. Subsequently, mean overall liking scores for each consumer cluster were calculated from the raw data, followed by an LSD post-hoc test to assess differences among clusters.

External preference mapping (EPM) was conducted to identify sensory drivers of consumer liking and disliking within each segment. While JAR and CATA provide directional guidance for optimizing specific attribute intensities and capturing consumer sensory perception, EPM regresses consumer liking scores onto the sensory profiles from descriptive analysis. This linkage between sensory and hedonic spaces identifies which quantifiable sensory characteristics drive consumer acceptance across segments, providing actionable targets for breeding applications. Principal component regression (PCR) was selected as the modeling approach to address multicollinearity among sensory attributes, reduce dimensionality, and facilitate visualization of cluster-wise preference patterns in a shared sensory space. The first two principal components (PCs), derived from PCA of the descriptive analysis data, were retained as they captured the majority of variance in the sensory space. For each individual consumer, overall liking scores were regressed onto the two PC scores using a quadratic model. Each consumer's predicted liking surface was then discretized at their personal mean liking score as the preference threshold — grid points with predicted liking above the threshold were coded as 1 (preference), and below as 0 (rejection). The discretized surfaces were stacked within each consumer segment identified from the internal preference mapping, and summed to obtain the aggregated response surface. The resulting map shows the percentage of consumers in each segment whose predicted

liking exceeded their personal mean at each point in the sensory space. The 25%, 50%, and 75% contour lines was used to separate the majority preference zone from the rejection zone.

Table 2.2 Descriptors, definitions, and references of sensory attributes that are significant across 43 dry lima bean entries ($p < 0.05$)

Descriptors	Definitions	Reference
<u>Flavor</u>		
Sweet green	Sweet and fresh green vegetable	1 T peas + 1 T hot water in 2 oz cup, MW 20 sec
Bitter green	Bitter, savory, green vegetable	2 g asparagus + 4 g broccoli + 2 g green bean + 1 T water in mug, MW 20 sec
Chickpea	Chickpea	1 T chickpea + 1 T hot water in 2 oz cup, MW 20 sec, gently crush
Kidney bean	Kidney bean	1 T kidney beans 1 T water in 2 oz cup, MW 20 sec, gently crush
Potato/starchy	Potato, cooked starchy	1:1 rehydrated mashed potato and starch solution (1:1 rice flour and water)
Buttery	Butter, creamy, dairy	7-8 g butter cube
Corn	Sweet, creamy, corn	1 T creamed corn, bring to room temperature
Earthy	Soil	1:1 soil and hot water
<u>Taste</u>		
Sweet	Sweetness	Low: 1 g sucrose/500 mL water High: 6 g sucrose/500 mL water
Bitter	Bitterness	Low: 0.05 g caffeine/500 mL water High: 0.2 g caffeine/500 mL water
Saltiness	Saltiness	Low: 0.05 g salt/500 mL water High: 0.7 g salt/500 mL water
Umami	Umami	Low: 0.1 g MSG/500 mL water High: 0.35 g MSG/500 mL water
<u>Texture/Mouthfeel</u>		
Wrinkle	The roughness of the seed coat surface on tongue in terms of wrinkliness	Min. and max. selected during training
Firmness	Force required to break the bean all the way down in a single bite	Min. and max. selected during training
Moistness	The moistness of single bean	Min. and max. selected during training

Initial Flow	The amount of cotyledon/contents that flows out of the bean at initial bite	Min. and max. selected during training
Seedcoat thickness	Force required to break/bite-off the seed coat at the beginning/end of a bite	Min. and max. selected during training
Texture variation	The inconsistency in texture from a bean to another	Min. and max. selected during training
Graininess	The mouthfeel of sandy/mealy particulates on tongue or in between teeth	Min. and max. selected during training
Chewiness	The number of mastication required to be able to swallow the slurry	Min. and max. selected during training
Difficulty swallowing	The relative difficulty to swallow the slurry	Min. and max. selected during training
Astringency	Overall dryness inside mouth after swallowing	Low: 0.1 g alum/500 mL water High: 0.4 g alum/500 mL water
<u>Appearance</u>		
Wrinkle/vein	The amount of wrinkles/vein occupying the surface of beans	Min. and max. selected during training
Damage	The amount of broken beans including fracture and seed coat peeling	Min. and max. selected during training
Individual size	The overall impression on the size of a single bean	Min. and max. selected during training
Size variation in a cup	The relative % difference in longitudinal and latitudinal length of individual beans	Min. and max. selected during training
Speckles	The relative amount of spots on bean surface	Min. and max. selected during training

*Panelists were exposed to majority of product set during training, generating texture scale in consensus and operational definitions were established prior to evaluation

2.3. Results and Discussion

2.3.1. Descriptive Analysis

2.3.1.1. Sensory Attributes

MANOVA confirmed the product differences at significance level of 0.05 (Wilks' $\lambda = 1.08 \times 10^{-5}$, $p < 2.2 \times 10^{-16}$). The 43 dry lima beans differed significantly across 26 out of 34 sensory attributes developed through descriptive panels ($p < 0.05$) (Table 2.2). The majority of significant sensory attributes fell in the texture/mouthfeel category, followed by flavor, appearance, and taste.

Dry lima beans differed significantly across green vegetable-like flavors such as “sweet green” and “bitter green,” which were represented by boiled peas and a mixture of cooked dark vegetables, respectively. Legume descriptive works on pulse puree reported similar terminology “green,” referring to pea-like flavors and represented by crushed green pea pods ([Chigwedere et. al, 2025](#); [Malcomson et. al, 2014](#)). Volatiles such as 2-butan-2-yl-3-methoxypyrazine, 2-methoxy-3-(2-methylpropyl)pyrazine, and 2-isopropyl-3-methoxypyrazine were associated with pea-like flavors ([Ritter et. al, 2022](#)). Bitter-green flavors were associated with alcohols such as 1-Penten-3-ol and 3-Hexen-1-ol, which have the odor descriptions of fresh, moss, intensely, vegetable, and green ([Sharan et. al, 2022](#)). These green characteristics are often considered off-flavors in legumes, primarily derived from lipid oxidation products of unsaturated fatty acids, which can be reduced by pre-processing of legume ingredients ([Zhang et. al, 2020](#); [Sharan et. al, 2022](#)).

Dry lima beans also differed significantly in the intensities of flavors commonly regarded as legume off-flavors, such as cooked bean/beany (i.e., “chickpea,” “kidney bean”) and “earthy.” “Chickpea” and “kidney bean” flavors were present at varying intensities across boiled pulses

such as navy beans, cranberry beans, and great northern beans ([Ponskhe et. al, 2025](#)). A sensory correlation study combining descriptive analysis and an electronic tongue found a strong positive correlation between cooked bean flavors/aromas and chemical constituents such as hexanal, linoleic acid, and linolenic acid ([Silva et. al, 2012](#)). Beany, earthy, and vegetable flavors were correlated amongst each other across common bean genotypes ([Bassett et. al, 2021](#)). These significant attributes may be considered as sub descriptors within “beany” flavor, often resulting in inconsistency in lexicon reporting across legume sensory studies ([Chigwedere et. al, 2025](#)). Like in green flavors, beany flavors are considered as off-flavors in legumes, thus limiting the intensities of these flavors may be a point of solution for cultivar selection ([Roland et. al, 2017](#)).

“Buttery” and “corn” were both related to sweet aromatics in dry lima beans. The former was characterized as dairy-sweet, with a cube of butter as its reference, and the latter was grain-sweet, with canned cream corn as its reference. These lexicons were found to be sub-categories of nutty flavors (i.e. "nutty -buttery" and "nutty-grain") by trained descriptive panels evaluating a range of food products ([Miller et. al, 2013](#)). While other descriptive studies on legumes often report nutty flavor as a significant attribute as a broader term, this may encompass subtler notes such as buttery and corn-like flavors since different terms may describe the same underlying flavor depending on the panelist training and consensus used ([Mkanda et. al, 2007](#)). Buttery, fatty, and greasy flavors were associated with 2,3-butanedione in fermented pea protein isolates ([Garcia-Arteaga et. al, 2021](#)). In whole legume, edamame cultivars with characteristic buttery flavor were preferred by U.S. consumers ([Johnson et. al, 2000](#)). Nutty-related flavors may also be imparted by pyrazines and alkylpyrazines due to Maillard reaction ([Mishra et. al, 2017](#); [Karolkowski et. al, 2021](#)). Reduction of available lysine content after hydrothermal

treatment may suggest the occurrence of Maillard reaction in legume ([Walker et. al, 1982](#); [Moussou et. al, 2016](#)).

Dry lima beans differed significantly across many taste attributes including “sweetness,” “bitterness,” “saltiness,” and “umami.” Another study found that bitterness was the only significant taste attribute among six varieties of dry common beans, whereas saltiness and sweetness differed significantly by location and location $\times$ variety interaction, respectively ([Mkanda et. al, 2007](#)). Non-volatile compounds including saponins and phenolic compounds (phenolic acids, flavonoids, condensed tannins) are known contributors to bitterness and astringency in pulses ([Karolkowski et. al, 2023](#)). Sweetness and umami were highly correlated with sucrose/fructose and glutamic acid/alanine content, respectively ([Masuda et. al, 1988](#); [Silva et. al, 2012](#)). Glutamic acid was one of the most abundant amino acids across 11 lima bean cultivars, existing in concentration of 16.0 – 21.4 g/16 g N ([Ologhobo et. al, 1983](#)).

Most of the texture/mouthfeel attributes referred to the overall eating experience such as “firmness,” “moistness,” and “texture variation” of individual beans. Some of the attributes such as “seed coat thickness,” “graininess,” “chewiness,” “difficulty swallowing,” and “astringency” may be related to seed coat properties. Variation in seed morphology and hydration may result in textural variation. Soaking dry legume seeds is an important preparation step prior to cooking, because it ensures hydration of cotyledon by water imbibition through micropores on seed coat ([Perera et. al, 2023](#)). Electron micrographs of legume hydration showed that hydration resulted in swelling of protein bodies and starch granules, and the matrix became loose ([Liu et. al, 1995](#)). Moreover, protein and starch content may affect subsequent sensory texture, as protein content and amylose/amylopectin ratio were related to higher perceived creaminess ([Casanas et. al,](#)

[2006](#)). These cross-species findings suggest that exploring proximate composition for individual cultivars may help relate sensory attributes to chemical composition.

Variation in appearance may come from the wrinkle/vein, individual size, and presence of damages. Seed size of individual beans in a single cup may also vary in dry lima beans. Seed size variation within a cultivar could affect proximate composition, as there was a significant difference in oil content in lupins of different size across three genotypes ([Crochemore et. al, 1993](#)). Speckles or seed coat markings are genotypically versatile traits observed across legume species ([Herniter et. al, 2019](#); [Wood et. al, 2020](#)). Appearance provides consumers with initial qualitative information about legume quality and may therefore affect consumer preference.

2.3.1.2. Principal Component Analysis

Fig. 2.1 shows the PCA biplot for flavor and taste attributes with individual scores being colored by size category. The first two PCs explained 68.9% of the total variance. PC1 (58.2%) had strong, positive correlation with “buttery,” “corn,” “starchy,” “chickpea,” “sweet green,” and “sweetness.” Meanwhile, PC1 had strong negative correlation with “kidney bean,” “earthy,” “bitter green,” and “bitterness.” PC1 thus creates a spectrum ranging from a sweet, mashed potato-like and buttery end with some chickpea flavor to the other end characterized by bitterness and unpleasant dark flavors. PC2 (10.7%) is mainly driven by “umami” and “saltiness” in the positive direction.

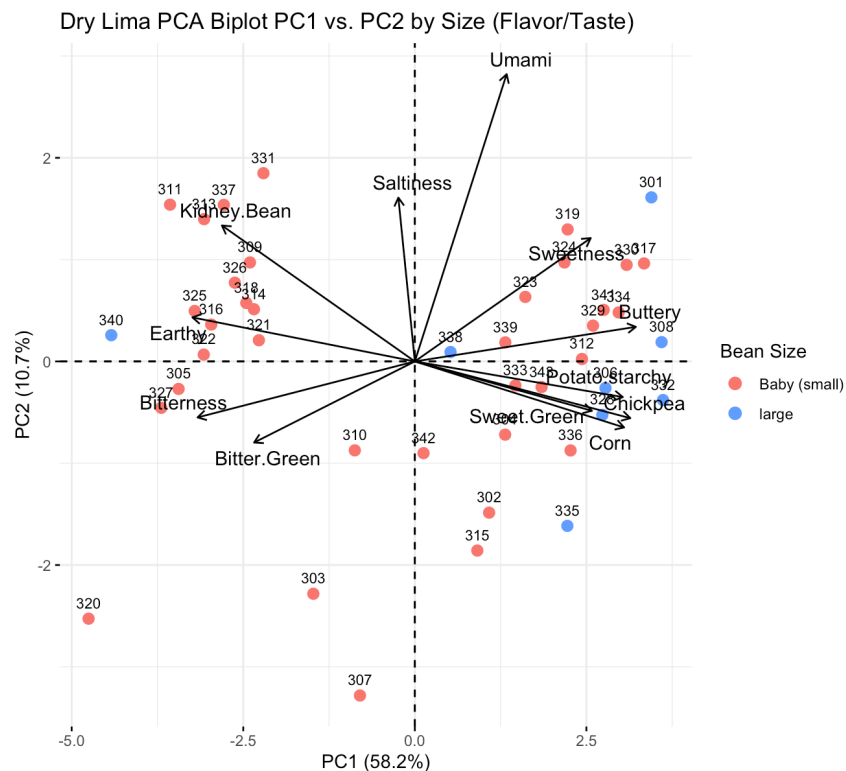


Fig. 2.1 PCA Flavor and Taste Attributes: PC1 (58.2%) vs. PC2 (10.7%), scores colored by bean size

Large-seeded cultivars are located on the far right side of the plot, whereas small-seeded cultivars are located closer to the center. It is noted that all the large-seeded cultivars in the study were white-seeded except for sample 340 (purple and white) on left and 308 (green) on right. Regardless of the seed-coat colors, large-seeded cultivars may have stronger flavor and taste intensities than the small-seeded cultivars. The boxplot also shows the same trend where large-seeded cultivars may have higher intensities for “buttery,” “chickpea,” “corn,” “sweetness,” and “umami” than small-seeded cultivars (Fig. 2.2). On the other hand, small-seeded cultivars tend to be stronger in “bitterness,” “kidney bean” and “saltiness” than large-seeded cultivars.



Fig. 2.2 Boxplot of mean intensities of all significant attributes by bean size

Dry legume seed size may be related to chemical composition and sensory qualities. Descriptive analysis across six common bean cultivars (*Phaseolus vulgaris*) discovered positive correlation between sweetness and cooked seed size ([Mkanda et. al, 2007](#)). The same study also found that the small-seeded cultivars were preferred least in consumer test, hypothesized due to the bitterness and metallic taste. Another study found that the common bean accessions with higher 100-seed weight tend to have higher sucrose content and lower citric acid, amylose, and starch ([Florez et. al, 2009](#)). In addition, there was a strong significant correlation between sucrose synthase activity during rapid seed filling and final seed size of chickpeas ([Turner et. al, 2009](#)). These findings across multiple legume species may suggest that legume cultivars with

large size may synthesize sucrose more actively, thus resulting in higher perceived sweetness. Moreover, legume seed coats may accumulate more phenolics than cotyledon does, regardless of its seed coat colors; there were total phenolics of 0.90 mg/100 g in cotyledon of brown common bean while there could be total phenolics of 86 mg/100 g seed coats ([Ranilla et. al, 2007](#); [Duenas et. al, 2006](#)). Large-seeded legume seeds may have lower phenolic contents than the small-seeded counterparts due to the inversely-proportional relationship between seed coat surface area (g) per gram of seeds with seed volume and the localization of phenolics in seed coat, thus resulting in lower bitterness and higher perceived sweetness ([Marathe et. al, 2011](#)).

Fig. 2.3 shows the PCA biplot for texture/mouthfeel attributes only. As in the previous biplot, scores are colored by seed size. PC1 (49.8%) explains approximately half of the total variance and is associated with overall eating experience. On the right-hand side, samples tend to be higher in “firmness,” “graininess,” “chewiness,” and “difficulty swallowing.” On the other hand, samples on the left may be more “moist” and easy to flow (“initial flow”). PC2 (16.7%) is related to seed coat properties, as samples may have more “wrinkles” and “seed coat thickness.” Small-seeded and large-seeded dry lima beans are separated along PC2 rather than PC1, indicating that large-seeded cultivars tend to have thicker seed coat with wrinkles. Some of the large-seeded white cultivars (left) appear to be more “moist” and “soft” than their small-seeded counterparts along PC1.

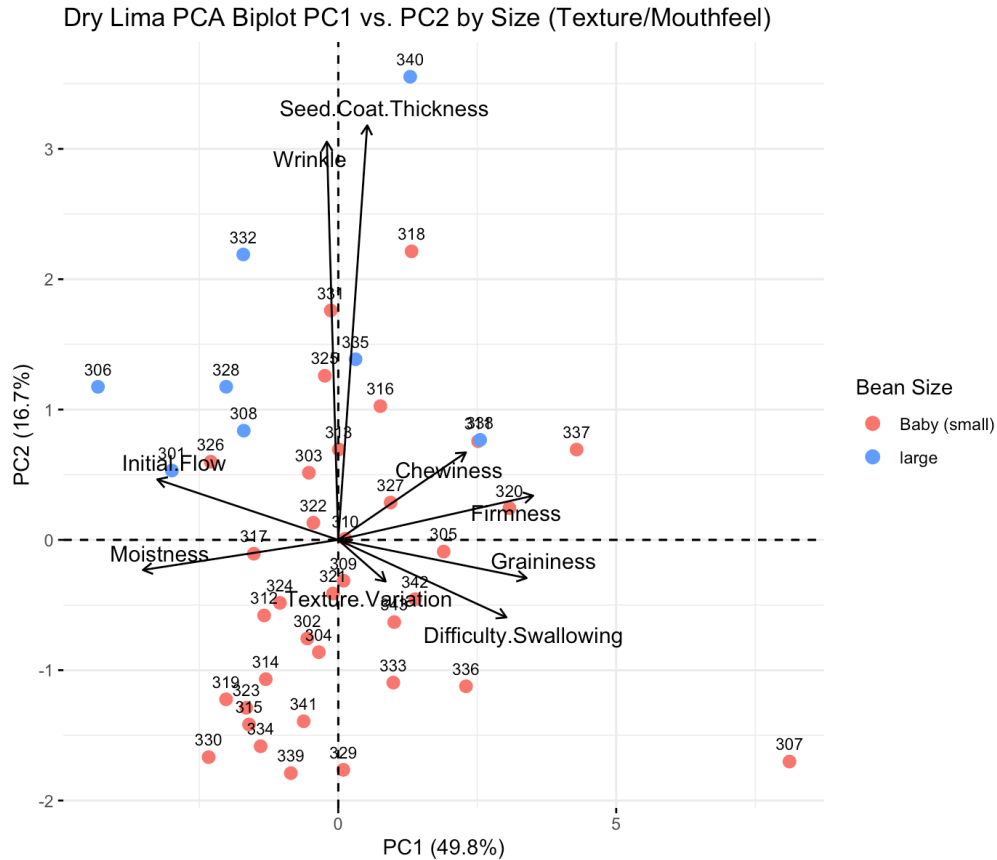


Fig. 2.3 PCA Texture/mouthfeel Attributes: PC1 (49.8%) vs. PC2 (16.7%), scores colored by bean size

Seed coat thickness and seed size were inversely proportional in some legume species, and thicker seed coat resulted in longer cooking time, but neither was applicable to the finding of this study ([Wang et. al, 2003](#)). On the other hand, faster cooking time was observed for common bean cultivars with the following traits: higher seed weight and lower seed coat percentage ([Bassett et. al, 2021](#)). However, genetic variance in seed coat property and subsequent traits may go beyond thickness. The seed coat is a multilayered structure composed of insoluble non-starch polysaccharides (i.e., cellulose, hemicellulose, and pectin), providing a protective layer and regulating chemical exchanges including water ([Zhong et. al, 2018](#)). Among these layers, the palisade layer is composed of hydrophobic substances such as cutin, lignin, pectin, and wax,

contributing to impermeability to water ([Wen et. al, 2024](#)). Common bean genotypes with thickest palisade layer had the slowest water imbibition during soaking stage ([Agbo et. al, 1987](#)). Furthermore, SEM imaging revealed small cracks on the cuticles of palisade layers in permeable soybean cultivars that were absent in impermeable cultivars ([Ma et. al, 2004](#)). Beyond these findings, variation in other seed coat microstructures may influence legume hydration properties ([Devkota et. al, 2022](#); [Luan et. al, 2017](#)). Collectively, these findings suggest that variation in seed coat thickness alone may not determine hydration and cooking properties, and other microstructural differences in the seed coat may also affect these properties.

Flavors and tastes were also variable across dry lima bean cultivars of different seed coat colors (Fig. 2.4). Fig. 2.4 depicts the same PCA biplot as Fig. 2.1 except that scores are now colored based on the seed coat color of respective samples. White-seeded and some white/green cultivars cluster on the right-hand side of the coordinate, and they are associated with “buttery,” “potato starchy,” “chickpea,” corn,” and “sweetness.” The boxplot (Fig. 2.5) shows that white/green cultivars may be stronger in “bitter green” and “sweet green” flavors than white cultivars. White and white/green cultivars are separated along PC2, where white-seeded cultivars tend to be stronger in “umami” and “saltiness” than white/green cultivars. On the left-hand of the plot, darker-seeded and speckled cultivars are clustered. These cultivars are associated with “kidney bean,” “earthy,” “bitterness” and “bitter green.”

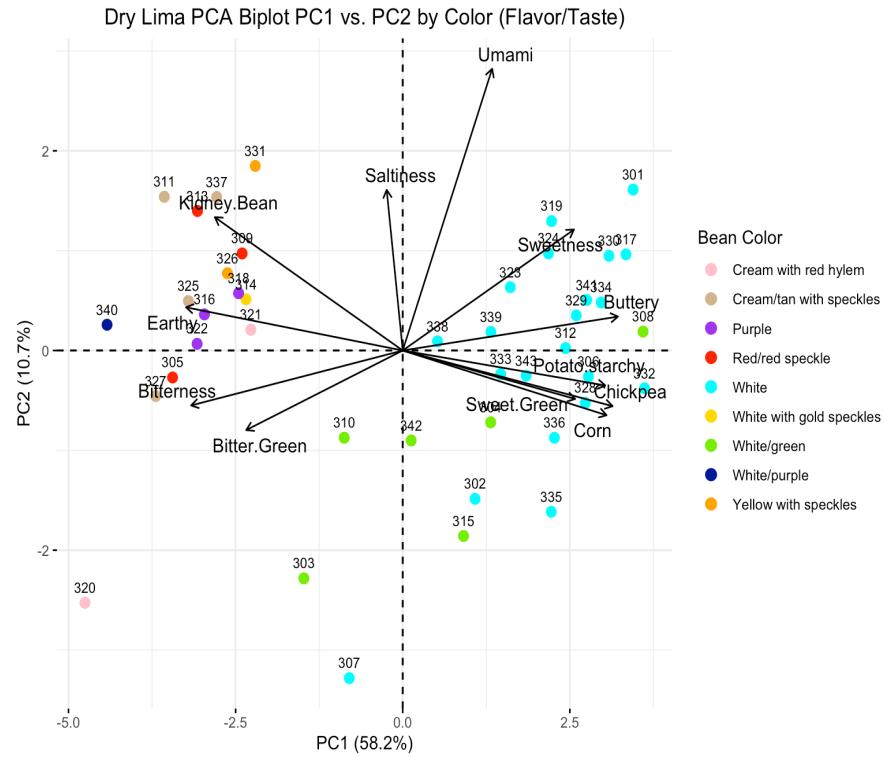


Fig 2.4 PCA Flavor and Taste Attributes: PC1 (58.2%) vs. PC2 (10.7%), scores colored by bean color

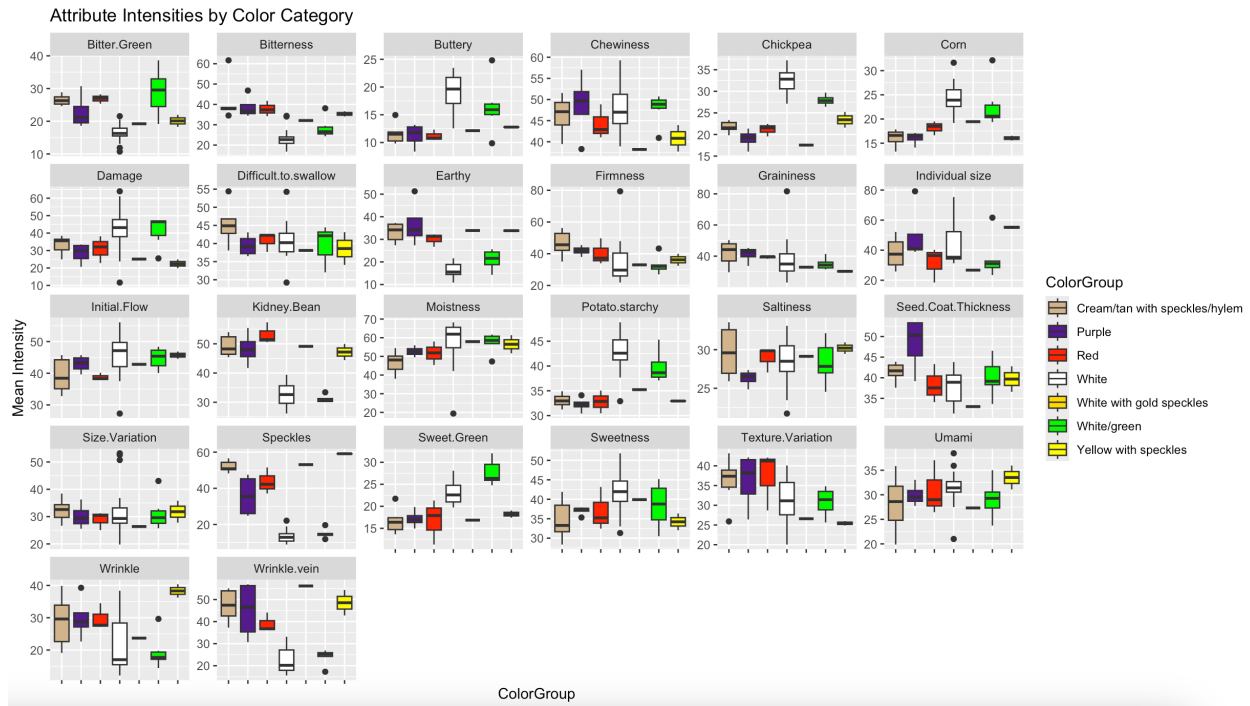


Fig. 2.5 Boxplot of mean intensities of all significant attributes by bean color

Seed coat colors vary and have an impact on sensory profiles across *Phaseolus* legume species. The white genotypes of common beans (*Phaseolus vulgaris*) were associated with starchy flavor and sweetness, whereas darker genotypes were associated with kidney-like flavors, and red mottled genotypes were close to vegetative and earthy flavors ([Bassett et. al, 2021](#)). Phenolic compounds are the primary pigments responsible for color variation among legume cultivars and may be associated with genetic regulation within and across market classes ([Uebersax et. al, 2022](#); [Campa et. al, 2023](#)). White-seeded cultivars contained the lowest amount of phenolics, and the presence of red speckles increased flavonoids and anthocyanins ([Madrera et. al, 2021](#)). Cultivars with pale yellow to cream colors contained flavonoid astragalin (kaempferol 3-O-glucoside) ([Beninger et. al, 1999](#)). Anthocyanins were the primary pigment present in black and red cultivars, and their specific anthocyanin composition varied ([Lin et. al,](#)

[2008](#)). Saponin concentration was also found to be greater in grey adzuki beans (50.94 mg DE/g) and least in white adzuki beans (22.09 mg DE/g) ([Desta et. al, 2023](#)).

Other than contributing to the bitterness and astringency of the products, polyphenols and saponin may influence flavor profile. There was a strong positive association between some phenolics (i.e. catechin gallate and kaempferol glycosides) and sensory attributes such as pea-pod taste, bitter taste, aftertaste, and astringent sensation in germinated lentil sprouts ([Troszyńska et. al, 2011](#)). Polyphenols have also been found to be effective inhibitors of lipoxygenase activity in soybeans and legume protein isolates ([Soendjaja et. al, 2024](#); [Zhang et. al, 2019](#)). Moreover, added polyphenols reduced formation of Maillard reaction products in ultra-processed milk, leading to the reduced cooked flavor intensity ([Colahan-Sederstrom et. al, 2004](#)). As phenolic compounds diffuse through the seed coat into the cotyledon upon soaking and cooking, the aforementioned interactions between polyphenols and other constituents may be initiated, resulting in variation in sensory profile ([Giusti et. al, 2019](#)). Saponins were found to interact hydrophobically with pea protein, thereby competing for or offering binding sites for other volatile compounds, resulting in suppression or enhancement of certain flavors ([Roland et. al, 2017](#)). While specific volatile and non-volatile compositions were not explored in the current study, the presence of natural plant metabolites might have influenced the observed variation in sensory profiles.

Variation in texture/mouthfeel was also introduced by seed coat color variation (Fig. 2.6). The PCA biplot shows the subtle separation between white-colored cultivars and dark-colored cultivars along PC1. Specifically, white and white/green cultivars tended to be more “moist” and “soft,” whereas cultivars with other colors tended to be more “firm,” “dry,” “grainy,” “chewy,” and “difficult to swallow.” Phenolic content in legumes may contribute to the hard-to-cook

phenomenon, also known as the lignification hypothesis, in which free polyphenols and free amino acids migrate from the seed coat to the cotyledon and form lignin-like products, leading to longer cooking time ([Chigwedere et. al, 2018](#)). Polyphenols may also impart dryness and difficult-to-swallow sensations through puckering of the epithelium ([Amarowicz et. al, 2005](#)).

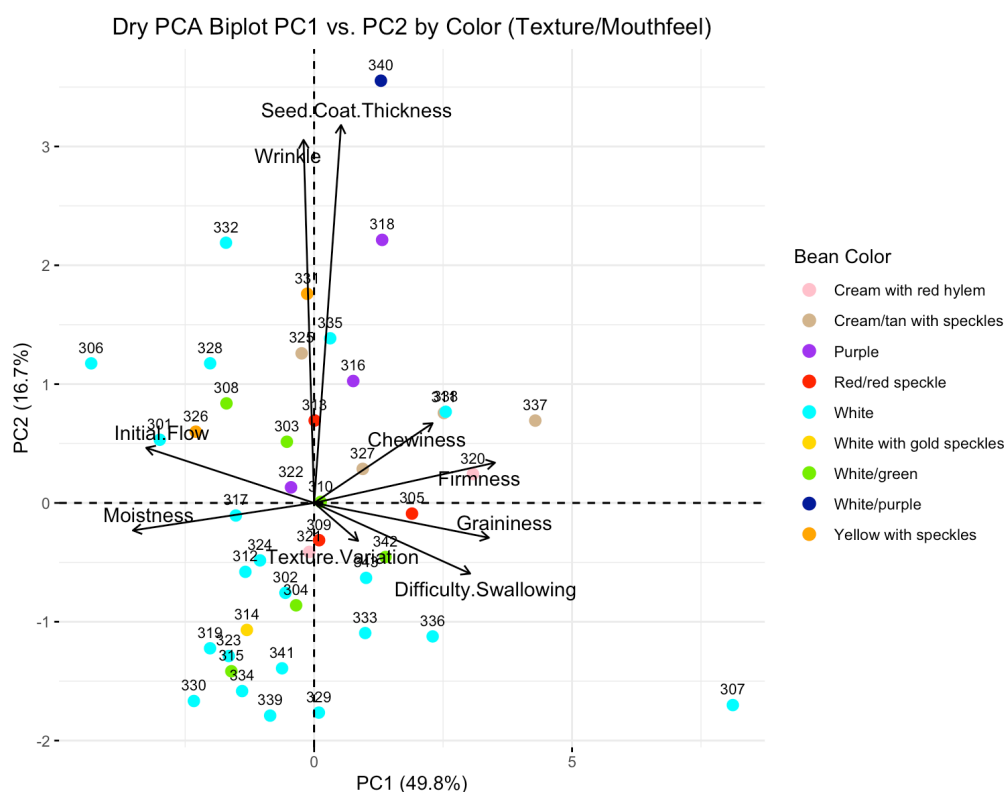


Fig 2.6 PCA Texture/mouthfeel Attributes: PC1 (49.8%) vs. PC2 (16.7%), scores colored by bean color

The appearance was variable across lima bean cultivars based on seed size and seed coat colors (Fig. 2.7 and 2.8). PC1 (46.2%) was driven by “wrinkles,” “speckles,” and “damage” whereas PC2 (30.6%) explains sizes such as “size variation” and “individual size.” The major variation due to seed size was based on “size variation,” where large-seeded cultivars tend to have more size variation within cultivar compared to small-seeded cultivars (Fig. 2.7). On the

other hand, variation in seed coat colors resulted in product separation along PC1 (Fig. 2.8). Specifically, white and white/green cultivars tend to be explained by more “damage” and less “wrinkles” and “speckles.” Other darker, phenolic-pigmented cultivars tended to be located on the opposite side of the plot, showing their association with “wrinkle” and “speckles.”

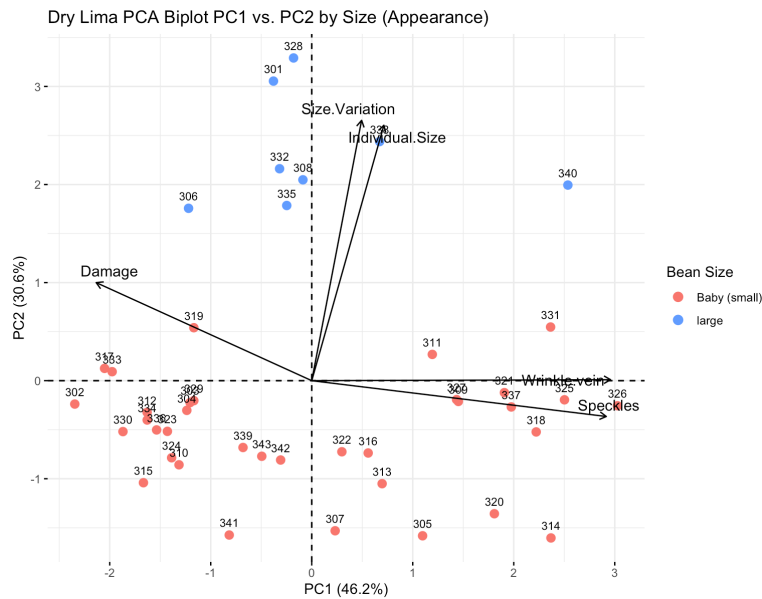


Fig 2.7 PCA Appearance Attributes: PC1 (46.2%) vs. PC2 (30.6%), scores colored by bean size

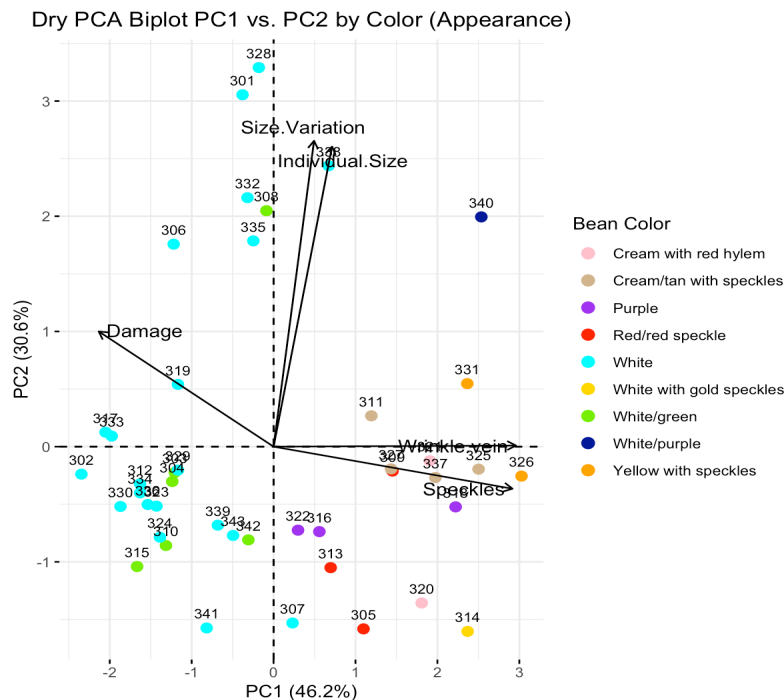


Fig 2.8 PCA Appearance Attributes: PC1 (46.2%) vs. PC2 (30.6%), scores colored by bean color

2.3.2. Consumer Test

2.3.2.1. Overall Liking and Attribute-Specific Likings

Participants ($n = 108$) tasted 12 dry lima beans and answered how much they like or dislike the sample on 9-point hedonic scale. Among the 12 samples, 6 of them were representative of the 6 clusters identified from the hierarchical clustering analysis on descriptive mean data (Fig. 2.9). Table 2.4 presents the mean and standard error of the mean for each product. Overall liking, appearance, size, color, flavor, and texture liking scores differed significantly across products (ANOVA, $p < 0.05$), with post-hoc LSD comparisons also shown in Table 2.3.

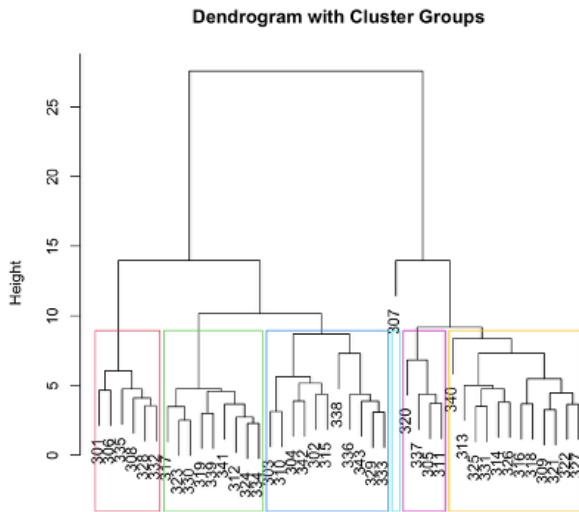


Fig. 2.9 Hierarchical clustering analysis of 43 dry lima bean entries based on mean sensory attribute intensities from descriptive analysis, used to identify six representative entries for consumer testing.

Participants first visually evaluated their likings of overall appearance, size, and color of the samples before eating them. In overall appearance, white baby samples including sample 307, sample 323, and sample 329 were liked the most. On the contrary, non-white samples with speckles (i.e. sample 327 brown with dark spots and sample 311 cream with dark spots) were disliked the most among the subsets of dry lima beans. For size liking, large samples (i.e., sample 306 and sample 332) had significantly higher liking scores than the rest of the small-seeded samples. By color, the samples with white seed coats were liked significantly better than the other-colored samples. However, sample 305, with pink speckled seed coats, was liked better than some of the white-seeded samples.

Participants were then asked to taste samples and evaluate their overall liking, flavor liking, and texture likings. Overall, sample 306, sample 332, and sample 323 were liked the best with mean overall liking of 6.09, 5.76, and 5.71, respectively. All of these were white-seeded dry lima beans. In addition to the white-seeded samples 306 and 332, pink speckled sample 305 was liked the most for flavor. On the other hand, samples 307 and 327 (white-seeded) and sample 311 (cream speckled) were disliked the most for flavor. Samples 306, 332, 323, and 305 were also liked the most for texture/mouthfeel, while sample 307 (small, white-seeded) was disliked the most for texture/mouthfeel.

Table 2.3 Mean and SEM of overall liking, likings of appearance, texture, flavor, color and size with LSD post-hoc comparison

Sample	Overall	Appearance	Texture	Flavor	Color	Size
302 Beija Flor	4.98 (0.18) ^{cd}	4.07 (0.18) ^e	4.75 (0.20) ^c	5.28 (0.17) ^{de}	5.46 (0.17) ^c	2.84 (0.05) ^{de}
305 Dixie Speckled	5.69 (0.14) ^{ab}	4.80 (0.19) ^d	5.64 (0.16) ^{ab}	5.80 (0.15) ^{ab}	5.65 (0.19) ^{bc}	2.47 (0.06) ^f
306 Dompe 95	6.09 (0.17) ^a	4.93 (0.18) ^{cd}	6.02 (0.18) ^a	6.14 (0.17) ^a	5.53 (0.15) ^c	4.17 (0.07) ^a
307 Fava Nova	3.91 (0.19) ^f	5.94 (0.15) ^a	3.45 (0.19) ^d	4.74 (0.17) ^f	6.15 (0.14) ^a	2.87 (0.04) ^d
323 Henderson	5.71 (0.16) ^{ab}	5.41 (0.16) ^b	5.61 (0.18) ^{ab}	5.76 (0.16) ^{abc}	6.08 (0.15) ^{ab}	2.90 (0.04) ^d
327 Jackson Wonder	4.34 (0.18) ^{ef}	3.51 (0.17) ^f	4.34 (0.18) ^c	4.73 (0.17) ^f	4.11 (0.19) ^e	3.05 (0.05) ^c
329 Mezcla Baby	4.87 (0.16) ^{cd}	5.37 (0.16) ^{bc}	4.45 (0.18) ^c	5.11 (0.14) ^{def}	5.57 (0.16) ^c	2.84 (0.05) ^{de}
332 UC 92	5.76 (0.16) ^a	4.75 (0.18) ^d	5.72 (0.18) ^{ab}	6.16 (0.15) ^a	5.61 (0.17) ^c	4.06 (0.07) ^a
334 UC Haskell	5.03 (0.17) ^{cd}	5.18 (0.17) ^{bcd}	4.57 (0.18) ^c	5.34 (0.16) ^{cde}	5.67 (0.16) ^{bc}	2.86 (0.04) ^d
343 DL 24R153 Mezcla	5.19 (0.18) ^c	4.74 (0.16) ^d	4.81 (0.19) ^c	5.50 (0.17) ^{bcd}	5.27 (0.15) ^{cd}	2.90 (0.04) ^d
303 C-elite	5.30 (0.16) ^{bc}	4.08 (0.18) ^e	5.40 (0.15) ^b	5.47 (0.17) ^{bcd}	4.94 (0.18) ^d	2.71 (0.05) ^e
311 G26215	4.68 (0.16) ^{de}	3.68 (0.16) ^{ef}	4.42 (0.17) ^c	4.95 (0.16) ^{ef}	4.25 (0.17) ^e	3.21 (0.05) ^b

* Values are means $\pm$ SEM. Means within a column followed by different letters are significantly different (LSD post-hoc test, $p < 0.05$).

The hedonic biplot (Fig. 2.10) showed that overall liking, flavor liking, and texture liking largely drove the variance in liking across products (52.9%), and these three vectors were positively correlated with one another. The attribute-wise correlation (Pearson, $p < 0.05$) showed that overall liking had significant positive correlation with appearance, color, flavor, texture, and size (Table 2.4). Size liking was significantly correlated only with overall liking, flavor liking, and texture liking.

Table 2.4 The Pearson correlation matrix ($P < 0.05$)

	Appearance	Overall	Color	Flavor	Texture	Size
Appearance	1.00	0.33***	0.75***	0.32***	0.26***	-0.05
Overall		1.00	0.36***	0.83***	0.81***	0.14***
Color			1.00	0.37***	0.30***	-0.02
Flavor				1.00	0.67***	0.14***
Texture					1.00	0.15***
Size						1.00

*Significant correlations are indicated by * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

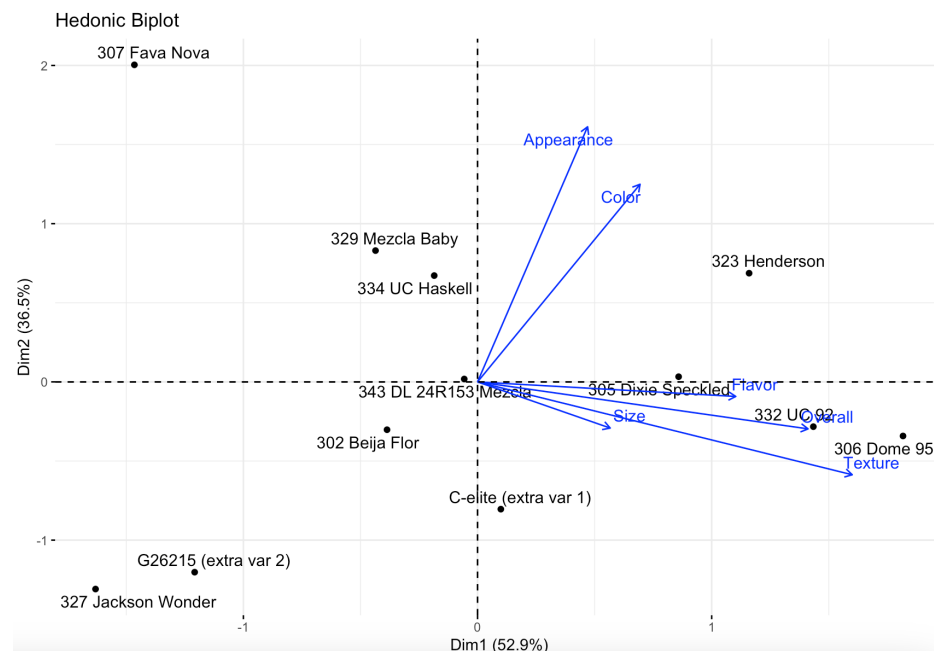


Fig. 2.10 Hedonic biplot of overall and attribute-specific likings

2.3.2.2. Just-About-Right (JAR) and Penalty Lift

Consumers rated the adequacy of specific sensory attributes (firmness, moistness, seed coat thickness, flavor, and sweetness) in three levels: too little, just-about-right (JAR), and too much. Supplementary table 2.2 summarizes the percentage of population for each attribute rating. Fig. 2.11 also shows the distribution of JAR scales per product across each JAR term. The Chi-square test or Fisher's exact test showed a significant difference in the distribution of JAR counts across samples for all attributes. In at least half of the samples, more than 50% of consumers rated the sample as too firm and too dry rather than just-about-right for firmness or moistness. For all samples, at least 50% of consumers agreed that the seed coat thickness was just about right. For sample 302, 323, and 303, none of the consumers said that the sample has too much sweetness, but they were split between JAR and too little sweetness.

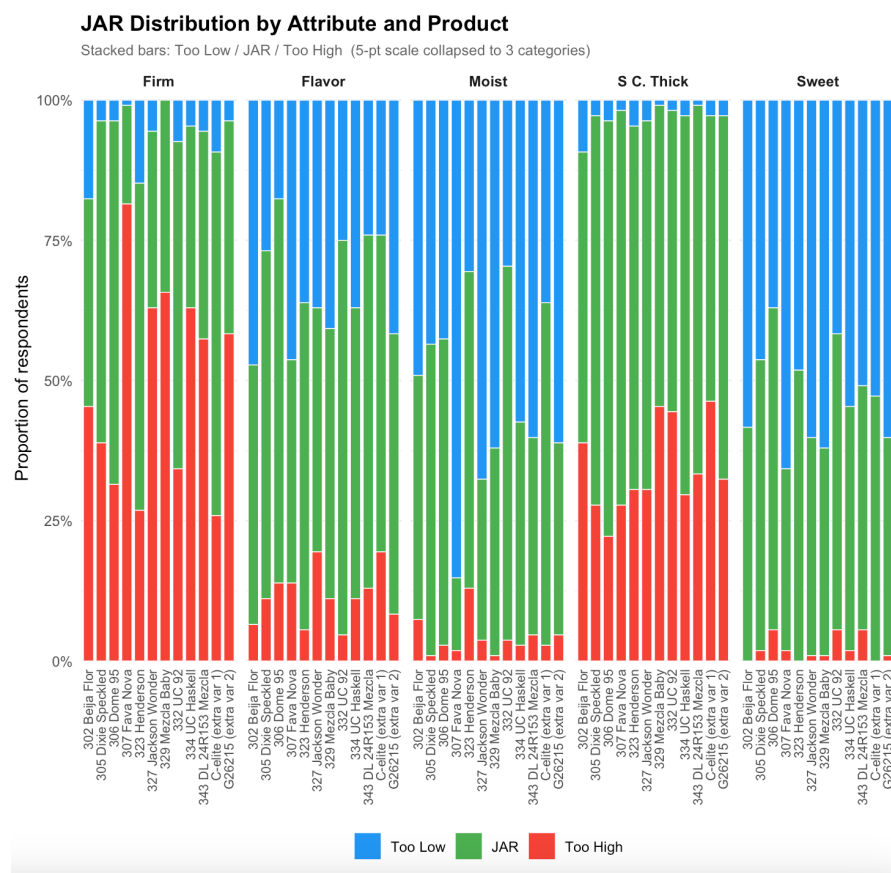


Fig. 2.11 Distribution of consumer responses (%) on the Just About Right (JAR) scale for attribute liking of dry lima bean cultivars

The penalty analysis was conducted to assess attributes that were critical in dropping in mean overall liking. Based on Student's t-test, the drop in mean liking score from those who rated attributes as JAR to those who rated them as too low or too high was significant for all attributes except too low seed coat thickness and too much sweetness. Fig. 2.12 shows the proportion of consumers rating for JAR attributes and their respective drop in hedonic scores. Attributes falling in the critical corner (i.e., more than 20% of consumer responses for too low/high adequacy resulting in a drop in hedonic score of at least 1) are deemed penalizing attributes. Dry lima bean cultivars were penalized for being too weak flavor, too much firmness, too much dryness, and too weak sweetness. The penalties associated with the latter three attribute

inadequacies may be particularly detrimental, given that more than 50% of consumer responses on these attributes resulted in a drop in hedonic score.

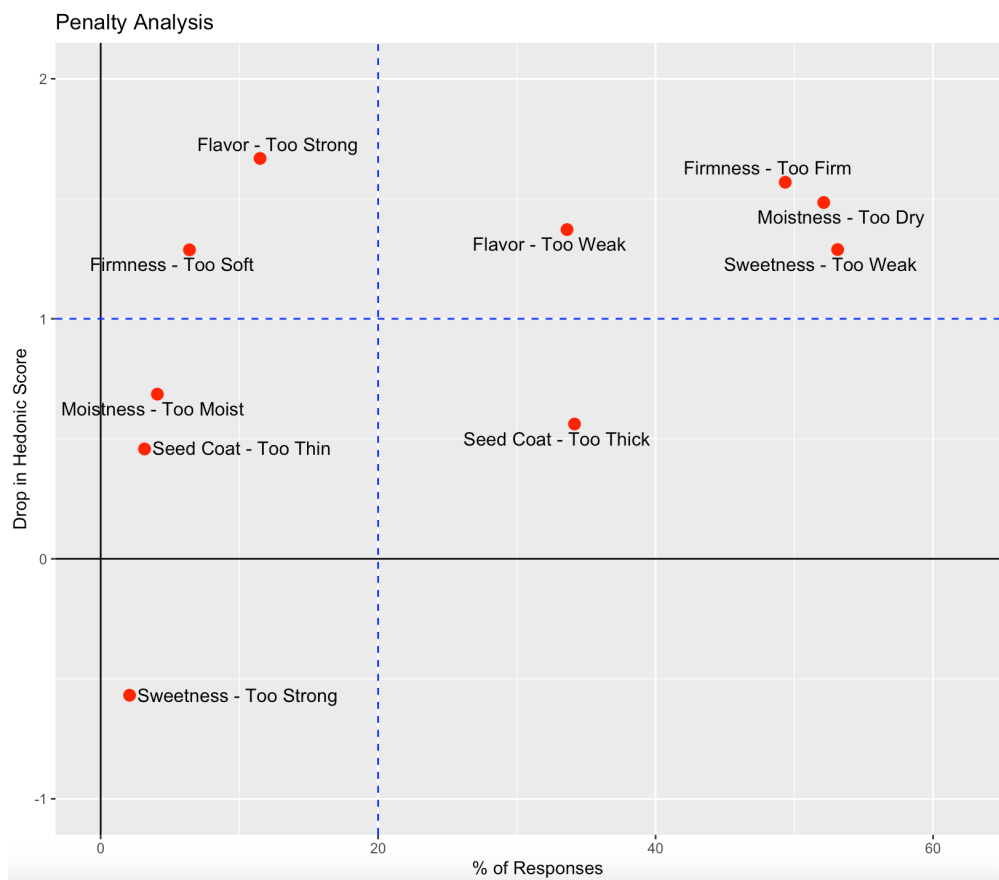


Fig. 2.12 Mean drop in overall liking associated with non-JAR responses for sensory attributes of dry lima bean cultivars (penalty analysis)

2.3.2.3. Check-All-That-Apply

The correspondence analysis was conducted on the check-all-that-apply (CATA) of 29 descriptors (Fig. 2.13). “Salty” was removed from further analysis due to the maximum selection frequency across products less than 10%. Based on Cochran’s Q test, the distribution of consumers selecting each attribute differed significantly across samples for all sensory attributes

except “umami” and “chewy” ($p < 0.05$). McNemar pairwise comparison with Bonferroni correction showed significant pairwise differences among samples across attributes.

CATA dimension 1 explains 44.8% of the variance and the second dimension explains 21% (Fig. 2.13). The three top-liked cultivars (i.e., 306, 332, and 323) are located on the right side of the plot. These samples are closely associated with attributes including “sweetness,” “buttery,” “creamy,” “corn,” “salty,” “potato starchy,” “moist,” and “umami.” On the other hand, the most disliked samples (i.e. 307, 327, 311) are located on the opposite end of the plot where they are associated with “firm,” bitter,” “earthy,” “chewy,” “grainy,” “astringent,” and “difficult to swallow.” The preferred cultivars were associated with sweet and flavorful notes and moist texture, whereas the disliked samples were generally bitter in flavor and taste. Moreover, the combination of firm, dry, and astringent mouthfeel may have resulted in a difficult-to-swallow experience.

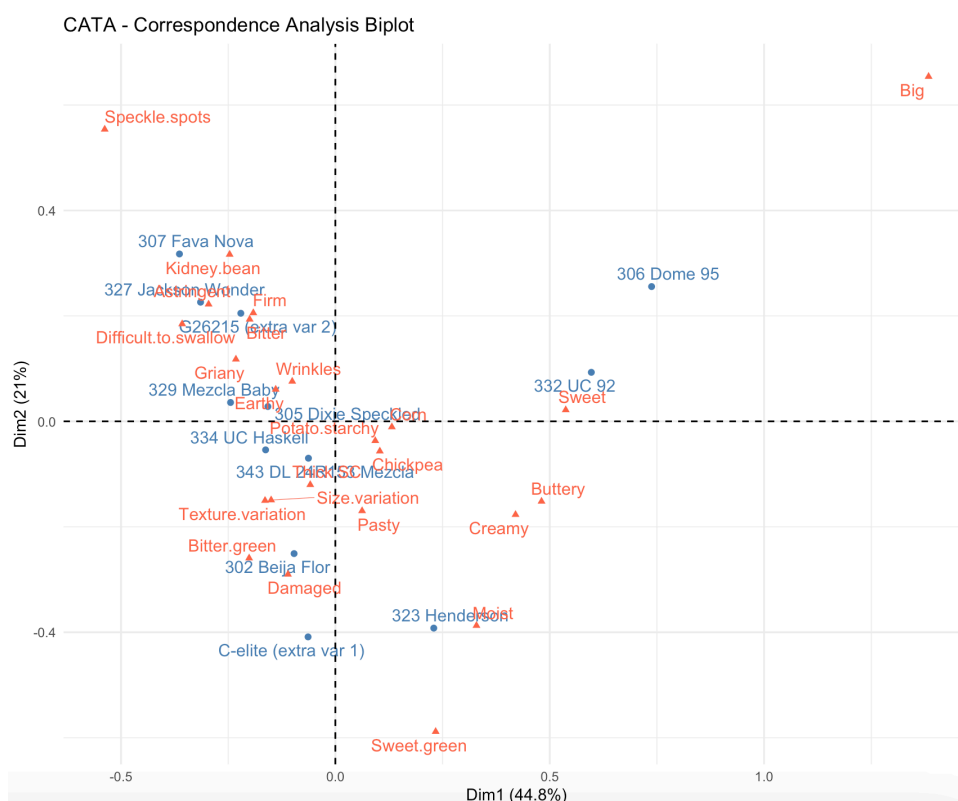


Fig. 2.13 Correspondence analysis of check-all-that-apply attributes

The penalty-lift analysis analyzed the relationship between consumers checking attributes and how this may improve their hedonic scores (Fig. 2.14). Student's t-test showed that mean overall liking differed significantly between consumers who selected an attribute and those who did not, for all attributes except “pasty,” “potato starchy,” and “corn” on the positive side. On the negative side of penalty, selection of “thick seed coat,” “texture variation,” “earthy,” “wrinkles,” and “size variation” may not significantly affect mean overall liking. An improvement in hedonic score of approximately 1 point was associated with products described as “creamy,” “sweet,” “buttery,” and “moist.” On the other hand, a drop in hedonic score of approximately 1 point was associated with products described as “difficult to swallow,” “astringent,” and “grainy.”

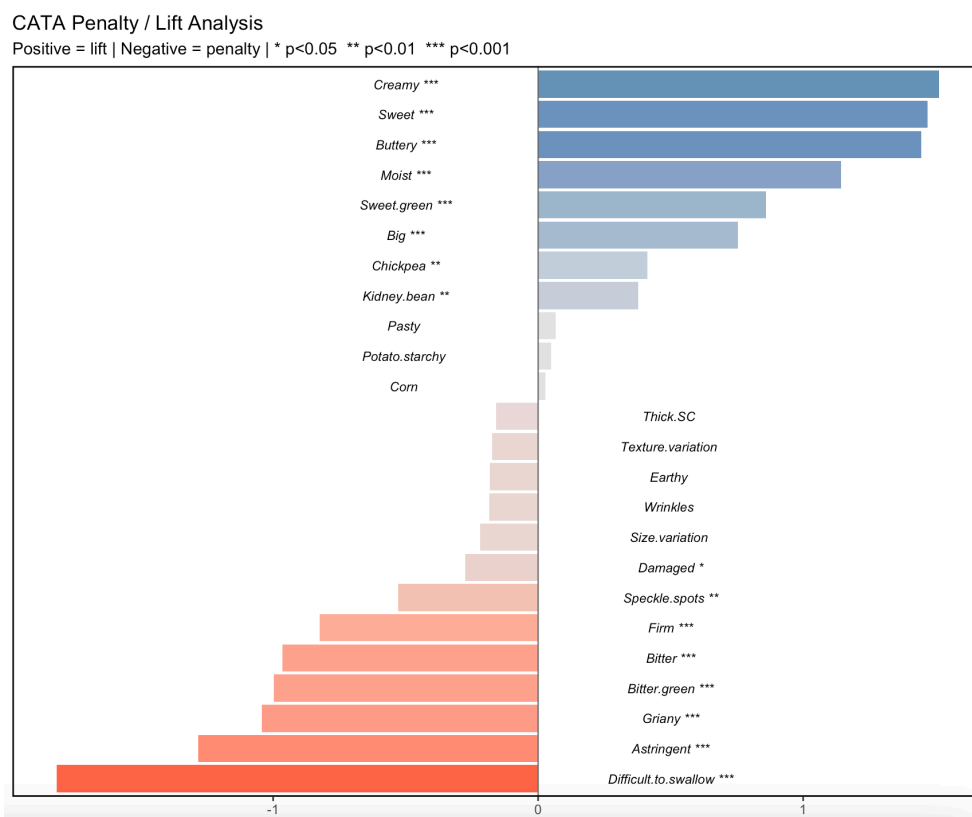


Fig. 2.14 CATA Penalty Lift Analysis

2.3.2.4. Internal Preference Mapping

Internal preference mapping and hierarchical clustering analysis on consumer liking scores identified two consumer segmentations (Fig. 2.15). Consumers were segmented in two clusters of similar size based on the centralized overall liking. Cluster 1 (red, $n = 53$) showed a strong preference for products located in the bottom right corner of the sensory map, such as sample 305 (baby, pink with dark speckles), 323 (baby, white), and 303 (baby, white or green). The cluster-wise mean of overall liking also shows that the mean overall liking of Cluster 1 for these products were significantly higher than that of Cluster 2 (Fig. 2.16). Cluster 2 (green, $n = 55$) showed a stronger preference for small-seeded white cultivars in particular. Cluster 2 had significantly greater liking for samples 307, 343, 329, 302, and 334, all of which are small-seeded white cultivars.

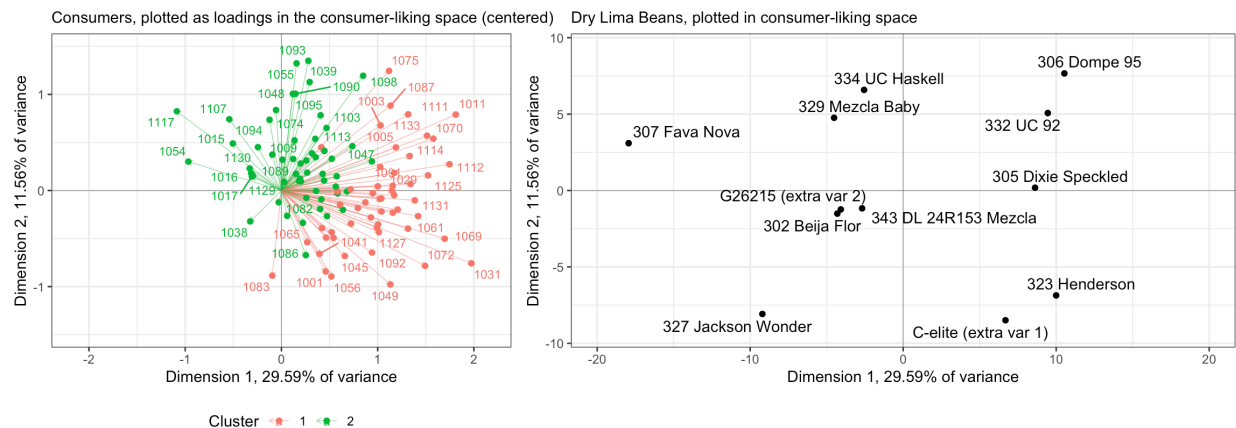


Fig. 2.15 Internal preference map: consumer segmentation based on the centralized consumer overall liking scores ($k = 2$) (left) and dry lima product space (right)

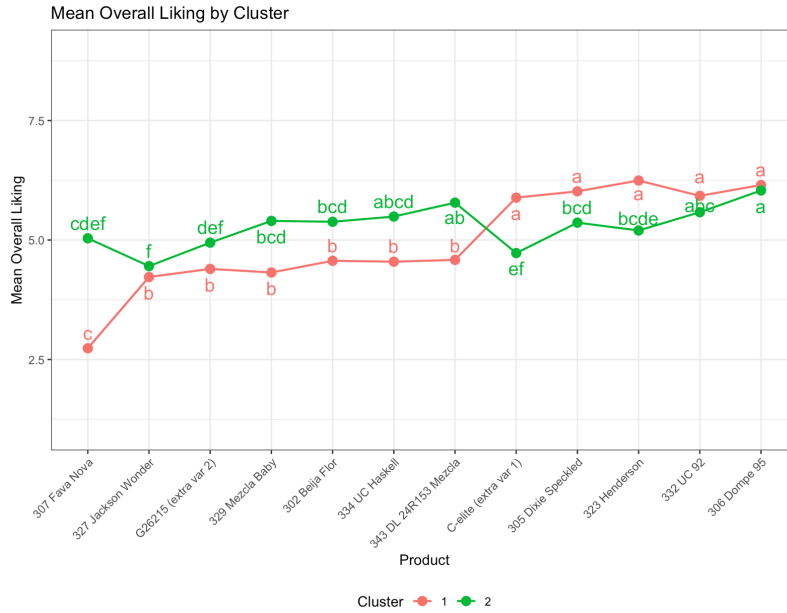


Fig. 2.16 Cluster-wise mean overall liking across products

2.3.2.5. External Preference Mapping

The external preference mapping shows the sensory drivers of liking and disliking per consumer cluster. The PCA across all attributes explained 44.4% and 22.1% of total variance in the first two dimensions of sensory space, respectively (Fig. 2.17). On the loading plot, PC1 (44.4%) is driven by both textural and flavor attributes, with positive associations with moistness, initial flow, sweetness, sweet green, and chickpea flavor, and negative associations with bitterness, earthy, kidney bean, firmness, graininess, and difficulty swallowing. PC2 (22.1%) is positively associated with appearance attributes such as wrinkling and size variation, as well as seed coat thickness, moistness, earthy, and kidney bean flavors, and negatively associated with chewiness, firmness, chickpea, sweet green, and corn flavors.

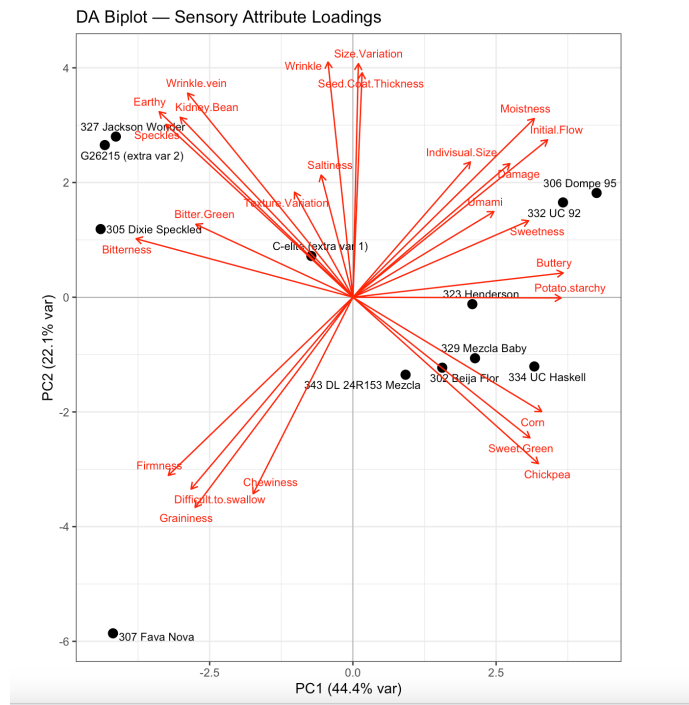


Fig. 2.17 PCA biplot: sensory attribute loadings and product scores in consumer test

Cluster 1 ($n = 53$) showed moderate model fit (mean $R^2 = 0.59$). However, the negative Q^2 indicates overfitting, likely due to the small number of products relative to the number of model terms. The preference surface for this cluster should therefore be interpreted as exploratory and limited to the current sample set. The preference map (Fig. 2.18) shows a band of at least 75% preference spreading across the upper portion of the sensory space, indicating that higher predicted liking was associated with PC2. Samples falling within this region include 306 Dompe 95, 332 UC 92, 305 Dixie Speckled, and C-elite. This broad preference band spans a wide range of flavor profiles, from kidney bean, earthy, and bitter notes on the left side to sweet, buttery, and potato-starchy notes on the right, suggesting that Cluster 1 consumers are generally accepting of diverse flavor profiles among dry lima bean cultivars. Some exceptions were observed. Samples 327 Jackson Wonder and G26215 fall within the 25% preference region in the upper left corner of the map, despite the generally high preference in that area. This may

suggest that Cluster 1 consumers do not prefer cultivars with particularly strong bitter and dark flavors, as well as dark flat-seeded appearances. In the lower half of the preference map, a large rejection region ($\leq 25\%$ preference) was observed, largely associated with firmness, dryness, and flavor attributes such as chickpea, sweet green, and corn. Small-seeded white cultivars fell near the 25–50% preference boundary, while 307 Fava Nova was located well within the rejection zone. Overall, Cluster 1 consumers appear tolerant of a wide range of flavor profiles but consistently disliked cultivars characterized by firmer texture, difficulty swallowing, and associated flavor attributes.

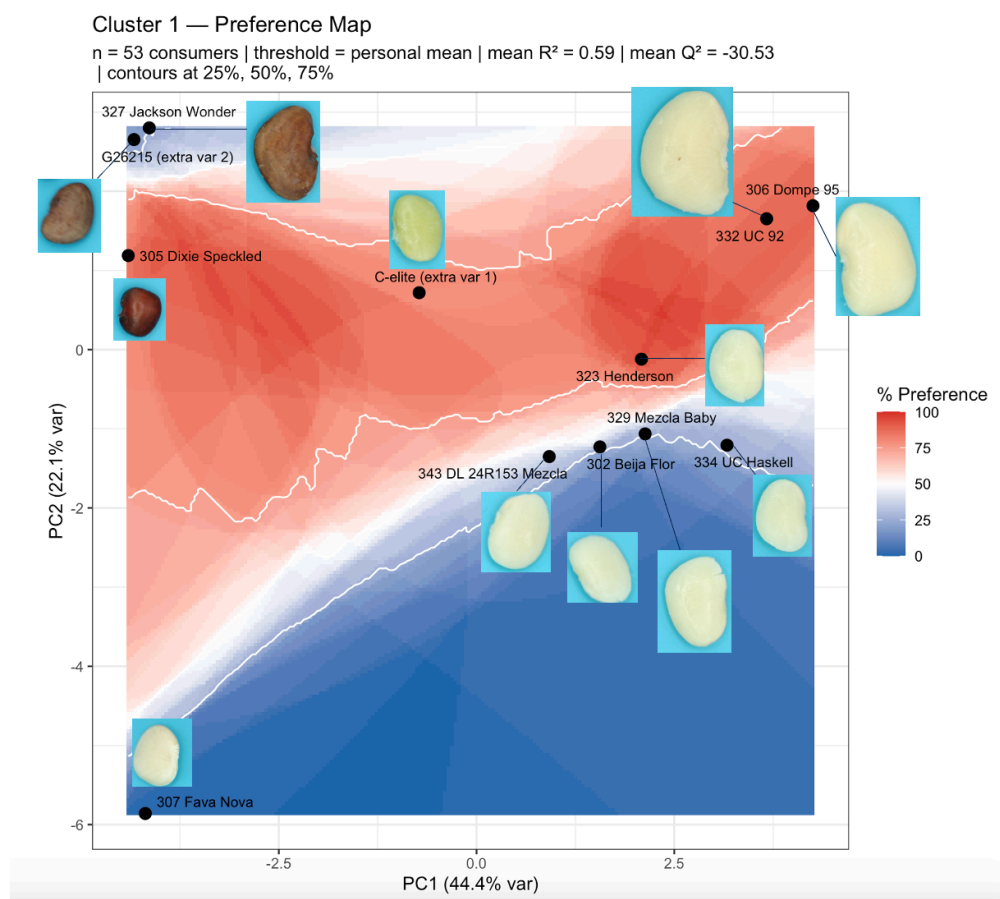


Fig. 2.18 External preference map for cluster 1 (n = 53)

Cluster 2 ($n = 55$, mean $R^2 = 0.54$) showed a similar yet distinct preference pattern compared to Cluster 1 (Fig. 2.19). The overall faint color across the map indicates low consensus among consumers in this segment, suggesting greater within-cluster heterogeneity in preference direction compared to Cluster 1. Two isolated high-preference regions were observed — one in the upper right and one in the lower left portion of the map. The 75% preference region on the upper right captured 332 UC 92 and 306 Dompe 95, the large white-seeded cultivars that were also highly preferred by Cluster 1. The preference concentrated toward the right side of the map suggests that Cluster 2 consumers favor cultivars characterized by higher moistness, sweetness, buttery, and potato-starchy flavor notes. In contrast, samples in the upper left quadrant received lower preference, as seen by C-elite no longer falling within the high-preference region — unlike in Cluster 1. Despite these differences, Cluster 1 and Cluster 2 share a common preference direction toward moist, soft, and sweet sensory characteristics. However, Cluster 2 showed lower overall consensus and a more selective preference specifically toward those traits, which are most strongly expressed in large, white-seeded cultivars.

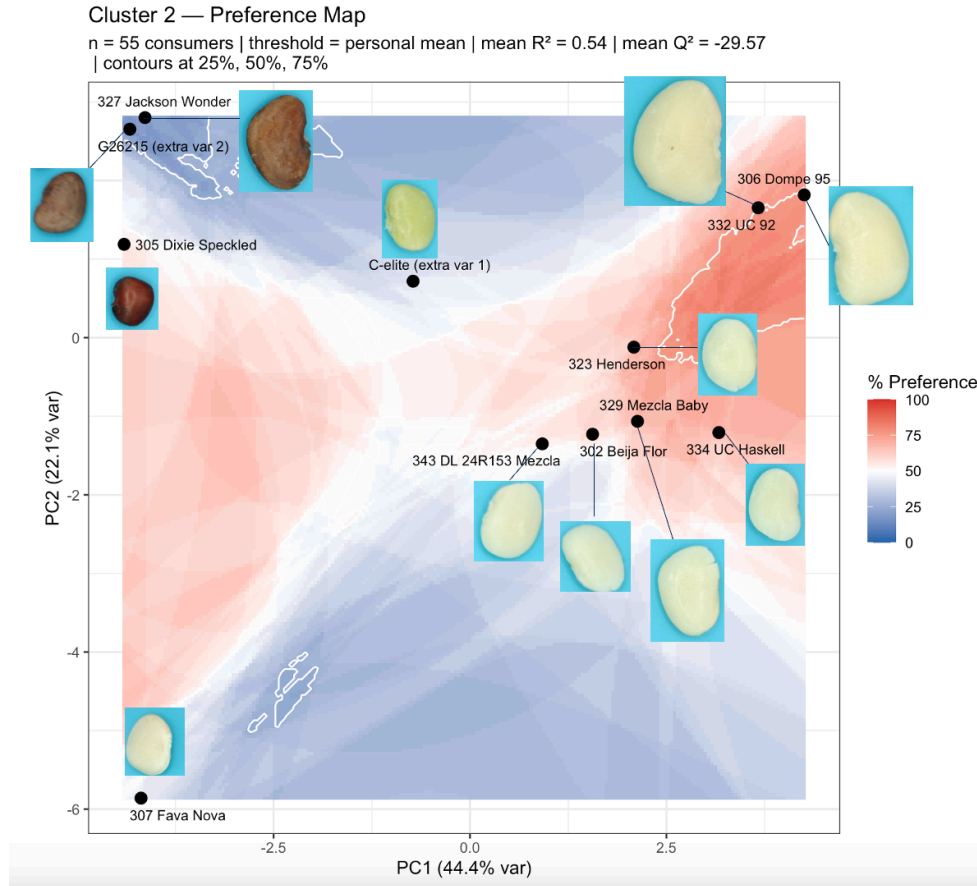


Fig. 2.19 External preference map for cluster 2 (n = 55)

The consumer demographic summary by cluster shows the demographic distributions per consumer cluster including gender, age, ethnicity, income, education, and diet (Table 2.5). Demographic characteristics including gender, age, ethnicity, income, education, and diet were comparable between clusters, with no notable differences observed. This suggests that the distinct sensory preference patterns identified between the two clusters were not attributable to demographic differences, but rather reflect genuine variation in consumer preference structure.

Table 2.5 Consumer Demographic Summary by Cluster (dry)

Variable	Category	Cluster_1 (53)	Cluster_2 (55)
Gender	Male	21 (39.6%)	17 (30.9%)
	Female	32 (60.4%)	38 (69.1%)
Age	18-24	15 (28.3%)	14 (25.5%)
	25-34	23 (43.4%)	24 (43.6%)
	35-44	10 (18.9%)	9 (16.4%)
	45-54	5 (9.4%)	5 (9.1%)
	55-60		3 (5.5%)
Ethnicity	White/Caucasian	20 (37.7%)	17 (30.9%)
	Hispanic/Latino	9 (17%)	8 (14.5%)
	Black/African American	2 (3.8%)	1 (1.8%)
	Native American/American Indian	1 (1.9%)	
	Asian	18 (34%)	25 (45.5%)
	Other	3 (5.7%)	3 (5.5%)
	Pacific Islander		1 (1.8%)
Income	<\$35,000	11 (20.8%)	10 (18.2%)
	\$35,000-\$50,000	8 (15.1%)	17 (30.9%)
	\$50,000-\$80,000	13 (24.5%)	10 (18.2%)
	\$80,000-\$150,000	13 (24.5%)	10 (18.2%)
	\$150,000-\$250,000	8 (15.1%)	5 (9.1%)
	>\$250,000		3 (5.5%)
Education	High school diploma	4 (7.5%)	2 (3.6%)
	Bachelor's degree	20 (37.7%)	22 (40%)
	Graduate/Professional degree	29 (54.7%)	31 (56.4%)

Variable	Category	Cluster_1 (53)	Cluster_2 (55)
Diet	Omnivore	45 (84.9%)	50 (90.9%)
	Vegetarian	3 (5.7%)	2 (3.6%)
	Vegan	1 (1.9%)	
	Pescatarian	2 (3.8%)	1 (1.8%)
	I don't know	2 (3.8%)	2 (3.6%)

2.4. Chapter Conclusion

This chapter investigated the sensory characteristics of 43 dry lima bean entries for breeding purposes. Variation in seed size and seed coat color was associated with variation in sensory profiles. White large-seeded cultivars tended to have stronger flavor intensities with more pronounced sweetness than their small-seeded counterparts. Large-seeded cultivars were also found to have thicker seed coats than small-seeded cultivars, though optimum cooking time was not directly proportional to seed coat thickness. Variation in flavor profile associated with seed coat color may be attributed to phenolics and other chemical components, though specific chemical compositions were not explored in this study. The consumer test across 12 representative samples from descriptive analysis revealed an overall preference for white-seeded cultivars associated with sweetness, moistness, and creaminess. Internal preference mapping revealed two major consumer segments. External preference mapping showed that both segments preferred moist and sweet cultivars, though Cluster 1 exhibited a broader band of acceptance in stronger consensus while Cluster 2 had a narrower acceptance region including only the large white-seeded cultivars with heterogeneity. Collectively, this information may serve as a guide toward selection of parental accessions with desirable traits, identification of target genes, and lima bean production tailored to preferred attributes. Future work may include sharing the lima

bean sensory map with breeders and conducting more detailed chemical analyses to establish connections between sensory attributes and their responsible physicochemical constituents.

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Chapter 3: Focus group: comparison and contrast of qualitative information regarding lima bean usages and knowledge between regular and non-regular lima bean users

3.1. Introduction

This chapter aims to investigate and compare the qualitative information of regular and non-regular lima bean consumers regarding their impression, opinions, and personal experiences on lima bean usages. Focus group serves to uncover underlying factors affecting regular consumption and non-consumption of lima beans across people through interactive group panel discussion guided by a moderator. The analysis included comparison and contrast of the findings between two populations, aiming to understand qualitative factors promoting and demotivating lima bean consumptions. Overall, this chapter addresses perspectives on consumer quality related to lima bean consumptions, offering a hint to lima bean marketing and breeding strategies from sensory science.

3.2. Materials and Methods

3.2.1. Participants

This study investigated qualitative information on lima bean usages across two populations: regular lima bean consumers (hereafter ‘regular consumers’) and non-regular lima bean consumers (hereafter ‘non-regular consumers’). The total of ten consumers ($n = 10$) and thirteen non-consumers ($n = 13$) were recruited for focus group. The screener form ensured that participants consume lima beans at least once a month to be an eligible panel for consumer pool. Demographic distribution for regular consumer and non-regular consumer panels is shown in Table 3.1. Screener also ensured that panels feel comfortable participating in a group discussion with other participants. For each population, participants were split into two groups based on their

schedule availability, resulting in two focus group sessions for each panel population. Each session included at least five panels for the data quality.

Table 3.1 Demographic distribution of consumer and non-consumer panels

	Regular Consumers (10)	Non-Regular Consumers (13)
Female	90%	53.8%
Male	10%	46.2%
18 -24	20%	38.5%
25 – 34	50%	15.4%
35 – 44	20%	7.7%
45 – 54	0%	30.8%
55 - 60	10%	7.7%
White/Caucasian	20%	23.1%
African American	0%	7.7%
Asian American	30%	15.4%
Latin American	10%	23.1%
Native American	10%	0%
Others	20%	30.8%

3.2.2. Questionnaire

A questionnaire was constructed for each regular consumer and non-regular consumer group, aiming to collect holistic qualitative data on population perspectives, understandings, insights, and opinions regarding lima beans.

The series of questions for regular consumers followed this general structure: 1) Lima bean consumption habits, 2) Awareness of lima bean varieties, 3) Perception and associations with the term "lima beans," 4) Lima bean purchase behavior, 5) Usage and preparation, 6) Likes and dislikes of lima beans, 7) Barriers and motivations, 8) Comparison with other legumes, 9) Choice of protein source, and 10) Future interest.

Questionnaires for non-regular consumers had a similar structure with slight modifications:

1) Consumption habits with a focus on lima bean eating experience prior to the consumer test, 2) Awareness of lima bean varieties, 3) Reasons for lima bean non-consumption, 4) Perceptions and impressions of lima beans based on the consumer test and past eating experience, 5) Comparison with other legumes, 6) Purchase decisions for legumes in general, 7) Choice of protein source, 8) Conditions for trial, and 9) Future interest.

3.2.3. Focus Group Protocol and Flow

Participants were welcomed into a conference room suitable for conducting focus group sessions. Once seated, participants were provided with a name tag and a participant consent form, ensuring that they understood their rights as volunteering panelists. The moderator and notetaker were also present in the same room. Each focus group opened with an introduction to the scope of the project and the focus group objectives. It was emphasized that there are no right or wrong answers and that differing opinions are welcomed. Panelists were also made aware that the session would be recorded and transcribed using a computer tool for research purposes only.

Each focus group was structured to collect panelists' qualitative opinions in a one-and-a-half to two-hour session. Recognizing that the majority of panelists had joined one or both of the previous consumer tests for lima beans, the moderator first asked an icebreaker question about their experience with the consumer test. The session then transitioned into questions further related to panelists' perspectives on lima beans, following the basic flow of the questionnaire outlined in Section 2.2. The moderator may have skipped or adjusted the flow of the questionnaire for each session as necessary based on the actual discussion. At the end of the questionnaire, panelists were invited to share any final comments and concluding thoughts. Afterward, panelists were provided with monetary compensation and dismissed.

3.2.4. Data Analysis

The investigator watched all four recordings while following the notes taken during the sessions. For each topic, relevant key findings and supporting quotes from multiple panelists were compiled into a single document. The summarized findings and quotes across all focus groups are reported in this paper.

3.3. Results

3.3.1. History of Lima Bean Consumption

After icebreaker questions and introductions around the table, the discussion was opened with a question regarding panelists' history of lima bean consumption and their patterns.

Regular Consumers:

Regular consumers consumed lima beans at least once per month both at home and at outside locations, and intake frequency may vary depending on the season, grocery store's availability, and personal preference on a given day. One participant also mentioned her encounter with lima beans after transitioning to a vegetarian diet, which gave her greater exposure to a variety of plant-based ingredients. Another panelist had a particular association between lima beans and winter due to their use in stews, as cooking dry beans for extended periods tends to heat up the house.

"I'm from India, so we have a lot of bean curries that we usually eat. In terms of lima beans, I try to get it every month, but it's just depending on what I feel [and what's available] in the store shelves. So, if I tend to gravitate towards lima bean, then I'm probably having a lot of lima beans that month."

"I don't want to heat up my whole house by boiling something on the stove for a while, so I kind of associate them more with winter and more, like stews. I'd probably eat lima beans maybe once or twice a month ... it's more of a winter thing than a summer thing for me."

The majority of regular consumers were first introduced to lima beans by family members through culturally familiar recipes, as something they had eaten while growing up. Others had no exposure to lima beans in childhood but encountered them through a product development assignment, which sparked their interest and left them pleasantly surprised by how much they enjoyed them. A few regular consumers had never tried lima beans until participating in consumer tests, but after doing so, they were pleasantly surprised and began incorporating them into their regular diet. For those who had eaten lima beans in childhood, the memories could be deeply nostalgic and playful — one panelist recalled playing with individual beans at the counter while her aunt was cooking.

"I grew up eating lima beans fairly often. My aunt would cook them a lot ... when I was really little, she would have me at the counter while she was cooking, and she would give me lima beans. I can't remember if they were dried or cooked, but she would give me them to play with, and group them into groups of numbers."

Regardless of their childhood exposure, some regular consumers expressed that they did not enjoy lima beans as children due to disliking the texture of beans or vegetables in general. However, as they grew older, they developed a greater appreciation for vegetables, built sensory tolerance, and expanded their palates, leading them to consume lima beans more often.

"When we were younger, parents cooked for us ...they bought lima beans ... kids don't like veggies in general, but when I'm getting older, I appreciate more about veggies and stuff, then I sometimes will buy lima beans and cook it."

Non-Regular Consumers:

While not currently regular consumers, the majority of non-regular consumers had still eaten lima beans on prior occasions. These included eating lima bean soup in childhood, encountering them while traveling, and tasting samples as part of a breeding program. Their impressions varied from positive to negative depending on the individual.

"Only once in a little town in Portuguese [in Central Valley, CA]. ... They had them in a soup. And those are interesting! And I haven't purchased it again, because I normally do black beans ... they were doing the trials [in a local market]."

"Maybe in soups and things like that. I remember having them [as a kid] out of the can but it wasn't good."

It was also noted that many non-regular consumers may have been consuming lima beans more frequently than they realized, through formats such as frozen vegetable mixes that include lima beans. Because lima beans are not prominently highlighted in these products, consumers may be unable to accurately assess their consumption frequency, often perceiving them simply as generic vegetables rather than a distinct ingredient.

"I've had also had lima beans before, and I feel like usually they come in the frozen makes of stuff, so they're in there. It's very well possible that people don't even know that those are lima beans ... they are more neglected and just considered as vegetables in general, but not particularly sold as a lima bean."

3.3.2. Impressions and Associations with Lima Beans

Panelists were then asked about their impressions of and associations with the term "lima beans," probing for positive or negative associations, specific imagery, and the origins of these impressions. Since the majority of panelists had also participated in one of the centralized location tests and learned about the variability in lima bean cultivars, they were also asked how their impressions of lima beans had changed after the consumer test.

Regular Consumers:

There was a mixture of negative, neutral, and positive impressions of "lima beans" among regular consumers. Despite connections to nostalgia, home, and culture through childhood dishes, panelists mentioned long-lasting negative impressions of certain sensory qualities of lima beans, such as being mushy, green, bland, and bitter. It was also noted that among American populations, the general impression of lima beans tends to be negative.

"Growing up as a child especially in America, I think there was a negative association with lima beans ... before the consumer test, I had associated them with being kind of mushy, and green, bland, and bitter ... I definitely disagree with that now [after consumer tests]... [However] in America, our general sentiment towards beans can be kind of negative."

However, impressions could shift toward positive as panelists learned proper cooking methods and broadened their preferences over time. Learning about the nutritional benefits offered by legumes also led some to associate lima beans with health and wellness. For others,

lima beans carried a special personal memory — one panelist recalled a nostalgic tradition of visiting a café with her mother each birthday to enjoy a particular lima bean dish.

"I have a very nostalgic bean dish ... when I was a kid, my mom used to take me to an Armenian cafe [in New York City for my birthday], and they had a butter bean dish with tomato paste and a ton of olive oil and fresh herbs. I would eat it on my birthday every year... now I make it a lot in the winter, because it reminds me of communicating with my mom."

Furthermore, learning about the versatility of different cultivars through the consumer test expanded panelists' interest and shifted impressions in a more positive direction. Specifically, the majority of regular consumers expressed strong interest and a notable shift in impression after tasting a large, creamy, and sweet succulent lima bean sample from the consumer test.

"[During my childhood,] I didn't like the texture of smaller, waxy textured [lima] beans ... [since joining the consumer test] I like the bigger, more buttery type ones."

Non-Regular Consumers:

Non-regular consumers had stronger negative associations with lima beans than regular consumers. Many panelists pointed to lasting childhood memories of picture books and cartoons in which lima beans were depicted as causing bodily transformation or were associated with threat. These biased food depictions during childhood may significantly shape children's understanding of what is safe and appealing to eat, carrying those aversions into adulthood.

"There's a book that a girl just didn't want to eat her lima beans, and then all sorts of body horror happened to her. I got the impression, like 'oh, so lima beans are gross,' that's basically what I'm walking away with."

"Watching an episode of SpongeBob as a kid, where he was force-fed with lima beans ... And then SpongeBob was sold by some random stereotypical punk or something ... and I'm like lima beans are bad."

In addition to media influence, non-regular consumers also held negative sensory impressions, associating the green color with bitterness and astringency. However, exposure to a variety of lima bean cultivars during the consumer test shifted their perspectives, moving from negative to a view of lima beans as a versatile, interesting legume that is safe and worthwhile to eat.

"It's one of those picture books that stays in your mind forever ... she eats them to make her better ... But then the lasting image [was] really scary. So it has negative [impression] ... I'm not that stressed about eating it [after consumer test]. If I could find them in stores, and obviously at a good price point, I think they'd be a great option."

"They were in the green presentation with the format, [and I] associated them with bitter taste [and] astringent, stuff like that. They tasted like meats. So, it's just the looks of it that I think it's intimidating for most people."

"There's a bunch of different flavors, and growing up, I felt like meat was the safe food. [One of the lima beans in consumer test] actually tasted like chicken broth ... super creamy, which, again, that's a texture I really like. So, I'm like, wow, I was missing out on that."

3.3.3. Purchase and Consumption Behaviors

To address knowledge gaps in purchase and culinary behavior between regular and non-regular consumers, panelists were asked about their lima bean and legume purchase behaviors, including purchase locations, product formats, factors influencing purchase decisions, and consumption contexts. These questions were directed exclusively to regular consumers.

Regular Consumers:

Regular consumers obtain lima beans from a variety of locations, including Costco, grocery stores, farmers markets, and specialty international markets. While they demonstrated broad knowledge of where to find both frozen fresh products and dry lima beans, they also expressed some difficulty locating them locally. In particular, shelf-stable dry lima beans tend to be more readily available in local grocery stores, whereas frozen succulent lima beans are more limited in availability.

"Greek market or the European International Crochet market. And I buy them in the dry form."

"Sometimes grocery store, but mostly Costco, and if I go to Sacramento, then I get the fresh ones."

Purchase decisions for lima beans may be influenced by convenience, freshness, price, and product availability. Many consumers highlighted the strong affordability of dry lima beans compared to animal proteins, while frozen succulent products tend to be slightly more expensive. Some consumers look for canned lima beans but have difficulty finding them locally. It was also noted that other legumes — such as kidney beans and black beans — are often the first choice

due to their wider availability. One panelist also mentioned the importance of packaging presentation, expressing a preference for transparent packaging without additional nutritional claims, as heavily labeled packaging can feel less authentic and may deter purchase.

"Some are transparent [package which] you can actually see the beans ... there's [other packages with] all these extra fancy labels, like, extra fiber, whatever probably going to stay away from that and just get the classic normal packaging."

Another panelist expressed a preference for seeing recommended recipes on the back of food packaging in general, but noted that this is rarely found on dry legume packages, including those for lima beans. She suggested that including cooking guidance on dry lima bean packaging could help non-regular consumers better understand how to use the product and encourage them to try it more often.

"I have never seen the package [with some recipes] in the back. For me, this is something that I really like in any food. But I think that with lima beans, or with bean in general, they don't have this kind of recipes ... I'm going to buy that one that have these recipes."

Regular lima bean consumers also demonstrated broad knowledge of culinary applications by sharing their go-to recipes. Frozen succulent beans can be prepared quickly by boiling with a pinch of salt, whereas dry lima beans require overnight soaking and planning the day before, followed by boiling for 20 minutes or cooking in a pressure cooker. Culinary applications were versatile, ranging from adding beans to salads, mixing with butter and corn, and serving as a rice side dish, to incorporating them into herbal soups, pasta sauces with cashew cream, Indian curry bases, and dishes cooked with animal proteins such as minced meat or chicken with seasonings.

3.3.4. Drivers of Liking and Disliking of Lima Beans from Consumer Perspectives

Both regular and non-regular consumers were asked about the reasons for liking or disliking lima beans in general. Questions probed multiple aspects including sensory qualities, accessibility, and nutritional qualities.

Regular Consumers:

Regular consumers identified several qualities they particularly liked about lima beans, many of which aligned with impressions discussed earlier. Inexpensiveness and nutritional benefits — including being considered a good source of protein and fiber — were consistently paired as favorable traits. The ease of preparation and ability to add lima beans to a variety of meals were also highlighted as qualities that allow consumers to boost nutrient intake with minimal cost and effort. Culinary versatility was another frequently mentioned positive attribute, with applications ranging from pasta sauces and dips to whole beans and incorporation into tomato-based vegetable dishes.

"They're so cheap that I kind of consider them free. It's one of the best nutrition per dollar that you can get."

"I like how it's a good source of protein and fiber too. It's easy to add in my salads anytime during the day. It's very convenient."

In addition to the sweet and creamy texture being highlighted as a favorable characteristic, the brown succulent cultivar was suggested as a potential substitute for kidney beans. The visual appeal of color variety among succulent beans was also praised. While

panelists expressed enthusiasm for the range of samples tasted during the consumer test, they were disappointed that most of those cultivars are not yet commercially available.

"Different colors are so pretty. Put them all together, like [in] pasta salad, having green, purple, brown, white, and yellow [lima beans to achieve] so many different colors. But it's really hard to find those."

Regular consumers also identified several dislikes. Dry lima beans in particular require advance planning and longer cooking times. Unlike frozen succulent lima beans or other ready-to-eat formats, dry beans must be soaked overnight before cooking — although some consumers manage this by preparing large batches at once for use throughout the week.

"You just have to plan in advance. The night before, you have to think that [you] need beans tomorrow. I forget about that most of it. So I do it in the morning, and I have to probably cook it by the evening."

"I don't like how long they take me to cook ... [But] it's like a one-time thing every week, so I do it in batch and I put it in my refrigerator. I can use it throughout the week."

Consumers also weighed the tradeoff between price and convenience. Frozen succulent beans were generally appreciated for their smoother texture and cooking convenience, though this comes at a higher price compared to dry shelf-stable lima beans.

"Anything that's a convenience [such as products in frozen section] is gonna have a price premium, as opposed to where something that's dry and shelf-stable probably doesn't require as much work."

Additionally, some consumers noted that certain lima beans can taste bitter and astringent, and that boiling soaked dry beans may cause seed coats to separate and interfere with the dish.

Non-Regular Consumers:

Non-regular consumers focused their dislikes primarily on inaccessibility. They reported difficulty locating lima beans in their local grocery stores, either because the product is simply unavailable or because it is not marketed as prominently as other popular legumes such as black beans and pinto beans.

"If there is availability in the markets, it's not broadcast that it is a lima bean, probably because at least people who are marketing it are scared that people might have negative associations about lima beans"

"I have my go-tos, because it's already a recipe that I make ... I don't think I see a lima beans in that section."

One panelist commented that lima beans may be less competitive than other legumes due to a lack of consumer familiarity and widely known recipes.

"If you are used to have pinto beans, you're familiar with that ... it's a competition of other beans that are displaced ... and then availability [of] recipes, but also the competition of the other beans in the market and the familiarity."

Non-regular consumers also extended their dislikes beyond lima beans to legumes in general, noting that beans can be time-consuming to prepare and that nutritional information is not always clearly communicated.

"I also feel like how many people who are super busy ... it takes that much to make it palatable."

"There's no published metrics, not widely available ... what are the macros for lime beans? ... Usually people will go for higher protein alternatives."

3.3.5. Awareness and Preference on Protein Sources

Questions on lima bean and legume consumption habits were followed by questions on panelists' awareness, understanding, and preferences regarding protein sources. They were asked whether they consume animal-based protein, whether they tend to favor a particular protein source, and their reasons for doing so.

Regular Consumers:

The regular consumer group was a mix of omnivores and vegetarians, each making choices between animal- and plant-based proteins on a varying basis. One panelist does not eat animal-based protein at all and relies primarily on beans and tofu. Others consume meat without strong preference. One panelist noted a tendency toward a bean-based diet due to lower ingredient cost and relative convenience in preparation.

"Kind of 50-50 [between the choice of protein], but probably leaning more bean-based just because it's cheaper [and] much easier for me to prepare a lot of beans and freeze some, versus if I cook chicken, I'm only gonna eat that for 2 or 3 days before I feel uncomfortable eating it."

Regardless of protein preference, regular consumers demonstrated familiarity with and fondness for tofu, citing cultural familiarity, culinary versatility, its value as a protein source, and ease of preparation compared to many other beans. These insights suggest that convenience is a key factor in protein selection among regular consumers, and point to an opportunity for lima bean market expansion through processed formats similar to tofu.

"I don't really eat any chicken or beef or anything like that. I just don't like it. My first choice is beans and then tofu."

"My priority is animals, but when talking about plans, I would choose Tofu and other legume products compared to the whole meat. In my culture, you can play more dishes with [tofu]."

Non-Regular Consumers:

Similar to regular consumers, the majority of non-regular consumers were largely indifferent about choosing between animal- and plant-based protein, with those who were indifferent emphasizing that meeting their daily protein intake mattered more than the source.

"I don't think I think about protein. Do I have enough today or not? Essentially, a little bit of everything."

"I don't worry about it. As soon as I have protein, I'm good."

Some non-regular consumers reported choosing plant-based proteins more often due to lower cost, dislike of meat textures, and growing awareness of potential health concerns associated with animal-based proteins. Some panelists also noted feeling pressured to increase protein intake in response to social media messaging.

"I had things like beef, poultry, eggs and all that. But recently, I've been trying to shift towards more plant-based sources, because I have read things about health, [sustainability], and potential complication."

3.3.6. Comparison with Other Legumes

This section asked panelists about their consumption patterns for other legumes, with a focus on comparing benefits and suitability with lima beans.

Regular Consumers:

Panelists also regularly consume other legumes in various applications, such as lentil soup, split pea soup, and chickpeas. Regular consumers generally considered lima beans to be a suitable substitute for other legumes in most cases — for example, adding lima beans to a salad is largely interchangeable with adding other types of legumes. However, it was noted that certain dishes call for specific legumes for cultural reasons, making substitution inappropriate in those contexts.

"My partner is Turkish, and there's a dish that has white rice, chickpeas, and little, tiny broken pieces of pasta. It's already a perfect, complete combination for the context"

Others noted that the lima bean category spans too broad a range — from small, bitter beans to large, sweet ones — for all cultivars to be appropriate across different dishes. While this diversity presents opportunities for versatile application, careful matching of cultivar type and sensory qualities to specific dishes is necessary.

"Lima bean as a category is so broad. You have smaller, more bitter ones, you have larger, softer, more sweet ones ... they could be a substitute for other types of beans."

When choosing between lima beans and other legumes on a given day, consumers noted that they sometimes select lima beans to diversify their diet and avoid eating the same ingredients repeatedly. On the other hand, familiarity and clearer culinary associations often lead them to choose other legumes instead, such as black beans for tacos, burritos, or rice dishes.

Non-Regular Consumers:

Non-regular lima bean consumers still consume other legumes regularly, including black beans, white beans, lentils, pinto beans, and kidney beans. They demonstrated broad knowledge of how to cook and incorporate these into meals based on traditional and cultural dishes, family recipes, and online resources. Culinary applications ranged from savory dishes to sweet bean-based desserts.

"Bean stew (Misir Wot), it's just commonly done in my house. It's just something I observed from my parents. With lentils, which I eat often, I have discovered... Ethiopians eat a lot of lentils."

"I got that knowledge from my mom, and a lot of that stuff. And every once in a while, when I feel like exploring, I [would] look up a recipe on how can I make something different."

For non-regular consumers, legume purchase decisions were influenced by factors similar to those identified by regular consumers for lima beans — primarily price, nutritional value, and product familiarity. While some panelists preferred canned legumes for convenience, others favored dry legumes, citing better taste as the reason for avoiding canned products.

"I'd probably also go for cans, because soaking takes a while, unless I'm making hummus, then I culturally have to do it overnight."

"Such a better deal to get it dry. It's so much less expensive. I don't like the [taste of] canned beans."

One panelist noted that dietary restrictions within her household influence her purchase decisions. Selecting ingredients that are nutritious and adaptable to a range of dietary needs is especially important when a particular ingredient serves as a primary protein source for some household members.

"My grandma is vegetarian. When we're buying ingredients for the family, we try to incorporate a lot of things that we could use both in non-vegetarian and vegetarian dishes ... if you have someone that you know is vegetarian, factors into how many other things you're buying, because it's a main source of protein."

Based on their lima bean eating experience prior to the consumer test, non-regular consumers expressed generally positive attitudes toward lima beans as an inexpensive source of nutrition. However, while some saw potential for incorporating lima beans into their existing legume dishes as substitutes, others were less certain, citing the wide variety of flavors and colors as making lima beans feel too distinct from other legumes to integrate into familiar traditional dishes.

"They all tasted very unfamiliar, despite the fact I was used to eating beans since childhood ... I was drawn to lentils because they tasted similar to the kinds of beans I was eating, but I can't say the same [for] lima beans. I would eat the big, fat, white [lima beans] on its own, but in terms of incorporating it into what I'm used to, I don't think so."

3.3.7. Improving Lima Bean Consumption Going Forward

After sharing their dietary patterns, food choices, and perspectives on lima beans and other legumes, panelists were asked how the lima bean market could be advanced to increase consumption in the United States. They were also asked about their future interest in trying new cultivars and lima bean products.

Regular Consumers:

Regular consumers suggested that the lima bean market could be advanced through greater advertisement and product development. Consumers expressed interest in new product formats such as bean paste, chips, and fried lima bean snacks. Among various attributes, the color variety of lima bean cultivars was highlighted as visually interesting and fun. The market could leverage this characteristic by developing a mixed rainbow bag of lima beans, similar to microwavable mixed frozen vegetables. While some consumers raised concerns about varying cooking times across cultivars and bean sizes, they noted that conventional vegetable mixes contain pre-cooked pieces, allowing for uniform microwaving regardless of the ingredient.

"The rainbow bag would work. The mixes of carrots and peas have different cooking temperatures, but they're all pre-cooked and then packaged. They're packaged totally different colors, if they were all ready to go [by] heat up."

"People do really like novel foods, and lima beans have to go for the novel thing with the fun colors and tastes and difference, because it's just not a common bean in the stores like black beans and kidney beans. Having something that's kind of unusual, fun, colorful, different flavors, and different sizes is maybe the better strategy."

Product availability was raised as an area for improvement. While regular consumers know where to obtain lima beans, they are still unable to find the full range of cultivars they encountered in the consumer test and expressed strong interest in seeing the large green cultivar brought to market.

"Availability. Not everywhere has it. If there were more places, would be easier to use it"

"If they started selling the big green ones and actually carrying more varieties."

Regular consumers also expressed a desire for improved marketing around nutrition and health benefits. Beyond general product awareness, highlighting the specific health benefits of incorporating lima beans into daily meals — such as potential benefits for blood sugar management — could positively shift consumer perception.

"If substituting lima beans to a daily diet will help diabetes or general [health]. I know that people substitute different carbs than directly eating rice."

Lima beans may also benefit from rebranding their name. The term "butterbean," which reflects the buttery and creamy texture of the bean, was discussed as a potentially more appealing alternative. While many panelists were unaware that lima beans and butter beans refer to the same thing, they agreed that the latter name is more descriptive and appealing.

"['Butterbean' is] an awesome name for a bean, and I feel like it describes pretty well what it is. I didn't even know that lima beans and butter beans were the same thing until a couple months ago."

Non-Regular Consumers:

Many non-regular consumers indicated that greater market availability and knowledge of culinary applications would increase their lima bean consumption. Without widely accessible information, consumers are unlikely to seek out lima beans when more familiar legume options are already available. Promoting dishes that are specifically suited to lima beans could give consumers a targeted reason to purchase them.

"I'm happy to eat them, it's just a matter of the availability and knowing what to do with them."

"Preparations, dishes and recipes would be something beneficial to know a little bit more about ... I'm gonna buy [lima beans] because I want to prepare this particular soup, or this particular salad."

In addition to greater in-store visibility, non-regular consumers also indicated interest in convenient product formats such as precooked or canned options. They also saw potential for lima beans to expand into the snack aisle.

"If anything's precooked or canned, then I would definitely reach for it more."

"Not only seeing them in the bean aisle, but also for the snacks aisle expansions [may be feasible]."

Social media was identified as a promising channel for increasing familiarity and generating interest in lima beans, with panelists noting that viral content tends to drive product demand and retail availability.

"It would catch on with TikTok or Instagram videos, [teaching people] this is how you make it at home. All of a sudden, it's on the shelves. That's usually the trend for anything"

Overall, increasing consumer exposure to lima beans across multiple platforms — including social media, in-store promotion, and food events — was seen as critical. Panelists emphasized that direct eating experience is particularly important for product familiarization, as trying lima beans in a restaurant or at someone else's table may be a more effective introduction than online advertising alone.

"I discover lots of new foods when I eat out, and then I actually want to try this.

Assuming I had never participated in this study, [seeing] lima beans online, I wouldn't be willing to try it. But if I went to a restaurant and tried it, it would be good to start, or someone else cooking it and then you can try it yourself at home after you figure out that you actually like it."

Non-regular consumers also expressed interest in learning about the diverse sensory qualities across lima bean cultivars. While the variety was found exciting, the breadth of options can feel overwhelming for those unfamiliar with the ingredient. Panelists suggested that marketing which clearly communicates the distinct flavor profiles of individual cultivars could make it easier for consumers to engage and find an entry point into the category.

"If the marketing can intentionally explain what each type tastes like, what you can achieve ... it's overwhelming how there are just all these different cultures that taste very different. I think it would be nice if we could understand that this one tastes like butter, this one tastes like this."

"If there's something special about certain of the varieties, then gets popular, I can see people entering that way and then expanding from there."

3.4. Discussion

Regardless of the current consumption pattern, those who had eaten lima beans during childhood through family recipes and as part of their culture did not necessarily like their texture and taste. Children may reject food primarily based on sensory qualities such as bad taste, bad smell, and disliking of appearance across genders, whereas the primary reason for food acceptance may be good taste for boys and curiosity for girls ([Sick et al., 2019](#)). Lima beans may be disliked by populations including children due to some undesirable sensory qualities such as bitterness and off-flavors that are attributed to volatile and non-volatile chemical constituents ([Chigwedere et al., 2021](#); [Saffarionpour, 2023](#)). Furthermore, children's general preference for smooth and homogeneous texture and disliking of fibrous and granular texture may also explain their disliking of cooked beans ([Zeinstra et al., 2010](#); [Chow et al., 2022](#)). Thus, populations may have generally disliked lima beans during childhood because of the inherent sensory qualities in legumes, though this does not determine subsequent consumption behavior in adulthood.

As one of the regular consumers mentioned, children may overcome their food dislikes and rejection over the course of their development due to extrinsic factors. Repeated exposure to certain foods during childhood may build familiarity and a perception of safety as a child grows up ([Nekisting et al., 2018](#)). These exposures may include interaction with parents, school teachers, and peers, such that children are more likely to try unfamiliar foods after seeing their parents and peers trying or offering those products, suggesting the influence of social factors on food choice development ([Harper et al., 1975](#); [Duncker 1938](#)). Parents may also implement feeding strategies to familiarize their children with eating vegetables ([Birch, 1999](#); [Brug et al., 2008](#)). Nutritional education may positively affect children's food neophobic attitudes, thereby increasing children's understanding of food-body relationships and vegetable intake ([Labyak et](#)

[al., 2021](#); [Gripshover et al., 2013](#)). Older children are more likely to understand vegetables in a health and nutrition context than younger children, in addition to developing coping skills for eating vegetables ([Zeinstra et al., 2007](#)). Beyond taste, engaging with non-taste sensory stimuli (i.e., visual, smell, touch) through interaction with real fresh produce is also an effective approach to increase the likelihood of tasting fruits, vegetables, and other food products that may be unfamiliar to most children ([Dazeley et al., 2015](#); [Coulthard et al., 2017](#); [Roberts et al., 2022](#)). These studies suggest that children may acquire a taste for vegetables as they grow up when provided with appropriate guidance, and that people may build tolerance and preference for vegetables including lima beans through adaptation and social influence.

Non-regular consumers consistently mentioned the influence of cartoons and picture books on their negative impressions of lima beans, emphasizing the long-lasting effects on their perception of food safety. Food exposure through media may influence food acceptance in children. Reading picture books portraying a target vegetable with young toddlers significantly increased parental ratings for willingness to taste, frequency of consumption, and amount of intake for initially unfamiliar vegetables across multiple studies ([Heath et al., 2014](#); [Masento et al., 2023](#); [Owen et al., 2018](#)). Furthermore, there was a significant association between exposure to fruit and vegetable TV ads and reported intakes of those products among children in European countries ([Klepp et al., 2007](#)). At the current stage, however, the use of media on vegetables may require improvement, given that almost none of the TV ads focus on fruits or vegetables, while children between 2 and 17 years old in the US are exposed to 29 to 40 hours of food advertisements per year ([Gantz et al., 2007](#)). Moreover, vegetables were less likely to be depicted with positive affection among 48 “food-mention” books out of the 100 “Favorite Books for Preschoolers,” suggesting that children are less likely to be left with a positive impression of

vegetables ([Goldman et al., 2016](#)). While the literature is limited on the effects of negative food portrayals on consumption behavior, comments by non-regular consumers suggest that media may require more careful representation of commonly unfavored vegetables so as not to further deter children from consuming those products.

Regular consumers commonly commented on desirable characteristics of lima beans such as inexpensiveness, nutrition, and versatile sensory experiences. This positive attitude among regular consumers and the non-regular consumers' general familiarity with other kinds of legumes could be explained by the mere exposure effect, the psychological phenomenon defined by Zajonc as "repeated exposure to a stimulus object enhances the subjects attitudes toward it" ([Zajonc, 1968](#)). The appreciated characteristics are the known inherent benefits of legumes in general, including the nutrient quantity offered for cheap cost, potentially reducing risks of health related diseases ([Marventano et al., 2016](#); [Leterme et al., 2002](#); [Vaz Patto et al., 2014](#)). On the other hand, non-regular consumers mainly complained about the perceived unavailability of lima beans in the market, while lima beans may in fact be available at local groceries and specialty international markets, as regular consumers mentioned. The study on socioeconomic inequalities in food purchasing found an association between perceived food availability and the actual purchase of such food, indicating that lack of transparency in market availability may prevent people from consuming specific foods ([Giskes et al., 2007](#)). Since both groups similarly showed positive response to the cultivars tasted during consumer test, launching new consumer-focused cultivars with appropriate marketing may increase consumer population.

Lima beans were criticized for taking a long time to prepare by both regular and non-regular consumers, making them an unfavorable protein source when other convenient ingredients are already available. Overnight soaking prior to boiling is generally recommended

to allow water imbibition through the seed coat and to hydrate starch granules inside the cotyledon, which is followed by gelatinization and protein denaturation ([Fabbri et al., 2016](#); [Wood, 2017](#)). Cooking time may largely vary across legume species, cultivars and genotypes, often ranging between 10 to over 50 minutes, and it has been one of the constraints against consumer acceptance of legumes ([Wang et al., 2005](#); [Binagwa et al., 2020](#); [Carbonari et al., 2025](#)). College students and working professionals may be most impacted by these constraints, as coursework and other workloads may limit their time for meal planning and preparation ([Pelletier et al., 2012](#); [Jones et al., 2014](#)). Several studies report the potential genetic markers responsible for controlling the cooking time of legumes as potential targets for breeding of faster-cooking cultivars ([Cichy et al., 2015](#); [Jacinto-Hernandez et al., 2003](#)). Alternatively, the time constraints in consuming legumes may be alleviated by selling cooked lima beans in ready-to-eat formats including canned, microwavable frozen packs, and meal kits, lifting the preparation burden from consumers.

Neither regular nor non-regular consumers were strongly attached to either animal- or plant-based protein. Some panelists were slightly in favor of plant-based proteins for reasons of cost, convenience in batch preparation, and health. The growing and aging global population has directed attention toward plant-based protein as a sustainable and complementary counterpart to conventional animal-based protein ([Smith et al., 2024](#); [Ismail et al., 2020](#)). Plant-based proteins and related ingredients are widely recognized for benefits in environmental sustainability, lower energy and resource requirement for production, low cost, nutritional benefits, and culinary versatility ([Prasad et al., 2025](#); [Henchion et al., 2017](#); [Aimutis, 2022](#)). Interestingly, many regular consumers showed a preference for tofu as a plant-based ingredient in their regular meals, favoring it for its versatile application, familiarity, and convenience. Some studies have

successfully produced tofu with partial substitution by other legume species, indicating that lima beans could also be tested and familiarized with consumers through tofu ([Panyoyai, 2025](#); [Mohamed et al., 1989](#); [Jayasena et al., 2010](#)).

As much as both regular and non-regular consumers were interested in exploring new cultivars, they suggested that the lima bean market needs further expansion and greater accessibility. Given consumer demand for convenient legume preparation, lima beans in pre-cooked and ready-to-eat formats may save consumers time, physical effort, and mental effort, thereby making the product more appealing and accessible ([Wales, 2009](#); [Affrifah et al., 2023](#)). When marketing lima bean cultivars with varied sensory qualities, sensory wheels may be used as a visual aid to help consumers understand the flavor characteristics and culinary applications of specific cultivars ([Chigwedere et al., 2021](#)). In addition to repeated taste exposure through food stands, inducing repeated non-taste exposure through social media posts and digital tools with positive affection toward lima beans may be effective at increasing familiarity and likelihood of trying them ([Heath et al., 2011](#); [Edwards et al., 2022](#); [Farrow et al., 2019](#)). Alongside the breeding effort to curate consumer-centered sensory experiences, these strategies may work together to support familiarization, convenience, and guidance toward lima bean consumption for both regular and non-regular consumers.

Despite these discoveries, it is important to acknowledge the limitations inherent to the qualitative nature of focus groups. While the sessions uncovered opinions and insights that were not captured by the quantitative methods in previous chapters, these findings cannot be used to infer differences between populations — particularly given that each consumer group was represented by two sessions, whereas three or more replicate groups would be needed to assess the consistency of results. These findings should therefore be interpreted as generating

hypotheses rather than confirming them. Follow-up quantitative surveys, designed around the insights uncovered here, would allow for confirmatory testing. Additionally, future focus groups encompassing greater demographic diversity may further illuminate the conditions underlying lima bean consumption and avoidance.

3.5. Conclusion

This chapter investigated the qualitative opinions, perspectives, and insights on lima bean usage across regular and non-regular lima bean consumers through focus groups. There was a general consensus across both groups that the breeding effort for innovation of new cultivars with desirable sensory qualities is interesting to hear about and try. While people may learn to like lima beans over the course of their development through repeated exposure, exposure to media with negative portrayals of lima beans may influence their acceptance and consumption patterns afterward. There may be additional underlying obstacles for non-regular consumers related to perceived unavailability in the market, which may be addressed by making market information more transparent and accessible. Reducing cooking and preparation time may be the most appreciated improvement when successfully achieved, given the extra preparation effort required for cooking legumes and the time constraints faced by many students and working professionals. In response to the breeding effort for consumer-focused cultivars, future consumers may appreciate having a sensory wheel as a visual aid for understanding the sensory characteristics of different varieties. These findings may add valuable information to breeding efforts and marketing strategies for the further promotion of lima bean consumption across the U.S. by closing the conceptual gap between regular and non-regular lima bean consumers.

3.6. Reference

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Thesis Conclusion

In conclusion, this project provided a comprehensive quantitative and qualitative exploration of sensory characteristics and consumer experiences for succulent and dry lima bean cultivars in the context of plant breeding. Among the 35 succulent and 43 dry lima bean cultivars selected based on agronomic traits and commercial relevance, significant differences in attribute intensities were observed across 30 and 26 sensory attributes, respectively ($p < 0.05$). The sensory descriptors identified in both succulent and dry lima beans were consistent with those reported in other legume descriptive panels in the literature. PCA by individual sensory modalities revealed associations between product sensory profiles and seed phenotypes. Large- and medium-seeded cultivars were strongly associated with more complex flavor profiles and higher sweetness in both succulent and dry lima beans. Cultivars with darker or pigmented seed coats tended to score higher in dark flavor notes including kidney bean, earthy, and bitter, compared to white and green cultivars, which may be attributed to phenolic compounds contributing to bitterness. A major contrast between succulent and dry lima bean cultivars was observed in the relationship between texture and seed size — large succulent cultivars were associated with higher moistness, softness, and thinner seed coats, whereas this pattern was less consistent among large dry cultivars. While direct cross-comparison between the two studies was limited by inconsistent cultivar selection, these findings may suggest changes in the physicochemical composition of structural materials in lima bean seeds during maturation. Consumer testing further revealed the direction of consumer liking and disliking for lima beans. Among succulent samples, large and medium green beans were the most liked, associated with descriptors such as big, creamy, buttery, sweet, moist, and sweet green. Among dry lima beans, large white cultivars and some small white cultivars were most preferred, similarly associated

with big, sweet, buttery, creamy, moist, and sweet green descriptors. The overlap in preferred descriptors across both studies points to a consistent liking direction toward sweet, moist, creamy, and buttery characteristics, which are most commonly expressed in large and medium cultivars. Internal and external preference mapping further revealed consumer segmentation and differences in liking direction. The three consumer clusters from the succulent consumer test showed a consensual preference toward moist, soft, and sweet cultivars, with additional appreciation for buttery, corn, and edamame flavor notes. The two consumer clusters from the dry lima bean consumer test shared a common preference for moistness and sweetness, with Cluster 1 showing broader acceptance of diverse flavor profiles and stronger within-cluster consensus compared to Cluster 2. Across both studies, the preferred sensory attributes were most consistently expressed in large-seeded cultivars with seed coats that are not strongly pigmented by phenolics.

In addition to quantitative characterization, focus group discussions revealed underlying gaps between regular and non-regular lima bean consumers regarding awareness and knowledge of market availability. While both groups had prior exposure to lima beans, a notable difference was observed in their childhood impressions. Regular consumers tended to associate lima beans with nostalgia and nutritional appreciation developed through repeated exposure, whereas non-regular consumers reported negative associations influenced by cultural references such as cartoons and books portraying lima beans unfavorably. Both groups reported an improved impression of lima beans following the consumer test, suggesting that strategic repeated exposure may be an effective approach for increasing national consumption. Additional efforts may include transparent communication of product benefits and culinary applications, as well as promotion of the most favored cultivars identified through consumer testing.

Despite these findings, several limitations should be acknowledged. Logistical constraints limited descriptive analysis data collection to duplicate evaluations. For dry lima beans, a soaking time of 10 hours was used instead of 12 hours, which was the soaking time to establish the consistent cooking time by Mattson cooker. However, the preliminary informal comparison by the investigator indicated no substantial sensory difference between 10 hours and 12 hours soaking times. Descriptive evaluation was also conducted under standard lighting rather than red light due to booth availability and scheduling constraints. Sample selection was based on cultivar availability from collaborating breeders across the United States, and farming location and practices were treated as random sources of variation, though these factors are inherently tied to each cultivar. Finally, the negative R^2 - Q^2 gap observed in each external preference map indicates model overfitting and limited predictive ability beyond the current sample set. However, given that the primary scope of this study was exploratory — aimed at providing general direction for breeding decisions — the identification of consumer segments and shared preference directions is considered sufficient to meet the study objectives.

The findings from this project, spanning multiple sensory and consumer studies, offer meaningful depth of insight into consumer experiences with lima beans to inform next steps in breeding. The shared preference direction across consumer clusters in both succulent and dry lima bean studies toward large, white/green cultivars with moist, sweet, and soft characteristics provides practical guidance for accelerated breeding efforts targeting broader consumer acceptance. The qualitative findings from focus group discussions further suggest opportunities for more effective marketing and consumer communication strategies, particularly in promoting the positive sensory attributes of lima beans and facilitating increased consumer exposure through tasting experiences.

Future efforts may also consider physicochemical analyses to identify key compounds responsible for the preferred sensory attributes, and to relate these findings to genetic information for more targeted and efficient breeding. In summary, the sensory characterization and in-depth consumer investigation conducted across succulent and dry lima bean cultivars in this project contributed to a better understanding of sensory profiles, drivers of consumer preference, and qualitative considerations for promoting consumption — collectively advancing the foundation for improving national lima bean consumption.