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Sensory acceptance and biological implications of volatile compounds in Mexican soybean germplasm

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Abstract: Sensory acceptance and biological implications of volatile compounds in Mexican soybean germplasm. Introduction: The growing demand for healthy foods has increased interest in soybean products due to their high protein content and bioactive compounds. However, consumer acceptance of these products is limited by undesirable flavors, largely attributed to lipoxygenase activity. **Objective:** Identify the volatile compounds responsible for off-flavors in beverages derived from Mexican soybean germplasm and analyze their impact on both sensory attributes and the plant's biological characteristics. **Materials and methods:** Beverages from eleven Mexican soybean varieties with normal lipoxygenase activity, two Japanese lipoxygenase-free materials, and one commercial beverage were evaluated. Sensory tests were conducted with untrained panelists, and volatile compounds were identified through gas chromatography. **Results:** Sensory analysis revealed significant differences in taste, appearance, and overall acceptance. Huasteca 200, though not lipoxygenase-free, stood out for its high sensory acceptance. Gas chromatography revealed variations in volatile compounds, such as hexanal and 1-octen-3-ol, associated with bitter flavors and biological traits like pest resistance. **Conclusions:** Huasteca 200 proved to be a promising variety for genetic improvement programs due to its favorable sensory profile. Volatile compounds such as hexanal and 1-octen-3-ol play a critical role in flavor perception and reflect important biological aspects. These findings underscore the potential of genetic selection to optimize both sensory quality and biological resistance in future Mexican soybean varieties. **Arch Latinoam Nutr 2025; 75(2): 87-96.**

Keywords: volatile compounds, beany flavor, lipoxygenase.

Resumen: Efecto de los compuestos volátiles en la aceptación sensorial e implicaciones biológicas en germoplasma de soya mexicana. **Introducción:** La creciente demanda de alimentos saludables ha impulsado el interés en los productos de soya, valorados por su alto contenido proteico y compuestos bioactivos. Sin embargo, la aceptación de estos productos por parte de los consumidores se ve limitada por los sabores desagradables, en gran parte atribuidos a la actividad de las lipoxigenasas. **Objetivo:** Identificar los compuestos volátiles responsables de los sabores indeseables en bebidas derivadas de germoplasma de soya mexicana y analizar su impacto en los atributos sensoriales y biológicos de la planta. **Materiales y métodos:** Se evaluaron bebidas de once variedades de soya mexicana con actividad normal de lipoxigenasas, dos materiales japoneses libres de esta enzima, y una bebida comercial. Se realizaron pruebas sensoriales con panelistas no entrenados y se identificaron compuestos volátiles mediante cromatografía de gases. **Resultados:** Los análisis sensoriales revelaron diferencias significativas en sabor, apariencia y aceptación general. Huasteca 200, aunque no está libre de lipoxigenasas, destacó por su alta aceptación sensorial. La cromatografía de gases mostró variaciones en la concentración de volátiles, como hexanal y 1-octen-3-ol, relacionados con sabores amargos y con características biológicas como la resistencia a plagas. **Conclusiones:** Huasteca 200 demostró ser una variedad prometedora para programas de mejoramiento genético debido a su perfil sensorial favorable. Los compuestos volátiles, como hexanal y 1-octen-3-ol, juegan un papel crucial en la percepción del sabor y también reflejan aspectos clave del comportamiento biológico, lo que resalta el potencial de la selección genética para optimizar tanto los atributos sensoriales como la resistencia biológica. **Arch Latinoam Nutr 2025; 75(2): 87-96.**

Palabras clave: compuestos volátiles, sabor afrijolado, lipooxigenasa.

Introduction

The fast-paced nature of modern life has driven a growing demand for convenient foods rich in essential nutrients like proteins, vitamins, and

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bioactive compounds (1). Soybean [*Glycine max* (L.) Merr.], a leguminous crop, is a significant source of proteins and bioactive compounds, including isoflavones and phenols, which offer various health benefits (2). Products incorporating soybeans or fortified with soybean protein, such as soybean beverages, tofu, oil, and sauces, have become increasingly popular (3).

However, many soybean-based products suffer from undesirable flavors due to lipoxygenase enzymes in soybeans (4). These enzymes produce volatile compounds during grain milling, leading to beany flavors that affect consumer acceptance (5). Lipoxygenases oxidize polyunsaturated fatty acids, generating hydroperoxides that degrade into compounds like aldehydes, alcohols, ketones, and furans, responsible for off flavors described as beany, herbal, metallic, and sulfurous (6,7). Major contributors include hexanal, 1-octen-3-ol, and benzaldehyde (8-10).

To enhance consumer acceptance, soybean beverages are now made from grains with both natural and induced genetic modifications that eliminate the effects of lipoxygenases (11,12). In Mexico, commercial soybean production struggles to meet local demand, resulting in a high dependence on imports from the United States (13). So far, genetic improvement efforts in Mexico have focused on yield and other agronomic traits, neglecting the sensory attributes of derived products (14-16). Therefore, this study aims to analyze the volatile compounds associated with undesirable flavors in beverages made from a group of Mexican soybean germplasm and their implications for sensory acceptance and plant biology.

Materials and methods

Fourteen soybean beverages were analyzed, eleven from commercially cultivated soybeans in Mexico developed by the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Additionally, two materials provided by the National Institute of Agrobiological Sciences (NIAS) in Japan, reported as lipoxygenase-free (17) and a SILK® brand commercial soybean beverage produced in Mexico (Table 1).

Soybean beverages preparation and sensory acceptance test. The beverages were prepared by soaking 140 g of grins in deionized water overnight, draining, and blending with 1 L of purified water. The mixture was heated to boiling (100 °C), 1 g of salt was added, then cooled to room temperature. Maltodextrin (2 g), soybean lecithin (1.2 g), xanthan gum (0.4 g), sodium citrate (1.8 g), and calcium carbonate (3 g) were added as emulsifiers, stabilizers, and thickeners. The beverages were stored at 4 °C until analysis (18). In May 2023, the sensory acceptance test was carried out with 20 untrained panelists (50% male, 50% female, aged 25-57 years) in a quiet environment. A 9-point hedonic scale was used, interpreted as follows: 1= Disliked extremely, 5= Neither liked nor disliked, and 9= Liked extremely. Although larger panels are often recommended for population-

Table 1. List of soybean germplasm analysed.

Number	Material	Origin	Adaptation	Progeny
1	JP30790	USA	USA	Unknown
2	JP28955	USA	USA	Unknown
3	Vernal	Mexico	Tamaulipas state	D77-12244 × Bedford
4	Huasteca 100	Mexico	Tamaulipas state	Santa Rosa x Jupiter
5	Huasteca 200	Mexico	Tamaulipas state	F815344 x Santa Rosa
6	Huasteca 300	Mexico	Tamaulipas state	H82- 1930 x H80- 2535
7	Huasteca 400	Mexico	Tamaulipas state	DM 301 individual selection
8	Tamesi	Mexico	Tamaulipas state	Santa Rosa x H80-2535
9	Huasteca 600	Mexico	Tamaulipas state	H88-1880 x H88-3868
10	Huasteca 700	Mexico	Tamaulipas state	Santa Rosa x F81-5517
11	Nainari	Mexico	Sonora state	Derived from Suaqui 86 (irradiated with cobalt 60)
12	Suaqui 86	Mexico	Sonora state	(Rad x Cajeme) x (Tetabiate x Cajeme)
13	GuayparimeS-10	Mexico	Sonora state	Nainari x PI-171443

level inference, the use of 20 panelists is adequate for exploratory sensory studies under controlled conditions. This approach is supported by previous evaluations of soybean beverages using similar sample sizes (19, 20), and aligns with standard recommendations for academic sensory testing (21, 22). The 14 soybean beverages, including the commercial control, were evaluated across three sessions with rest intervals between them to prevent taste fatigue. Samples were served at room temperature. The methodologies followed were based on Ugochi *et al.* (19) and Alhendi *et al*. (20).

Identification of volatile compounds. In July 2023, the volatile compounds 1-hexanol, hexanal, 1-penten-3-ol, and 1-octen-3-ol were identified in a previously prepared soybean beverage without additives. The identification was conducted using reference standards from Sigma Aldrich (USA). The analysis was conducted through Gas Chromatography-Mass Spectrometry (GC-MS) following Solid Phase Extraction (SPE) with a C18 column, and molsin (*Aspergillus protease*) was employed during the process. First, the proteolysis of soybean beverage involved adding 0.25 g of molsin to 50 mL of beverage at pH 2.4-2.5 adjusted with 1 N HCl. Samples were then incubated at 30°C for 21 h to hydrolyze the proteins, centrifuged at 1000 rpm for 10 min, and filtered through Whatman #4 paper to obtain a clear filtrate. Then, the filtrate was injected into the solid-phase column at a flow rate of 0.6 mL min-1 and washed with 5 mL of distilled water. Compounds adsorbed in the column were eluted with 0.2 mL of methanol and subsequently with 2 mL of a hexane and diethyl ether mixture (3:1 v/v) at a flow rate of 0.6 mL min-1 (9).

2 μL of the eluted sample was injected into an Agilent technologies gas chromatograph (model 7890A), with an Agilent capillary column measuring 30 m in length x 0.250 mm in diameter (Scientific, USA). The column oven temperature was maintained at 70 °C for 10 min with an initial increase to 150 °C at a constant rate of 3 °C min-1, followed by a second increase to 220 °C at a constant rate of 20 °C min-1, and held at 220 °C for 5 min. The analytes eluted from the gas chromatography were detected using a flame ionization detector connected to a computer (9). To ensure identification of volatile compounds, chromatograph analysis results were compared with spectra of pure homologous compounds from the standard, matching retention times. For quantification, spectra were normalized, considering peak areas of all compounds, and expressed as a percentage (relative abundance) (23).

Statistical analysis. The results of the sensory analysis and volatile compounds underwent analysis of variance (ANOVA) and a Tukey test to identify differences among soybean beverages. A principal component analysis (PCA) was conducted to detect clusters and elucidate potential correlations between traits and soybean beverages (24). The analysis was performed using the statistical software InfoStat v 2020 (25).

Results

Sensory acceptance analysis. ANOVA analysis revealed highly significant differences ($p < 0.05$) in flavor, appearance, mouthfeel, and overall impression for the soybean beverages (Table 2). Tukey test comparisons indicated significant differences ($p < 0.05$) across all sensory traits. Notably, the control drink received the highest ratings across all analyzed traits. Among the Mexican beverage soybean varieties, the Huasteca 200 exhibiting higher average values in aroma, flavor, mouthfeel, and overall appearance, as well as exceptional average values in color and appearance (Table 3). The PCA analysis show that the first three principal components captured 99% of the total variation of the sensory acceptance traits. On the positive side of PC1 (85%) the control soybean beverage exhibited high association whit all six analyzed sensory acceptance traits. Conversely, on the negative side, beverages from varieties JP30790, Suaqui 86, Nainari, Huasteca 600, Huasteca 700, Huasteca 400, and Vernal were located, showed a low association with sensory acceptance attributes, resulting in decreased acceptance among the panelists.

In the center of the PCA biplot, a cluster of soybean beverages from varieties Huasteca 100, JP28955, Tamesí, Huasteca 300, and Guayparime S-10 was integrated. This group demonstrated intermediate association and values in sensory attributes, leading to moderate acceptance by the panelists. Notably, the soybean beverage from the variety Huasteca 200, positioned in the positive direction of PC1 and the negative direction of PC2, indicated a positive

Table 2. Analysis of variance of six sensory traits of acceptance in soybean beverage from Mexican commercial soybean germplasm.

Variety	Mean squares				p-value		
	Model	Soybean beverage	Panelist	Error	Model	Soybean beverage	Panelist
Aroma	359.1	54.7	304.4	1427.8	***	**	***
Color	475.9	52.6	423.3	1745.6	***	*	***
Taste	581.4	232.3	349.1	2985.6	***	***	***
Appearance	428.9	96.1	332.7	2104.1	***	***	***
Mouthfeel	682.1	205.1	477.1	2943.1	***	***	***
Overall acceptance	473.4	211.2	262.2	2554.1	***	***	***

*, **= significant difference; *** = highly significant difference.

Table 3. Comparison of the means of six sensory traits in soybean beverage from Mexican commercial soybean germplasm.

Variety	Means (p < 0.05)					
	Aroma	Color	Flavor	Appearance	Mouthfeel	Overall acceptance
Control	6.28±0.24[a]	6.83±0.08[a]	6.52±0.30[a]	6.93±0.10[a]	6.68±0.08[a]	6.72±0.12[a]
Huasteca 100	5.63±0.06[b]	6.20±0.41[b]	5.53±0.51[c]	6.05±0.28[b]	5.70±0.23[c]	5.77±0.33[c]
Huasteca 200	5.68±0.33[b]	6.30±0.41[b]	5.95±0.35[b]	6.17±0.48[b]	6.10±0.18[b]	6.17±0.33[b]
Huasteca 300	5.55±0.44[b]	6.35±0.45[b]	5.35±0.61[c]	6.22±0.32[b]	5.47±0.43[c]	5.55±0.54[c]
Huasteca 400	5.47±0.29[b]	5.82±1.00[b]	4.62±1.63[c]	5.37±1.16[b]	4.78±1.71[c]	4.77±1.33[c]
Tamesí	5.42±0.42[b]	6.43±0.29[b]	5.12±0.61[c]	6.25±0.40[b]	5.43±0.68[c]	5.48±0.56[c]
Huasteca 600	5.35±0.77[b]	6.38±0.74[b]	5.37±1.58[c]	6.12±0.92[b]	5.18±1.59[c]	5.50±1.34[c]
Huasteca 700	5.35±0.65[b]	5.97±0.70[b]	5.20±0.28[c]	5.83±0.51[b]	5.30±0.33[c]	5.32±0.28[c]
Suaqui 86	5.57±0.28[b]	6.25±0.78[b]	4.72±1.25[c]	5.90±0.83[b]	4.92±1.38[c]	5.00±1.15[c]
Nainari	5.55±0.44[b]	6.43±0.54[b]	4.70±0.58[c]	6.12±0.60[b]	5.08±0.67[c]	5.13±0.50[c]
Guayparime S-10	5.55±0.52[b]	6.43±0.45[b]	5.48±0.68[c]	6.13±0.16[b]	5.55±0.48[c]	5.55±0.63[c]
JP 28955	5.67±0.28[b]	6.55±0.35[b]	5.00±0.26[c]	6.08±0.15[b]	5.28±0.49[c]	5.37±0.55[c]
JP 30790	5.22±0.61[b]	6.10±0.58[b]	4.53±1.67[c]	5.85±0.68[b]	5.02±1.36[c]	4.95±1.39[c]
Vernal	5.20±0.87[b]	6.03±1.12[b]	4.88±2.25[c]	5.67±1.36[b]	4.92±2.23[c]	4.97±2.27[c]

Means with a common letter are not significantly different (p > 0.05)

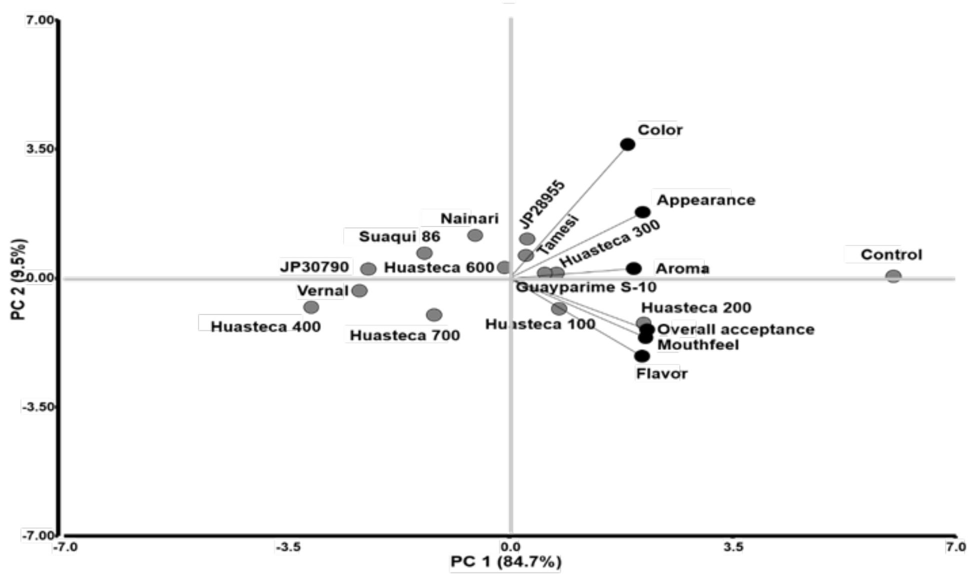

Figure 1. Biplot graphic depicting six sensory traits of acceptance in soybean beverage from Mexican commercial soybean germplasm.

association and high values in attributes such as aroma, overall acceptance, mouthfeel, and flavor, suggesting significant acceptance of these attributes among the panelists (Table 3, Figure 1).

Relative quantification of volatile compounds. Relative quantification of the volatile compounds hexanal, 1-octen-3-ol, 1-hexanol, and 1-penten-3-ol was achieved in eight Mexican soybean beverages, while it was not possible in five others. Hexanal and 1-octen-3-ol were undetectable in the beverages derived from Huasteca 100, Huasteca 200, Huasteca 300, Guayparime S-10, and JP30790. ANOVA revealed significant differences ($p < 0.05$) for hexanal, 1-octen-3-ol, and 1-hexanol among the Mexican soybean beverages (Table 4). Subsequent mean comparison using Tukey's test showed significant differences ($p < 0.05$) for hexanal and 1-octen-3-ol. The varieties Huasteca 600 and JP28955 exhibited the highest levels of these compounds and were significantly different from the other varieties (Table 5).

PCA facilitated the establishment of associations between identified volatile compounds and the analyzed population of Mexican soybean beverages. The biplot graph of PC1 explained 58% of the total

Table 4. Analysis of variance of volatile compounds identified in soybean beverage from Mexican commercial soybean germplasm.

Compound	Mean squares				p-value		
	Model	Variety	Repetition	Error	Model	Variety	Repetition
1-hexanol	299.99	291.08	8.91	195.11	ns	*	ns
1-penten-3-ol	73.14	69.08	4.06	73.49	ns	ns	ns
hexanal	139.74	135.78	3.96	34.02	**	***	ns
1-octen-3-ol	16.53	15.5	1.04	4.16	**	***	ns

ns= not significant; *,**= significant difference; *** = highly significant difference.

Table 5. Comparison of the means of four volatile compounds identified in soybean beverage from Mexican commercial soybean germplasm.

Variety	Means (p < 0.05)			
	1-hexanol	1-penten-3-ol	hexanal	1-octen-3-ol
Huasteca 400	90.7^{a}	6.2^{a}	2.9^{c}	0.11^{b}
Huasteca 600	97.4^{a}	0.9^{a}	1.5^{c}	0.08^{b}
Huasteca 700	87.2^{a}	3.5^{a}	8.9^{a}	0.43^{b}
Tamesí	93.7^{a}	3.2^{a}	2.9^{c}	0.10^{b}
Suaqui 86	97.4^{a}	0.7^{a}	1.8^{c}	0.04^{b}
Nainari	89.4^{a}	3.8^{a}	6.7^{b}	0.12^{b}
Vernal	93.6^{a}	1.3^{a}	4.0^{c}	1.12^{b}
JP28955	90.3^{a}	2.4^{a}	4.9^{c}	2.49^{a}
Huasteca 100+	-	-	-	ni
Huasteca 200+	-	-	-	ni
Huasteca 300+	-	-	ni	-
Guayparime S-10+	-	-	-	ni
JP30790+	-	-	ni	ni

ni= not identified; +=materials that were not included in the ANOVA and PCA. Means with a common letter are not significantly different (p > 0.05).

variance, with volatile compounds 1-hexanol and hexanal carrying the highest descriptive weight in PC1. This differentiation allowed for the distinction of varieties Huasteca 600 and Suaqui 86, characterized by high values in 1-hexanol, and the Huasteca 700 variety, exhibiting elevated values in hexanal. Orthogonality of PC2 described 29% of the explained variation in Mexican soybean beverages, with the volatile compounds 1-penten-3-ol and 1-octen-3-ol contributing significantly to the explained variation. This enabled differentiation of varieties with higher values in these volatile compounds, specifically Huasteca 400 and JP28955, respectively (Figure 2 and Table 2).

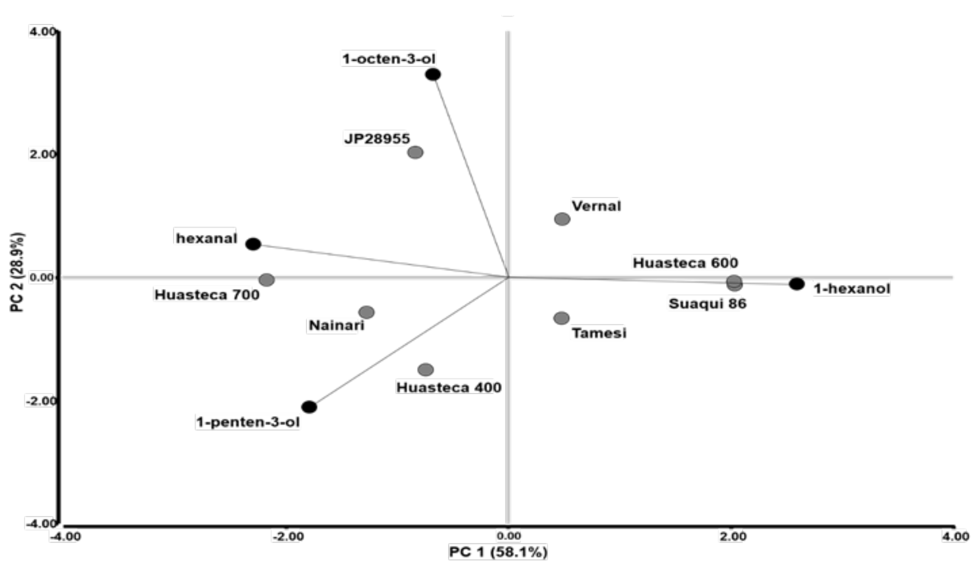

Figure 2. Biplot graphic illustrating the identified volatile compounds in soybean beverage from Mexican commercial soybean germplasm.

Discussion

Sensory analysis and volatile compounds in soybean beverages. The sensory analysis of soybean beverages derived from Mexican varieties revealed high ratings for visual attributes such as color, aroma, and appearance, although deficiencies were noted in flavor and mouthfeel. The Huasteca 200 variety stood out with a favorable sensory profile, comparable to the control beverage, possibly due to its volatile composition, particularly the presence of 1-hexanol and hexanal. Although Huasteca 200 showed higher relative sensory scores among Mexican varieties, its scores did not exceed the general acceptance threshold (>6), indicating the need for further improvement before being considered suitable for consumer markets. 1-hexanol was more abundant in all samples, while hexanal was absent in JP30790 and Huasteca 300, suggesting that 1-hexanol plays a significant role in the bitter taste of JP30790.

1-hexanol and other volatile alcohols, such as 1-penten-3-ol, seem to influence the sensory profile (26), even when lipoxygenase (LOX) activity is reduced or absent (27). This suggests the existence of other biochemical mechanisms modulating the production of these compounds, as evidenced by previous studies on the low genetic variation in the *Lox* 1, *Lox* 2, and *Lox* 3 genes in JP30790 (28). Although the absence of LOX activity was expected to mitigate undesirable flavors, this finding indicates that other genetic and molecular factors are involved in the generation of volatiles in soybeans.

1-penten-3-ol, a volatile compound derived from fatty acid hydroperoxides, also plays an important role in flavor (29-31). These hydroperoxides are generated from linoleic and linolenic acids, which are substrates for LOX enzymes. Both Huasteca 600 and Suaqui 86 showed lower relative abundances of 1-penten-3-ol and 1-octen-3-ol but higher levels of 1-hexanol, suggesting that fatty acid composition influences the production of volatiles and, consequently, the sensory profile.

Huasteca 600, although it presented an intermediate sensory profile, contains lower levels of linoleic and linolenic acids, which could explain the lower abundance of 1-penten-3-ol and 1-octen-3-ol compared to other varieties (32). While the fatty acid levels in Suaqui 86 are not fully defined, gas chromatography suggests that it may share this characteristic with Huasteca 600, contributing to the reduction of unpleasant flavors.

Genetic influence on volatile composition. The Huasteca 300 and Guayparime S-10 varieties presented three additional volatile compounds compared to JP30790, including 1-hexanol in both and hexanal in Guayparime S-10. These varieties showed higher sensory acceptance, likely linked to a nonsynonymous change in exon six of the *Lox* 2 gene, affecting the functionality of lipoxygenase 2 in the C/C homozygous genotype, thereby reducing the incidence of undesirable flavors (28).

Soybean beverages derived from Huasteca 100 and Huasteca 200 also stood out in sensory acceptance, with the notable presence of 1-octen-3-ol only detected in Huasteca 300. This highlights the complex interaction between volatiles and flavor perception. This compound was not detected in Guayparime S-10, Huasteca 100, Huasteca 200, or JP30790, which could be explained by genetic and environmental influences, as the production of 1-octen-3-ol is not directly dependent on LOX activity (29-31).

Relationship with pathogen resistance. Guayparime S-10 is the result of a cross between Nainari, which is tolerant to whiteflies (*Bemisia tabaci*), and PI-171443, which is resistant to geminivirus (16). The absence of 1-octen-3-ol in this variety coincides with the lack of pest stress, as in Nainari it has been observed that the production of this compound increases under stress conditions (33). The Huasteca 100 and Huasteca 200 varieties, which share Santa Rosa as a progenitor, also lacked 1-octen-3-ol. Santa Rosa is known for its resistance to frogeye leaf spot (*Cercospora sojina*) (14), suggesting a possible relationship between genetic resistance to pathogens and the absence of certain volatiles.

The case of JP28955 is particularly interesting, as despite being a null variety for LOX activity, it presented the highest relative abundance of 1-octen-3-ol. This finding contradicts the belief that lipoxygenases are the only pathway for the production of this compound, highlighting the need to explore alternative mechanisms for volatile biosynthesis.

Implications for genetic improvement. This study emphasizes the importance of understanding the relationships between soybean genetics, environmental conditions, and the presence of volatile compounds to optimize the sensory profile of soybean beverages. The absence of hexanal in certain varieties, such as JP30790 and Huasteca 300 (34-36), suggests that genetic improvement aimed at eliminating these compounds could be a viable approach to reduce undesirable flavors.

Varieties such as Guayparime S-10, which do not produce 1-octen-3-ol under low pest infestation conditions, offer a model for future research on the genetic and environmental interactions in volatile biosynthesis. Furthermore, variability in the production of 1-penten-3-ol, associated with fatty acid composition, underscores the potential to use genetic improvement tools to modify these volatile profiles and improve the sensory acceptance of soybean-based products. Although none of the samples achieved optimal hedonic values, Huasteca 200 demonstrated superior sensory characteristics within the evaluated Mexican germplasm. Additionally, the relative presence or absence of specific volatile compounds suggests potential genetic and biochemical pathways for improvement.

Finally, these results provide a baseline for future genetic improvement strategies targeting both sensory quality and biological resistance in Mexican soybean varieties, contributing to the development of products with greater market acceptance.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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