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Sensory and Consumer Sciences

Characterizing the Flavor of New Zealand Native Plants Using Consumer-Derived Attributes and Gas Chromatography–Mass Spectrometry

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ABSTRACT

Understanding the flavor properties of Aotearoa-New Zealand native plants is essential for their successful incorporation into foods and beverages. This study characterized the flavor of six edible plant species using consumer sensory evaluation and gas chromatography–mass spectrometry (GC–MS) of volatile compounds. Standardized liquid infusions were prepared for all species, and a lexicon of 21 flavor attributes was developed through six consumer focus groups ($n = 36$). A Rate-All-That-Apply (RATA) evaluation with consumers ($n = 121$) provided attribute intensity ratings and sample overall liking (9-point scale). Flavor attributes differed significantly across species. Kiokio received the highest liking (5.62), characterized by "sweet," "fruity," "fresh," and "floral" notes. Horopito followed (4.98), defined by "spicy" and "peppery" pungency. Scores below the scale midpoint were observed for Red matipo (4.56), dominated by "green tea" notes, and Kawakawa (4.47), associated with "herbal" and "minty" attributes. Lemonwood (2.52) and Pikopiko (2.59) were the least liked, driven primarily by intense "bitter" and "astringent" notes. GC–MS annotated 69 volatile compounds across species, of which a subset of 20, primarily terpenes and aldehydes, best explained variation in key flavor attributes (e.g., terpinen-4-ol and *trans*-calamenene for "spicy"). Generalized Procrusters Analysis revealed strong sensory–chemical alignment for Horopito, Kawakawa, and Red matipo, whereas Kiokio, Lemonwood, and Pikopiko showed weaker alignment, indicating that some major taste drivers arise from nonvolatile constituents. The findings provide foundational flavor characterization for New Zealand native plants and offer practical guidance for ingredient development, processing optimization, and formulation strategies to maximize consumer acceptance.

Practical Applications

The comprehensive flavor characterization, including sensory attributes and underlying volatile compounds, provides valuable data for the New Zealand food industry to strategically utilize these native plants. By identifying attributes that positively (e.g., Sweet, Fresh, Fruity) and negatively (e.g., Bitter, Astringent) influence consumer liking, product developers can tailor processing or formulations to optimize acceptability. Specifically, the dominance of Spicy/Peppery notes in Horopito and Sweet/Fruity notes

in Kiokio suggests clear paths for incorporation into novel food and beverage products, supporting the growth of a sustainable edible native plants industry led by Māori (indigenous people of Aotearoa-New Zealand) agribusiness.

1 | Introduction

In response to growing concerns about the environmental impacts of contemporary food systems, there is evidence that segments of consumers are actively seeking foods they perceive as more sustainable (von Meyer-Höfer et al. 2015), and market demand for products carrying sustainability-related attributes continues to increase (Lucas et al. 2021; Nes et al. 2024). "Sustainable foods" encompass a broad and heterogeneous set of product categories and attributes, ranging from production practices to naturalness and provenance (Van Bussel et al. 2022). One category attracting particular and increasing attention is edible native plants. Within this broader context, one area attracting particular attention is the use of natural plant-derived ingredients for flavoring, which aligns with clean-label trends and efforts to reduce reliance on synthetic additives. Consumers often perceive flavors obtained from botanicals or minimally processed plant extracts as more natural and environmentally compatible than synthetic flavorings, even when the underlying flavor molecules may be chemically identical (Aschemann-Witzel et al. 2019). Furthermore, research suggests that interest in edible native plants is emerging internationally (Chen and Qiu 2012; Schunko and Vogl 2020), driven by their association with naturalness, low-input production, and perceived environmental compatibility. In New Zealand, these trends intersect with a distinctive ecological context, where approximately 190 native plants are documented as edible (Crowe 1990) and are adapted to the country's unique environmental conditions (Wardle 1985). Several of these species were traditionally harvested and consumed by Māori, the indigenous people of Aotearoa-New Zealand, whose culinary practices reflect longstanding relationships with local flora (Roskruge 2012; Roskruge 2014). Renewed attention to native plants therefore offers not only environmental and economic potential but also cultural relevance and growing opportunities for Māori agribusiness. Despite this potential, most edible native plants in New Zealand are neither commercially cultivated nor widely available. A small number of companies have begun producing native plant ingredients and products, but the industry remains emerging and is predominantly centered on two species, Horopito (*Pseudowintera colorata*) and Kawakawa (*Piper excelsum*). Scaling this sector requires a deeper understanding of the key sensory attributes of native plants (flavor and aroma). Such knowledge would support optimization of growing and processing conditions to enhance ingredient quality, strengthen communication across the supply chain from production through formulation, processing and marketing, and enable the development of new products that align with consumer expectations and drive purchase intent.

A key limitation in the existing literature is the focus on odor alone. Hutchings et al. (2025) characterized the orthonasal odor of six edible native plants using a consumer-derived lexicon and gas chromatography–mass spectrometry (GC–MS) analysis of dried leaves. The evaluated species were Horopito, Kawakawa, Pikopiko (*Asplenium bulbiferum*), Red matipo (*Myrsine australis*), Kiokio (*Parablechnum novae-zelandiae*), and Lemonwood (*Pittosporum eugenioides*). The study identified 42 volatile compounds contributing to aroma and demonstrated that terpenoid-rich species such as Horopito and Kawakawa exhibited clear sensory–chemical alignment. However, the plants were not consumed when evaluating odor attributes, which represent a partial component of flavor perception arising from the integration of taste, retronasal aroma, and trigeminal sensations, some of which are driven by nonvolatile compounds (Taylor 2002). To date, no published work has established a sensory lexicon for describing the flavor of edible New Zealand native plants. Limited scientific research has characterized the sensory profiles of only few individual species, and there is no literature linking their sensory properties to consumer acceptability. For instance, Obst (2014) evaluated the sensory attributes of Kawakawa using a trained panel, while Torrico et al. (2023) used a consumer napping method to map aroma associations for Kawakawa, Lemonwood, Pikopiko, Kiokio, Red matipo, and Kanono. However, as in the study conducted by Hutchings et al. (2025), Torrico et al. (2023) focused only on olfactory perception, and participants did not consume the plants.

To ensure valid comparisons across species, standardized sample preparation is essential. Many edible native plants cannot be consumed raw or as whole leaves. Water-based extraction, therefore, represents the most appropriate method for sensory evaluation and aligns with current commercial formats for Kawakawa and Horopito teas (e.g., Oku 2024; Ti Ani 2024). A standardized infusion also enables meaningful comparisons of flavor intensity, chemical extraction patterns, and consumer liking across plant species with diverse morphologies and phytochemical profiles. In this context, the present research addresses a critical knowledge gap by evaluating flavor attributes, beyond just odor, across six edible New Zealand native plant species using liquid infusions prepared under controlled, standardized conditions. Thus, the objectives of this study were to: (1) develop a consumer-derived flavor lexicon for six New Zealand native edible plants; (2) characterize flavor profiles and liking of standardized liquid infusions using Rate-All-That-Apply (RATA) of sensory attributes with consumers; (3) profile volatile compounds using solid-phase microextraction (SPME)–GC–MS and identify volatiles associated with key sensory attributes; and (4) integrate sensory and chemical data to evaluate the correspondence between flavor perception and volatile composition and identify the flavor attributes that drive or reduce consumer liking. Combining consumer-led sensory profiling with volatile analysis provides a more complete understanding of the sensory drivers that influence acceptability and identifies the chemical compounds underpinning key flavor attributes, thereby informing the development of high-quality, commercially viable native plant ingredients and supporting the sustainable diversification of New Zealand's food system.

TABLE 1 | Species, source, and processing used to prepare liquid infusions in this study.

Species	Source within New Zealand	Date harvested	Process
Horopito (*Pseudowintera colorata*)	Supplied dehydrated by Karoo Ltd., Ruapehu region (ground, dried leaves)	March 2023	1. Boil dehydrated leaves at 100°C (2.5 g leaves/L) for 2 min 2. Sieve (0.6 mm) 3. Cool at 20°C, store in zip-lock bags, freeze (−18°C)
Kawakawa (*Piper excelsum*)	Foraged in the Manawatu region (fresh, whole leaves)	April 2023	1. Wash fresh leaves 2. Blend fresh leaves in a food processor 3. Boil leaves at 100°C (200 g leaves/L) for 2 min 4. Sieve (0.6 mm) 5. Cool at 20°C, store in zip-lock bags, freeze (−18°C)
Pikopiko (*Asplenium bulbiferum*)	Supplied by Karoo Ltd., Rotorua region (fresh, young furled shoots)	April 2023	1. Wash and remove leaves from shoot 2. Boil shoots for 30 min at 100°C (333 g/L) 3. Sieve (0.6 mm) 4. Cool at 20°C, store in zip-lock bags, freeze (−18°C)
Red matipo (*Myrsine australis*)	Foraged in the Manawatu region (fresh, whole leaves)	April 2023	1. Wash fresh leaves 2. Dehydrate at 35°C for 6 h 3. Blend fresh leaves in a food processor 4. Boil dried leaves at 100°C (10 g leaves/L) for 2 min 5. Sieve (0.6 mm) 6. Cool at 20°C, store in zip-lock bags, freeze (−18°C)
Kiokio (*Parablechnum novae-zelandiae*)	Foraged in the Manawatu region (fresh, young furled shoots)	April 2023	1. Wash and remove leaves from the shoot 2. Boil shoots for 30 min at 100°C (333 g/L) 3. Sieve (0.6 mm) 4. Cool at 20°C, store in zip-lock bags, freeze (−18°C)
Lemonwood (*Pittosporum eugenioides*)	Foraged in the Manawatu region (fresh, whole leaves)	April 2023	1. Wash fresh leaves 2. Blend fresh leaves in a food processor 3. Boil leaves at 100°C (100 g leaves/L) for 2 min 4. Sieve (0.6 mm) 5. Cool at 20°C, store in zip-lock bags, freeze (−18°C)

2 | Materials and Methods

2.1 | Sample Preparation and Presentation

Four species, Kawakawa, Red matipo, Kiokio, and Lemonwood, were foraged in the Manawatū region, New Zealand, in April 2023; whereas Horopito and Pikopiko were sourced commercially (Karoo Ltd.). Karoo Ltd. supplied Horopito foraged in the Ruapehu region (March 2023) and Pikopiko from the Rotorua region (April 2023).

To ensure a consistent basis for evaluating flavor among the six plant species, standardized liquid infusions (tea-like preparations) were prepared by boiling the edible part of the samples, either leaves or young curled shoots for a defined period (Table 1). Preparation parameters varied slightly between species, as each formulation was optimized, in consultation with development chefs from The Development Kitchen (TDK, Wellington, New Zealand), to achieve comparable flavor intensity across species while guaranteeing microbiological safety for sensory evaluation (Table 1). Because the six plant species differ markedly in intrinsic flavour intensity, pilot testing was conducted prior to the consumer study to minimize dominance effects during sensory evaluation. An in-house panel of four experienced sensory researchers evaluated the infusions and iteratively adjusted plant-to-water ratios until no sample was perceived as overpowering relative to the others. The objective was not to equalize intensity but to achieve balanced perceptual exposure across samples. Infusions were packed in flexible pouches and stored at −20°C for up to 2 months before sensory evaluation. Prior to sensory testing, all infusions were analyzed by an accredited microbiology laboratory to confirm microbial safety.

Packed infusions were thawed in water and served at 20°C. Samples were presented simultaneously as 15 mL portions in 30 mL plastic sampling cups labeled with three-digit random codes (Supporting Information Appendix A). Consumers were instructed to evaluate the samples following the order specified on their ballot and to verify each sample code before starting the assessment. Participants were also provided with a spit cup, allowing them to expectorate if desired.

2.2 | Ethical Approval

Ethical approval for this study was obtained from the Lincoln University Human Ethics Committee (Application No. HEC2022-39).

2.3 | Development of a Lexicon for Flavor

A flavor lexicon was developed through six consumer focus-group sessions, each comprising six participants (three females and three males) evaluating the six plant infusions, for a total of 36 consumers (18 females, 18 males). These sessions were the same as those reported by Hutchings et al. (2025), who used them to develop the odor lexicon, and flavor generation occurred concurrently within the same groups. Participants were staff and students based in the Te Rourou building at Massey University campus, Palmerston North, New Zealand.

Each session began with an overview of the project and a short introduction to descriptive analysis terminology, clarifying the difference between descriptive, hedonic, and intensity terms. Participants then tasted each infusion individually, listed all flavor descriptors they perceived, and subsequently discussed each sample as a group to capture additional attributes. A final lexicon was developed by evaluating the frequency of reported descriptors and consolidating similar terms based on consensus among the researchers, merging synonyms judged to describe the same sensory perception (Table 2).

2.4 | Rate-All-That-Apply Trial With Consumers

A total of 121 consumers participated in the RATA evaluation held at the RFH Building, Lincoln University, New Zealand. Recruitment and screening procedures followed those described by Hutchings et al. (2025), and participant demographics are summarized in Supporting Information Appendix B.

Following completion of a 15-min aroma RATA task (Hutchings et al. 2025) and an enforced 5-min break, participants completed the flavor RATA assessment described in this study. This exercise lasted approximately 25 min, and each participant evaluated all six infusions in each test.

The RATA session took place in isolated sensory booths, on touch screen tablets, using Red Jade sensory software (CA, USA). Sample order followed a balanced randomized design. Participants were asked to sip each sample and answer the RATA question for each attribute from the flavor lexicon (Table 2). For each infusion, participants were instructed: "Please taste the sample. Which of the following words describe this sample?" For every attribute selected, participants rated intensity on a 5-point scale (1 = slightly applicable, 5 = very applicable), consistent with the format of Ares et al. (2014). After the RATA exercise, consumers also evaluated the liking of each of the samples using a 9-point hedonic scale (Peryam and Pilgrim 1957). To minimize carry-over effects, participants were required to take a bite of water cracker and a sip of mineral water between samples. The temperature in the sensory booths was 21°C–22°C.

2.5 | Gas Chromatography–Mass Spectrometry

Volatile compounds from the liquid infusion samples were extracted by SPME and analyzed using GC–MS following the methods of Bovolenta et al. (2014) and Diez-Simon et al. (2019). For each plant species, five replicate samples (n = 5) were prepared by adding 0.5 mL of infusion to 9.5 mL of LCMS grade water (Merck Life Science Ltd., New Zealand). Each sample was added to a 20 mL headspace (HS) vial containing 1.0 g of sodium chloride (NaCl) to increase the partition coefficient of the volatile organic compounds (VOCs) (Bakierowska and Trzeszczyński 2004). 4-Methyl-2-pentanone ($C_6H_{12}O$; CAS no.: 108-10-1; Merck Life Science Ltd., New Zealand; 100 ppb in LCMS grade water) was added as an internal standard for monitoring run quality and data normalization. Samples were vortexed for 10 s and then loaded onto a vial rack. The blank comprised water (10 mL) replacing the infusion, with other components remaining the same.

Sample handling was performed using an AOC-5000 autosampler (PAL system, CTC Analytics AG, Switzerland). Each vial was heated at 40°C for 30 min while agitated at 500 rpm. A 2 cm, 50/30 µm film thickness DVB/Carboxen/PDMS Stableflex SPME Fiber (Supelco) was then inserted into each vial and exposed to the HS for 30 min without agitating. Analytes from the fiber were desorbed onto a GC column through a splitless injector at 240°C for 1 min, and subsequently maintained at a split ratio of 1:30. The fiber was removed from the injector after 20 min.

Chromatographic separation and compositional analysis of volatiles were performed using a Shimadzu gas chromatography system (QP-2010 Plus) in tandem with a mass spectrometer (TQ 8040), equipped with an SH-624 column (60 m, 0.32 mm i.d., 1.8 µm film thickness, Shimadzu, Japan). The carrier gas was helium (column flow rate of 3.09 mL/min). GC–MS was carried out using the following temperature program: initial temperature was set at 40°C and held for 2 min, followed by 5°C/min ramp to 120°C and held for 7 min, followed by 7°C/min ramp to 190°C and held for 9 min, followed by 10°C/min ramp to a final temperature of 220°C and held for 5 min. The injection temperature was set at 240°C. Detector parameters used for GC–MS analyses were as follows: interface temperature, 240°C; ion source temperature, 200°C; mass spectrometry was performed using Q3 scan with an m/z 35–350 scanning range. Chromatograms and mass spectra were evaluated using the LabSolutions software (Shimadzu, Japan).

TABLE 2 | Consumer-led flavor lexicon development for six selected New Zealand native plant species using six focus-group sessions with six consumers per session (total $n = 36$).

	Combining redundant terms and merging terms	Selected word	Frequency across all focus groups (total)
1	Bitter, medicine	Bitter	148
2	Spicy, spice, heat, hot, warm, chilli	Spicy	66
3	Peppery, pepper, black pepper	Peppery	41
4	Astringent	Astringent	34
5	Sour, tangy, sharp	Sour	31
6	Sweet	Sweet	25
7	Dry	Dry	21
8	Green tea	Green tea	19
9	Grassy, grass	Grassy	16
10	Tea, black tea	Black tea	15
11	Woody	Woody	12
12	Earthy	Earthy	11
13	Citrus, lemon	Citrus	10
14	Fresh	Fresh	9
15	Fruity	Fruity	8
16	Oily	Oily	8
17	Mint, minty	Minty	8
18	Floral	Floral	6
19	Metallic	Metallic	6
20	Ginger	Ginger	6
21	Herbal	Herbal	4

Post-run peak integration was automatically performed based on a slope of 750/min with 1000 min (T.DBL) accounting for drift in slope with time, 3 s peak width, and a minimum peak area of 5.0E4. Annotation was based on a minimum 90% similarity search with the Flavor and Fragrance Natural and Synthetic Compounds mass spectral database (FFNSC 1.3, Shimadzu, Japan). Peak intensity of VOCs was normalized to the corresponding peak intensity of the internal standard (×100 ppb).

2.6 | Data Analysis

2.6.1 | Consumer Study (RATA)

The RATA data were analyzed following the approach described by Meyners et al. (2016), where responses were treated as parametric data and a mean intensity score was calculated for each sensory attribute. Attributes not selected by a participant were assigned a value of zero. A mixed effects model was used with plant species as a fixed factor and consumer as a random effect, followed by Duncan's multiple range test to identify significant pairwise differences. Principal component analysis (PCA) was used to visualize relationships among flavor attributes and to illustrate the positioning of the six infusions within a common two-dimensional space. To explore the influence of specific flavor attributes on consumer liking, a penalty-lift analysis was carried out following the method of Varela and Ares (2014). In this analysis, RATA data were treated as binary (presence/absence), consistent with the Check-All-That-Apply (CATA) framework. All analyses were performed using XLSTAT software (Addinsoft, Paris, France).

2.6.2 | Volatile Compounds (GC–MS)

To identify volatile compounds associated with sensory attributes, a stepwise multiple regression analysis was conducted using the mean values per species for both chemical compounds and flavor attributes. The regression procedure applied entry and removal probabilities of PIN = 0.05 and POUT = 0.1, respectively, to generate a subset of volatile compounds most strongly linked to the sensory descriptors. A total of 20 volatile compounds (from an initial pool of 69 annotated compounds) were retained as the best predictors of the sensory data. Because stepwise regression is sensitive to multicollinearity (Chong and Jun 2005; Graham 2003), the discriminant ability of the selected compounds was further evaluated by one-way ANOVA, which confirmed significant differences among samples ($p < 0.01$). Pearson correlation coefficients were also calculated between volatile compounds and sensory attributes, with the highest correlations typically corresponding to the first compounds selected by the stepwise regression model. To assess overall correspondence between chemical and sensory datasets, the RV coefficient (Robert and Escoufier 1976) was calculated, providing a measure of matrix similarity and adequacy of variable selection. Finally, a Generalized Procrustes Analysis (GPA) (Dijksterhuis and Gower 1991; Seisonen et al. 2016) was performed using the mean sensory intensities (RATA) and mean relative intensities of the selected volatile compounds, allowing visualization of relationships between chemical composition and sensory perception. All statistical analyses were conducted using XLSTAT software, version 2021.1.1 (Addinsoft, Paris, France).

3 | Results and Discussion

3.1 | Overall Results and Discussion Across Species

3.1.1 | Flavor Lexicon Derived From Consumer Focus Groups

Consumer focus groups generated a broad set of descriptive terms for the six native plant infusions. After consolidating synonyms and removing redundancies, 21 flavor attributes formed the final lexicon (Table 2). "Bitter" was the most frequently cited descriptor (n = 148), indicating that bitterness was a dominant perceptual element across several species. This high frequency for a basic taste attribute highlights the critical role of taste perception in the flavor profile of liquid infusions compared to the odor-only assessment of dried leaves by Hutchings et al. (2025). "Spicy" (n = 66) and "Peppery" (n = 41) also appeared prominently, reflecting the characteristic pungency reported for plants such as Horopito and Kawakawa (Hutchings et al. 2025). A group of attributes associated with mouthfeel or trigeminal effects, "astringent" (n = 34) and "dry" (n = 21), was also repeatedly mentioned. Descriptors linked to vegetal or tea-like notes were common. These included "green tea" (n = 19), "grassy" (n = 16), and "black tea" (n = 15). Additional plant-derived terms such as "woody," "earthy," "herbal," and "citrus" were reported with moderate frequency, suggesting diverse botanical flavor notes among species. Less frequently mentioned, but still relevant, were "sweet" (n = 25), "fresh" (n = 9), and "fruity" (n = 8) attributes. A small group of terms related to specific aromatic nuances, such as "minty," "floral," "metallic," and "ginger," was retained due to their consistency across focus groups and their relevance for differentiating plant species. Overall, the lexicon reflects a combination of taste, aroma-derived flavor, and trigeminal sensations, capturing the sensory diversity of the selected native plants and providing the descriptive terms for the subsequent RATA evaluation by consumers.

3.1.2 | Flavor Intensity and Overall Liking Across Species

Table 3 and Figure 1 present the sensory characterization of the six evaluated plant species. Table 3 provides the mean intensity scores for flavor attributes and the overall consumer liking for the six liquid infusions, revealing significant differences ($p <$ 0.05) across the species for 19 of the 21 measured attributes. Only the attributes "dry" and "oily" did not exhibit significant differences across the species evaluated ($p >$ 0.05). "Bitter," "spicy," "peppery," and "herbal" consistently showed mean intensity scores above 2, and in some species above 3, on a 5-point scale. "Sweet," "green tea," "grassy," "fresh," "fruity," "minty," and "floral" attributes never exceeded a mean score of 2 in any species, while "sour," "earthy," "citrus," "metallic," and "ginger" remained below a mean intensity of 1 across all samples. The PCA biplot explaining 70% of the variation in the data, visually confirmed that the six species show highly differentiated flavor profiles (Figure 1). Overall liking also showed significant differences across all species in Table 3 ($p <$ 0.0001). In general, the liquid infusions were not highly liked, with all species receiving mean liking scores below 5 (neither like nor dislike) on the 9-point hedonic scale, except for Kiokio. These lower acceptability scores reflect the evaluation of plants as plain infusions prepared for sensory characterization, rather than as ingredients incorporated into familiar food matrices. The penalty-lift analysis quantifies the change in consumer liking when a specific flavor attribute is selected compared to when it is not selected, providing crucial insight into the drivers of acceptability among species (Figure 2). "Sweet," "fresh," "floral," and "fruity" notes had the highest positive influence on overall liking, while "bitter," "astringent," and "dry" attributes resulted in the greatest penalties, significantly reducing consumer acceptability of the liquid plant infusions.

3.1.3 | Integrated Sensory and Chemical Analyses

Stepwise multiple regression was performed using the mean volatile peak intensities and mean sensory attribute intensities to identify a shortlist of compounds most strongly associated with the sensory attributes (Table 4). It was found that several primary taste and fresh-related attributes, including "bitter," "astringent," "sour," "sweet," "dry," "fresh," "fruity," "oily," "floral," and "metallic," were not explained by the 20 selected volatile compounds, indicated by 0 in Table 4. This outcome confirms that some of these complex perceptions in the liquid infusions are governed by nonvolatile compounds, such as sugars, organic acids, and polyphenols, rather than the volatile compounds quantified by the GC–MS methodology (Yu et al. 2014), which supports the need for complementary phytochemical analysis in future studies. For the attributes that were explained by the volatile compounds, distinct relationships emerged between specific sensory perceptions and their chemical drivers. The pungent-related attributes showed strong correspondence with terpene-rich profiles. For example, the "spicy" flavor was primarily associated with terpinen-4-ol, a compound characterized by "earthy," "musty," "nutmeg," and "woody" notes, and with *trans*-calamenene described as "herb spice." The 20 volatile compounds identified through stepwise regression as key contributors to flavor attributes showed marked quantitative differences across the six native plant species for 19 compounds ($p <$ 0.0001), with the alkane *n*-nonane being the only exception (p = 0.167) (Table 5). These differences reinforce the sensory differentiation observed in the RATA and PCA analyses and highlight the distinct phytochemical signature that underlie each infusion's flavor profile. For example, species with pungent sensory profiles, including "spicy," "herbal," or "woody" notes, particularly Horopito and Kawakawa, were characterized by high levels of specific terpenoids. In contrast, species with more balanced or milder sensory profiles, such as Kiokio and Red

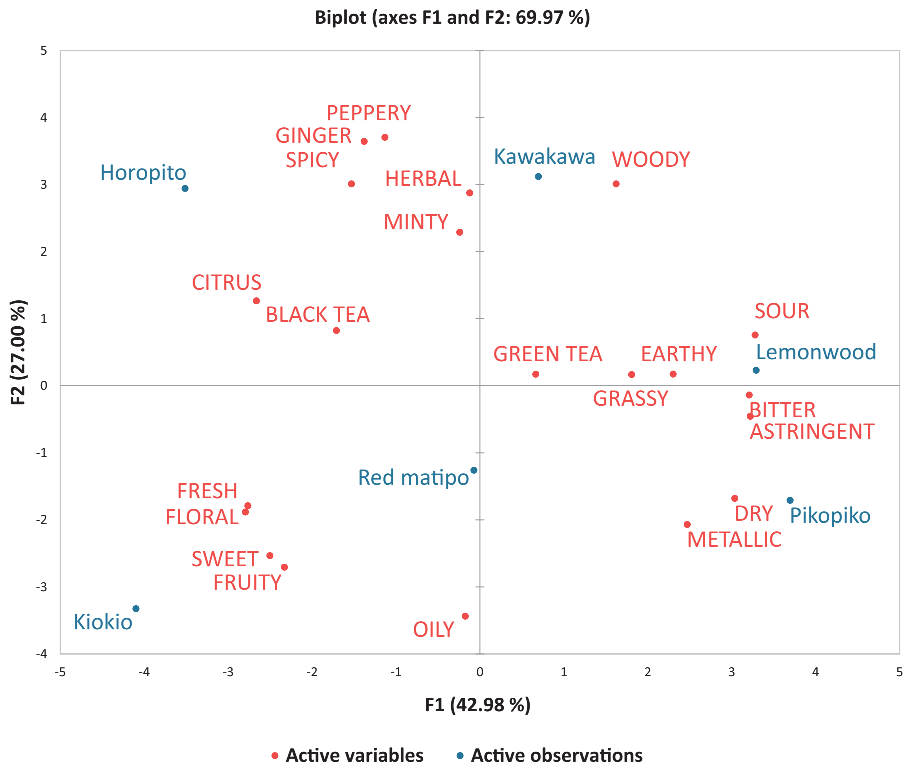

FIGURE 1 | Principal component analysis (PCA) biplot for consumer flavor attribute evaluation using Rate-All-That-Apply (RATA) for liquid infusions from six New Zealand native plant species. Blue, plant species; Red, flavor/taste attribute.

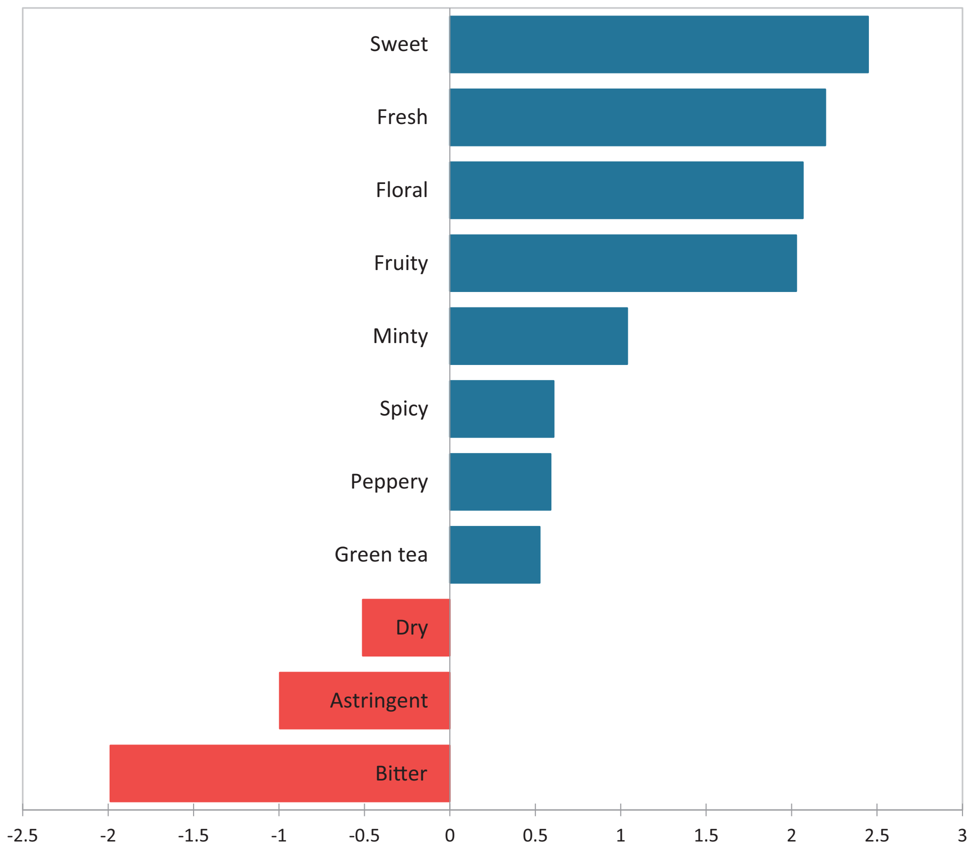

FIGURE 2 | Results of the penalty-lift analysis for liquid infusions from the six New Zealand native plant species for flavor attributes. The values indicate a change in liking when an attribute was ticked compared to when it was not ticked by panelists.

TABLE 3 | Flavor intensity (mean) and overall liking for liquid infusions across six New Zealand native plant species ($n = 121$).

	Kawakawa	Red matipo	Horopito	Lemonwood	Kiokio	Pikopiko	p value (two-way ANOVA)
Bitter	1.901c	1.256d	0.364e	3.876a	0.405e	3.273b	<0.0001
Spicy	0.810b	0.322c	2.959a	0.380c	0.132c	0.289c	<0.0001
Peppery	1.355b	0.455cd	2.545a	0.669c	0.107d	0.331cd	<0.0001
Astringent	0.669b	0.587b	0.331b	1.198a	0.355b	1.140a	<0.0001
Sour	0.322ab	0.248abc	0.149bc	0.455a	0.017c	0.455a	0.001
Sweet	0.107c	0.405b	0.314bc	0.058c	1.455a	0.066c	<0.0001
Dry	0.388	0.413	0.215	0.488	0.331	0.579	0.164
Green tea	0.884b	1.686a	0.388c	0.521c	0.231c	0.496c	<0.0001
Grassy	1.504ab	1.702a	0.165e	1.149bc	0.471de	0.835cd	<0.0001
Black tea	0.182b	0.231b	0.521a	0.421ab	0.372ab	0.182b	0.047
Woody	1.165a	0.430b	0.628b	0.975a	0.372b	0.603b	<0.0001
Earthy	0.967a	0.669ab	0.215c	0.777ab	0.504bc	0.686ab	0.000
Citrus	0.372a	0.322a	0.339a	0.083b	0.339a	0.041b	0.002
Fresh	0.463b	0.661b	0.479b	0.140c	1.182a	0.149c	<0.0001
Fruity	0.124c	0.529b	0.165c	0.025c	1.405a	0.017c	<0.0001
Oily	0.215	0.413	0.182	0.165	0.388	0.397	0.062
Minty	1.083a	0.190b	0.174b	0.033b	0.231b	0.066b	<0.0001
Floral	0.322bc	0.397bc	0.496b	0.174c	1.231a	0.140c	<0.0001
Metallic	0.157b	0.240b	0.132b	0.397b	0.240b	0.653a	0.000
Ginger	0.628a	0.124b	0.785a	0.066b	0.116b	0.124b	<0.0001
Herbal	2.273a	1.339b	1.223bc	1.025bc	0.959bc	0.826c	<0.0001
Liking	4.471c	4.562c	4.983b	2.521d	5.620a	2.587d	<0.0001

Note: Attribute intensity was measured using the RATA methodology (0–5 scale) while overall liking was measured using the 9-point hedonic scale. For each attribute, a two-way ANOVA was used to determine if a significant difference was observed across the six species. Pairwise comparisons were determined using Duncan's new multiple range test (different letters between pairs denote a significant difference of $p < 0.05$).

matipo, showed more moderate distributions of aldehydes and terpenes linked to "citrus," "floral," and "sweet" notes.

The GPA provided an integrated multivariate comparison of the sensory (RATA) and chemical (volatile) datasets, allowing a direct evaluation of how well the volatile profiles accounted for the flavor distinctions perceived by consumers (Figure 3). The GPA showed a close correspondence between the two datasets, indicating that the major sensory differences among the species are largely consistent with the chemical variation captured by the 20 selected volatile compounds. This overall agreement suggests that the volatile profile is an important driver of sensory differentiation, with species occupying similar regions in the sensory space tending to align closely in the chemical configuration. However, the degree of alignment was not uniform across species, and the residuals provide a clearer indication of the extent to which the chemical data reflected the sensory patterns of each species (Figures 3 and 4). Horopito, Kawakawa, and Red matipo showed the strongest agreement, with low Procrustes residuals indicating that their sensory profiles, driven by pungent, herbal, woody, citrus, or floral notes, were well explained by the selected volatile compounds. Kiokio and Lemonwood showed only partial alignment, as their aromatic cues were captured by the chemical data, but key taste attributes, particularly sweetness in Kiokio and bitterness or astringency in Lemonwood, were not explained by the volatile profiles. Pikopiko demonstrated the weakest correspondence, reflecting a flavor profile dominated by green, bitter, and astringent notes largely attributable to nonvolatile constituents. Overall, the GPA highlights that while volatiles account for much of the differentiation among species with strong aromatic signatures, species with milder, greener, or more taste-driven profiles require additional analysis of nonvolatile compounds to fully explain their sensory characteristics.

3.2 | Results and Discussion for Individual Species

The sensory and chemical results are discussed below for each species, ordered by their overall consumer liking, from highest to lowest (Table 3).

3.2.1 | Kiokio (*P. novae-zelandiae*)

Kiokio achieved the highest overall consumer liking mean score (5.62, Table 3) among the six plant species. Kiokio's desirable

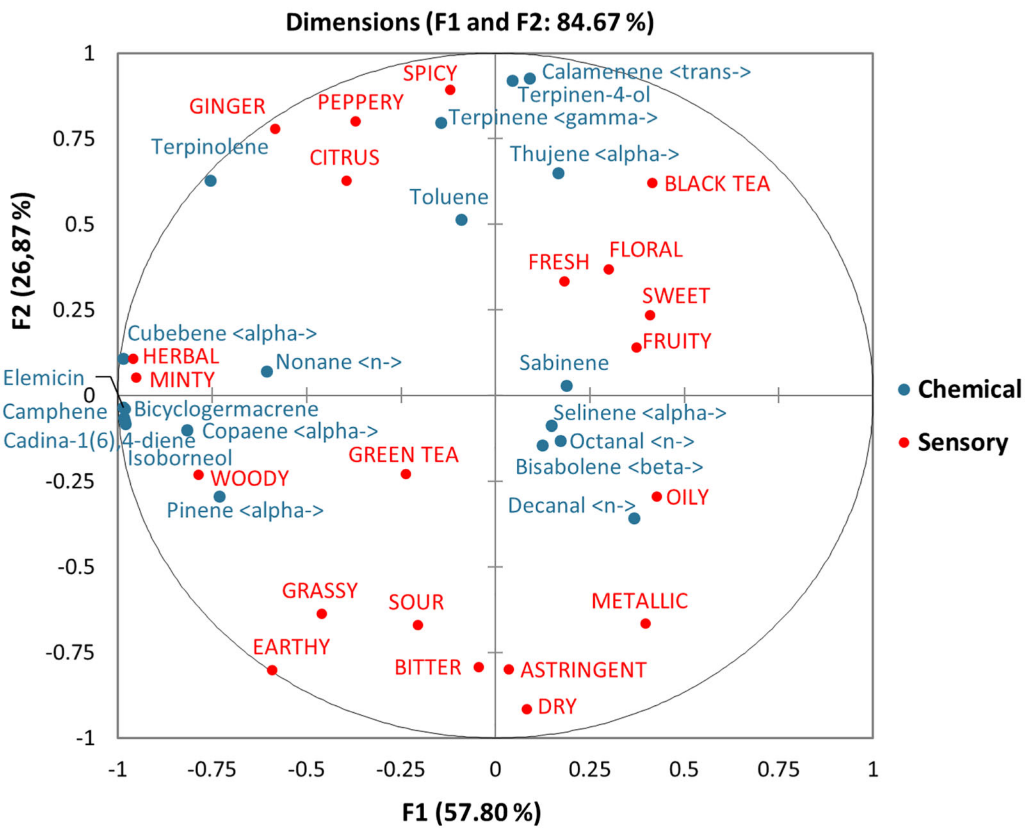

FIGURE 3 | Generalized Procrustes Analysis (GPA) plot linking the intensity of flavor attributes (RATA data) with peak intensity data of selected volatile compounds ($n = 20$).

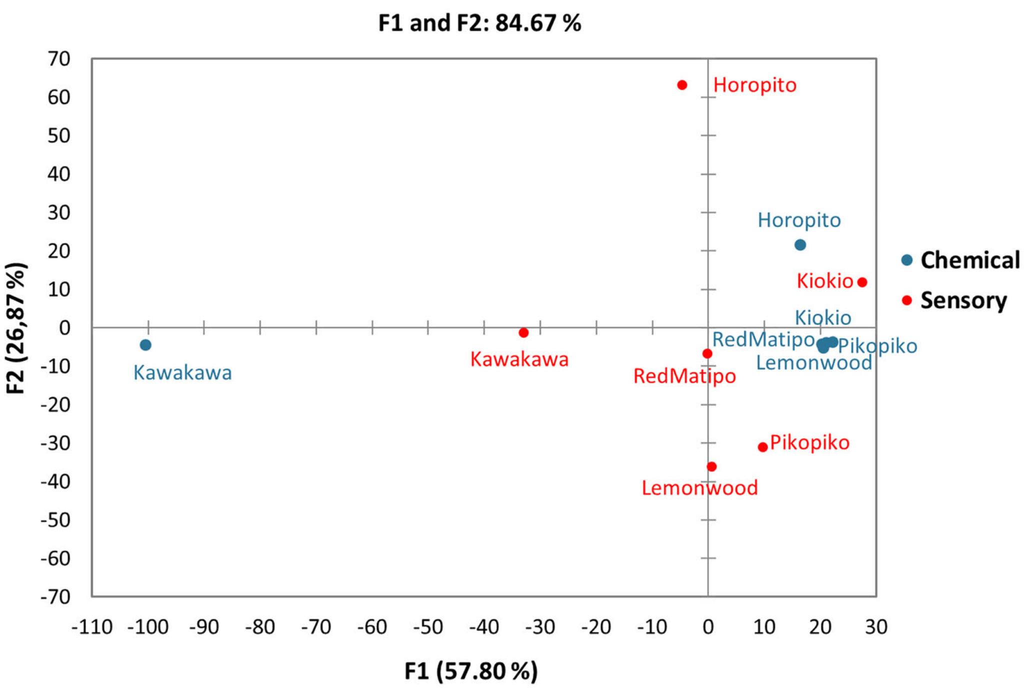

FIGURE 4 | Plot from GPA discriminating the six New Zealand native plant species based on flavor intensity data using RATA (sensory) and based on peak intensity data from selected volatile compounds (n =20) (chemical).

TABLE 4 | Volatile compounds ($n = 20$) that best explained each flavor attribute according to stepwise regression (probability for entry PIN = 0.05 and probability for removal POUT = 0.1), and corresponding flavor descriptor based on publicly available databases ([1]FEMA, [2]GoodScents).

Flavor/taste attribute	Selected volatile compounds	Flavor/taste descriptor
Bitter	0	—
Spicy	Terpinen-4-ol	Earth, must, nutmeg, wood[1]
	trans-calamenene	Herb spice[2]
Peppery	*gamma*-terpinene	Bitter, citrus[1]
	n-nonane	Gasoline[2]
	alpha-pinene	Cedarwood, pine, sharp[1]
Astringent	0	—
Sour	0	—
Sweet	0	—
Dry	0	—
Green tea	*beta*-bisabolene	Floral[1]
	n-octanal	Citrus, fat, green, oil, pungent[1]
	Sabinene	Woody[2]
	alpha-cubebene	Herbal, waxy[2]
Grassy	*alpha*-pinene>	Cedarwood, pine, sharp[1]
	Terpinolene	Pine[1]
Black tea	*alpha*-thujene	Woody, green, herbal[2]
Woody	Copaene <alpha->	Woody, spicy, honey[2]
Earthy	*trans*-calamenene	Herb spice[2]
	Terpinen-4-ol	Earth, must, nutmeg, wood[1]
	alpha-copaene	Woody, spicy, honey[2]
	Toluene	Sweet[2]
Citrus	Toluene	Sweet[2]
Fresh	0	—
Fruity	0	—
Oily	0	—
Minty	Cadina-1(6),4-diene	Woody[2]
	Bicyclogermacrene	Green, woody, weedy[2]
	n-decanal	Floral, fried, orange peel, penetrating, tallow[1]
	Isoborneol	Camphor, must[1]
Floral	0	—
Metallic	0	—
Ginger	Terpinolene	Pine[1]
	Camphene	Camphor, mothball, oil, warm[1]
	Elemicin	Spicy, floral[2]
Herbal	*alpha*-cubebene	Herbal, waxy[2]
	alpha-selinene	Amber[2]

flavor profile was characterized by the highest mean intensities for "sweet," "fruity," "floral," and "fresh," and low mean intensities for "bitter" and pungency ("spicy" and "peppery"). The "sweet," "fresh," "floral," and "fruity" attributes were identified by the penalty-lift analysis as having the greatest positive impact on overall liking (Figure 2). These findings align with reported consumer preferences for mild, low-bitterness herbal or tea infusions, where excessive bitterness and astringency reduce overall liking, and sweeter, smoother flavor profiles are preferred (Torrico et al. 2023; Wang et al. 2022; Yang and Lee 2020). PCA positioning (Figure 1) confirms that Kiokio lies away from clusters defined by pungent or bitter attributes, reinforcing its comparatively balanced sensory profile. These findings differ from the results of the previous odor study (Hutchings et al. 2025), where Kiokio was the second least liked odor and was associated with notes of "fishy," "earthy/musty," and "dry grass/hay," contributing negatively to consumer liking. Differences in sample form (dried vs. liquid infusion) may have contributed to these undesirable attributes, as drying can promote oxidative or degradative changes that generate off-notes not present in fresh material. The relative increase in consumer liking when transitioning from smelling the dried sample to tasting the liquid infusion further

TABLE 5 | Peak intensities (×100 ppb) of selected 20 volatile compounds across the six New Zealand native plants species.

Compound	Kawakawa	Red matipo	Horopito	Lemonwood	Kiokio	Pikopiko	Pr > *F* (model)	Pr > *F* (sample)
Alcohol								
Isoborneol	1.356a	0.128b	0.083b	0.101b	0.096b	0.120b	<0.0001	<0.0001
Terpinen-4-ol	1.731b	0.194b	37.187a	0.162b	0.138b	0.185b	<0.0001	<0.0001
Aldehyde								
Decanal <*n*->	0.053c	0.059c	0.045c	0.964a	0.673b	0.047c	<0.0001	<0.0001
Octanal <*n*->	0.040b	0.547a	0.045b	0.052b	0.053b	0.055b	<0.0001	<0.0001
Alkane								
Nonane <*n*->	1.952a	1.251a	0.932a	0.031a	1.006a	1.453a	0.167	0.167
Benzene								
Elemicin	181.218a	14.918b	19.693b	14.440b	12.924b	14.670b	<0.0001	<0.0001
Toluene	0.326b	0.669a	0.442ab	0.024c	0.326b	0.025c	<0.0001	<0.0001
Terpene								
Bicyclogermacrene	0.563a	0.042b	0.045b	0.053b	0.040b	0.040b	<0.0001	<0.0001
Bisabolene <beta->	1.085b	10.521a	0.686b	0.879b	0.773b	1.053b	<0.0001	<0.0001
Cadina-1(6),4-diene	1.863a	0.154b	0.165b	0.124b	0.146b	0.117b	<0.0001	<0.0001
Calamenene <*trans*->	0.671b	0.649b	7.441a	0.597b	0.843b	0.615b	<0.0001	<0.0001
Camphene	32.056a	0.107b	0.104b	1.034b	0.098b	0.081b	<0.0001	<0.0001
Copaene <alpha->	6.846a	0.129d	2.060c	4.741b	0.154d	0.172d	<0.0001	<0.0001
Cubebene <alpha->	23.786a	0.312c	4.665b	0.352c	0.420c	0.470c	<0.0001	<0.0001
Pinene <alpha->	14.552a	11.971b	0.406d	5.563c	0.497d	0.488d	<0.0001	<0.0001
Sabinene	0.087c	0.082c	1.039b	1.947a	0.077c	0.059c	<0.0001	<0.0001
Selinene <alpha->	0.976b	10.311a	1.152b	0.897b	1.101b	0.771b	<0.0001	<0.0001
Terpinene <gamma->	0.588b	0.063c	1.980a	0.659b	0.047c	0.049c	<0.0001	<0.0001
Terpinolene	0.607a	0.045b	0.543a	0.043b	0.051b	0.051b	<0.0001	<0.0001
Thujene <alpha->	0.058c	0.065c	1.368a	0.767b	0.057c	0.067c	<0.0001	<0.0001

Note: Values within a row followed by different letters differ significantly ($p < 0.05$).

indicates that the specific preparation method (boiling the young-furled shoots for 30 min) was critical. The boiling process likely extracted or concentrated desirable water-soluble nonvolatile flavor components, which subsequently mitigated or masked the negative volatile compounds responsible for the disliked raw odor.

Chemically, Kiokio showed moderate but broadly distributed volatile intensities rather than extreme peaks (Table 5). Aldehydes such as decanal and octanal were present, which can impart "green," "citrus," and "floral" notes that complement rather than dominate taste (González-Mas et al. 2019), consistent with the relatively low concentrations of most terpenes in this species. The GPA produced moderate residuals for Kiokio, indicating that while volatiles contribute to its flavor profile, nonvolatile taste-active compounds likely play an important role in enhancing palatability (Figures 3 and 4). Overall, Kiokio's higher consumer liking scores reflect a favorable balance of mild volatiles and low levels of strong negative taste drivers.

3.2.2 | Horopito (*P. colorata*)

Horopito received the second-highest liking score (4.98) and was rated significantly higher ($p < 0.0001$) than the other plant infusions except Kiokio. However, its mean score remained near the midpoint of the hedonic scale, indicating relative liking within the sample set rather than high consumer acceptance (Table 3). Horopito's flavor profile was strongly characterized by pungent, trigeminal sensations, showing the highest mean intensities for "spicy" and "peppery" attributes. Horopito also scored high for "ginger" and "black tea" and low for "bitter" relative to the other plant infusions (Table 3). PCA places Horopito within the sensory space highlighted by "spicy," "peppery," "ginger," "black tea," and "citrus" notes (Figure 1). Penalty analysis confirmed that both "spicy" and "peppery" attributes had a positive influence on Horopito's consumer liking (Figure 2), reflecting consumer preference for "peppery" and "spicy" sensations in some botanical infusions, also observed by Torrico et al. (2023). These results agree with those reported in the odor study by Hutchings et al. (2025), where Horopito was the most liked odor (mean score = 6.96) characterized by similar notes such as "peppery," "spicy," "herby," "minty," and "citrus." The mean liking score observed in this study (4.98), close to the midpoint of the hedonic scale, indicates that the flavor perception of plant infusions, while contributing positively, did not increase the acceptability beyond the odor of dried samples.

The flavor profile of Horopito was chemically underpinned by its high relative abundances of pungent volatiles, aligning with its popular recognition as New Zealand's "pepper tree" (Rasmussen 2014). Stepwise regression indicates that the "spicy" flavor was driven by terpinen-4-ol with reported descriptors as "earth," "must," "nutmeg," and "wood," and *trans*-calamenene described as "herb spice" (Table 4). The "peppery" attribute was associated with gamma-terpinene described as "bitter" and "citrus," *n*-nonane reported with "gasoline" descriptor, and alpha-pinene noted for its "cedarwood," "pine," and "sharp" flavor descriptors. Furthermore, the "ginger" attribute was driven by the terpenes terpinolene described as "pine" and camphene as "camphor" and "warm," and benzene elemicin described as "spicy"; while "black tea" was associated with the terpene alpha-thujene described as "woody," "green," and "herbal." GC–MS results in Table 5 confirmed that Horopito had the highest peak intensities for the alcohol terpinen-4-ol and the terpenes *trans*-calamenene and gamma-terpinene, high relative abundances for alpha-thujene and terpinolene, and moderate abundances for elemicin and camphene. The GPA yielded low residuals for Horopito, indicating strong agreement between its volatile profile and consumer flavor perception (Figures 3 and 4). Thus, in Horopito the flavor is largely volatile-driven, with terpenoid chemistry explaining both its characteristic peppery flavor and its perceived spiciness. From a product perspective, Horopito's pronounced terpenoid profile supports its use as a spice or condiment where pronounced pungency is desirable providing a clear pathway for commercial application. It is already incorporated into several New Zealand retail products, particularly spice blends and seasonings (e.g., Spicecraft 2025).

3.2.3 | Red Matipo (*M. australis*)

Red matipo ranked third in overall liking (4.56); however, the mean score remained below the hedonic scale midpoint, suggesting that consumer acceptance was limited and primarily relative to the lower-rated samples. Its flavor profile was dominated by "green tea" and "grassy" notes, alongside modest "fruity" and "floral" attributes and relatively low "bitter" intensity. These attributes collectively align with consumer-preferred characteristics in herbal beverages, where clean, mild, tea-like, and fresh notes are favored over strong bitter or trigeminal sensations (Lawless and Heymann 2010). The penalty-lift analysis supports this interpretation, showing that positive notes such as "fruity," "floral," and "green tea" increased consumer liking, whereas "bitter" consistently reduced it (Figure 2). Red matipo's balanced profile, combining positive flavor notes with low negative drivers, accounts for its higher acceptability relative to more bitter species. Multivariate analysis further supports these associations positioning Red Matipo near "green tea," "grassy," "fresh," "floral," and "fruity" descriptors (Figure 1). The predominance of "green tea" notes is notable given its traditional use in New Zealand as a minty, tart, and herbal tea (Crowe 1990). The infusion preparation used in the present study (boiling dried leaves for 2 min) appears to emphasize these mild, tea-like characteristics. These results are consistent with those of Hutchings et al. (2025), who found that Red matipo's odor was characterized by "sweet," "fruity," "sour," "leafy," and "green tea" notes. This contrasts with Torrico et al. (2023), who boiled, washed, and blended fresh leaves for 10 min and reported broccoli-, artichoke-, and oregano-like odors. These findings indicate that the processing method, plant state (fresh vs. dried), and heating time influence the release of volatile and nonvolatile constituents, with shorter infusion-style preparations from dried leaves favoring mild, tea-like flavors, while prolonged boiling of fresh material enhances vegetal and cooked-green notes.

The "green tea" flavor attribute was associated with beta-bisabolene, *n*-octanal, sabinene, and alpha-cubebene volatiles using stepwise regression (Table 4). Published flavor databases describe these compounds as contributing floral (β-bisabolene), citrus (octanal), woody (sabinene), and herbal (α-cubebene) notes. The "grassy" attribute was primarily associated with alpha-pinene and terpinolene compounds, which are characterized by "cedarwood" and "pine" descriptors. These associations are supported by GPA (Figure 3) and the low residuals (Figure 4), indicating a strong alignment between Red matipo's sensory and chemical profiles. Analysis of volatiles showed the highest relative abundance in Red matipo's infusions among the species for the terpenes beta-bisabolene and alpha-selinene and the aldehyde *n*-octanal (Table 5). Overall, Red matipo presents a balanced, tea-like flavor profile indicating good potential for use in infusions or blended formulations.

3.2.4 | Kawakawa (*P. excelsum*)

Kawakawa ranked fourth in overall consumer liking (mean 4.47) with similar ($p > 0.05$) scores to Red matipo infusion (Table 3). Its flavor was characterized by the highest mean intensity scores for "herbal" and "minty" attributes. It was also highly associated with "woody" and "ginger," and moderately with "peppery" and "bitter" notes. Penalty-lift analysis indicated that "minty" and "peppery" attributes contributed positively, whereas "bitter" contributed negatively to overall liking (Figure 2). The PCA positioned Kawakawa in an herbaceous and minty sensory region (Figure 1), consistent with its known phytochemical composition and traditional use as a strongly aromatic medicinal plant and tea (Butts et al. 2019). Kawakawa was the second most liked odor by consumers in the study by Hutchings et al. (2025) characterized by "sour," "sweet," "floral," and "fruity" notes, while Torrico et al. (2023) reported "vanilla-sweet," "fruity," and "mint" aroma attributes using the napping technique. These differences reflect variations in sample preparation (dried-leaf infusions vs. dried leaves and boiled fresh leaves), sensory method (flavor vs. odor-only evaluation), and perceptual context, with the current study emphasizing flavor attributes driven by retronasal aroma and taste, whereas the earlier studies captured primarily orthonasal aromatic qualities.

Stepwise regression identified the volatile compounds associated with its flavor descriptors highlighting alpha-cubebene ("herbal") and alpha-selinene ("amber") as the strongest contributors to the "herbal" attribute, while cadina-1(6),4-diene ("woody"), bicyclogermancrene ("green," "woody," and "weedy") and isoborneol ("camphor" and "must") contributed to "minty" sensations. "Woody" was associated with copaene described as "woody" and "spicy," and "ginger" with terpinolene, camphene, and elemicin characterized as "pine," "camphor," and "spicy," respectively. Kawakawa and Horopito showed the most distinctive volatile profiles among the six species. Notably, Kawakawa exhibited a terpene-dominant volatile profile relative to the other species, which likely underpins its pronounced aromatic complexity (Table 5). Key terpenoids included camphene, alpha-cubebene, alpha-pinene, alpha-copaene, and bicyclogermacrene; and the benzene derivative elemicin, a major Kawakawa metabolite (Jayaprakash et al. 2022). GPA results further confirmed low Procrustes residuals, indicating strong agreement between Kawakawa's chemical profile and its sensory perception (Figures 3 and 4). Overall, Kawakawa infusion is characterized by a terpene-rich volatile profile that drives its distinctive "herbal," "woody," "minty," and "ginger"-like sensations. While this accounts for its flavor identity and moderate acceptability, formulation strategies such as blending, sweetening, or pairing with other ingredients may help mitigate bitterness and enhance consumer appeal without compromising its characteristic herbal notes (Lawless and Heymann 2010).

3.2.5 | Pikopiko (*A. bulbiferum*)

Pikopiko was the second least liked species (2.59), uniquely characterized by having a significantly higher mean intensity for "metallic" flavor compared to all other species (Table 3). It also exhibited high mean intensities for "bitter" and "astringent," and the presence of "dry" notes. Consistent with the overall results, the penalty-lift analysis showed that "bitter," "astringent," and "dry" notes produced the largest negative hedonic penalties, directly explaining the low consumer liking scores (Figure 2). These results are aligned with previous studies. Pikopiko was the least liked odor in Hutchings et al. (2025), where it was associated with "fishy," "earthy/musty," "dusty," and "hay"-like notes. Similarly, Torrico et al. (2023) reported negative orthonasal descriptors, including "fishy," "algae/seaweed," and "spoiled-food" notes. Chemically, Pikopiko showed generally low peak intensities for the 20 selected volatiles by stepwise regression (Table 5) and lacked dominant terpenoid markers that characterized more liked species such as Horopito and Kawakawa. Several of Pikopiko's key negative sensory attributes, particularly "bitter," "astringent," "dry," and "metallic," were not explained by the 20 selected volatile compounds (Table 4), indicating a dominant role for nonvolatile taste-active compounds and other volatiles that were not captured among the HS–SPME–GC–MS volatiles. This mismatch yields the highest Procrustes residual in the GPA and indicates weaker correspondence between the measured volatiles and sensory perception, indicating that its flavor may be primarily taste-driven rather than aroma-driven (Figures 3 and 4). Traditionally, Pikopiko shoots are consumed cooked (peeled, steamed, boiled, or fried), processes that are likely to reduce "green," "bitter," and "metallic" notes through leaching, thermal degradation, or Maillard-derived masking effects. The results are consistent with other studies where leafy, chlorophyll-rich matrices generate strong green/astringent sensations that reduce acceptability unless mitigated by processing or formulation strategies that modulate their nonvolatile taste-active constituents (Deng et al. 2022).

3.2.6 | Lemonwood (*P. eugenioides*)

Lemonwood was the least liked species by consumers (2.52) with similar ($p > 0.05$) scores to Pikopiko infusion (Table 3). Lemonwood was defined by the highest mean intensity for "bitter," scoring significantly higher than all other species. It also shared the highest intensity score for "astringent" with Pikopiko, combined with moderate "woody" notes. Both "bitter" and "astringent" attributes were significant negative contributors to consumer liking, driving its low acceptance score (Figure 2). This pattern is consistent with well-established consumer aversion to strong bitter, astringent, and chlorophyll-derived notes in plant-based foods and beverages (Cavallo et al. 2019).

Similar to Pikopiko, the dominant negative sensory characteristics ("bitter" and "astringent") were not explained by the selected volatile compounds (Table 4). Lemonwood did, however, show the highest peak intensity for the aldehyde *n*-decanal and the terpene sabinene, along with the presence of other moderately abundant terpene compounds (byciclogermacrene, camphene, alpha-copaene, gamma-terpinene, thujene) (Table 5). Decanal has been described as "orange peel," while sabinene and the other terpenes as "woody."

Despite its characteristic lemony odor when fresh leaves were crushed, "citrus" flavor intensity in the infusion was extremely low. This discrepancy is consistent with the limited extraction of hydrophobic citrus aldehydes during short boiling times, as compounds such as decanal and octanal exhibit low water solubility and are prone to volatilization during heating (González-Mas et al. 2019). In the odor-only study using dried leaves, Hutchings et al. (2025) reported moderate liking (5.6) and described Lemonwood as mainly "leafy" and "grassy," with relatively low "citrus" odor intensity. In contrast, Torrico et al. (2023) observed distinctly "citrus" notes when using washed and blended fresh leaves boiled for 10 min, a method far more likely to release surface-bound essential oils and mechanically disrupt oil glands. These methodological differences, particularly the use of fresh versus dried leaves, greater tissue disruption, and longer heating, can explain why "citrus" odor was more pronounced in the study by Torrico et al. (2023) but minimally expressed in both the Hutchings et al. (2025) study and the present infusion-based flavor evaluation.

The shift from a moderately liked odor in the study by Hutchings et al. (2025) to a strongly disliked flavor in the present infusion study demonstrates that bitterness and astringency from nonvolatile constituents dominate the flavor experience, overriding the pleasant odor characteristics identified in the previous research. GPA residuals were moderate, indicating that while the volatile profile explains some aroma attributes ("woody" and "orange peel" notes), it fails to account for the major flavor drivers of consumer dislike (Figures 3 and 4). Overall, Lemonwood's intense bitterness and astringency make it poorly suited for consumption as a standalone infusion. However, its high decanal and sabinene abundance suggests potential value as a low-dose aromatic ingredient, for example, in blended teas, seasonings, or formulations where bitterness is intentionally balanced or masked.

4 | Conclusion

This research characterized the complex flavor profiles of six Aotearoa-New Zealand edible native plants, integrating consumer sensory data (RATA and overall liking) with GC–MS volatile analysis. The results are significant in establishing descriptive terms (lexicon) for the unique flavor of each species and the fundamental determinants of their flavor acceptance in a liquid infusion format. Volatile profiles, particularly terpenoids and aldehydes, were effective in discriminating among species with pronounced aromatic signatures, yet were insufficient to explain key flavor attributes such as bitterness, astringency, sweetness, and metallic notes. These findings underscore the need to integrate volatile and nonvolatile phytochemical data when characterizing botanical flavor systems and developing palatable native plant ingredients. Across species, consumer liking was primarily driven by "sweet," "fresh," "floral," and "fruity" notes, whereas "bitter," "astringent," and "dry" attributes reduced acceptance. These results emphasize that successful food applications will require tailoring extraction, formulation, and processing approaches to enhance desirable flavor-active volatiles and manage bitterness or astringency arising from nonvolatile compounds. Future research incorporating nonvolatile profiling and processing optimization will be essential for fully understanding and targeting the flavor drivers that support consumer acceptance and product innovation of New Zealand native plants.

Author Contributions

Carolina E. Realini: conceptualization, investigation, funding acquisition, writing – original draft, methodology, visualization, writing – review and editing, project administration, supervision, resources. **Santanu Deb-Choudhury**: investigation, writing – review and editing, methodology. **Arvind K. Subbaraj**: methodology, investigation, writing – review and editing, data curation. **Luis Guerrero**: formal analysis, writing – review and editing, conceptualization, methodology. **Damir D. Torrico**: conceptualization, investigation, methodology, writing – review and editing, supervision, resources. **Elizabeth E. Ham**: methodology, writing – review and editing. **Scott C. Hutchings**: conceptualization, investigation, methodology, data curation, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

Ares, G., F. Bruzzone, L. Vidal, et al. 2014. "Evaluation of a Rating-Based Variant of Check-All-That-Apply Questions: Rate-All-That-Apply (RATA)." *Food Quality and Preference* 36: 87–95. https://doi.org/10.1016/j.foodqual.2014.03.006.

Aschemann-Witzel, J., P. Varela, and A. O. Peschel. 2019. "Consumers' Categorization of Food Ingredients: Do Consumers Perceive Them as 'Clean Label' Producers Expect? An Exploration With Projective Mapping." *Food Quality and Preference* 71: 117–128. https://doi.org/10.1016/j.foodqual.2018.06.003.

Bakierowska, A.-M., and J. Trzeszczyński. 2004. "Dependence of the Water/Gas Partition Coefficient of Volatile Organic Compounds on the Ionic Strength of Sodium Chloride Solution." *Journal of Solution Chemistry* 33, no. 4: 329–338.

Bovolenta, S., A. Romanzin, M. Corazzin, et al. 2014. "Volatile Compounds and Sensory Properties of Montasio Cheese Made From the Milk of Simmental Cows Grazing on Alpine Pastures." *Journal of Dairy Science* 97, no. 12: 7373–7385.

Butts, C. A., J. W. Van Klink, N. I. Joyce, et al. 2019. "Composition and Safety Evaluation of Tea From New Zealand Kawakawa (*Piper excelsum*)." *Journal of Ethnopharmacology* 232: 110–118.

Cavallo, C., G. Cicia, T. Del Giudice, R. Sacchi, and R. Vecchio. 2019. "Consumers' Perceptions and Preferences for Bitterness in Vegetable Foods: The Case of Extra-Virgin Olive Oil and Brassicaceae—A Narrative Review." *Nutrients* 11, no. 5: 1164.

Chen, B., and Z. Qiu. 2012. "Consumers' Attitudes Towards Edible Wild Plants: A Case Study of Noto Peninsula, Ishikawa Prefecture, Japan." *International Journal of Forestry Research* 2012, no. 1: 872413.

Chong, I.-G., and C.-H. Jun. 2005. "Performance of Some Variable Selection Methods When Multicollinearity Is Present." *Chemometrics and Intelligent Laboratory Systems* 78, no. 1–2: 103–112.

Crowe, A. 1990. *Native Edible Plants of New Zealand*. Hodder and Stoughton.

Deng, S., G. Zhang, O. O. Aluko, et al. 2022. "Bitter and Astringent Substances in Green Tea: Composition, Human Perception Mechanisms, Evaluation Methods and Factors Influencing Their Formation." *Food Research International* 157: 111262.

Diez-Simon, C., R. Mumm, and R. D. Hall. 2019. "Mass Spectrometry-Based Metabolomics of Volatiles as a New Tool for Understanding Aroma and Flavour Chemistry in Processed Food Products." *Metabolomics* 15, no. 3: 41.

Dijksterhuis, G. B., and J. C. Gower. 1991. "The Interpretation of Generalized Procrustes Analysis and Allied Methods." *Food Quality and Preference* 3, no. 2: 67–87.

González-Mas, M. C., J. L. Rambla, M. P. López-Gresa, M. A. Blázquez, and A. Granell. 2019. "Volatile Compounds in Citrus Essential Oils: A Comprehensive Review." *Frontiers in Plant Science* 10: 12. https://doi.org/10.3389/fpls.2019.00012.

Graham, M. H. 2003. "Confronting Multicollinearity in Ecological Multiple Regression." *Ecology* 84, no. 11: 2809–2815.

Hutchings, S. C., S. Deb-Choudhury, A. K. Subbaraj, et al. 2025. "Characterizing the Odor of New Zealand Native Plants Using Sensory Analysis and Gas Chromatography–Mass Spectrometry." *Journal of Food Science* 90, no. 2: e70050.

Jayaprakash, R., F. Ramzan, J. Miles-Chan, M. Foster, R. Mithen, and C. Pook. 2022. "Exploring the Chemical Space of Kawakawa Leaf (*Piper excelsum*)." *Nutrients* 14, no. 23: 5168.

Lawless, H. T., and H. Heymann. 2010. *Sensory Evaluation of Food: Principles and Practices*. 2nd ed. Springer.

Lucas, S., L.-G. Soler, and C. Revoredo-Giha. 2021. "Trend Analysis of Sustainability Claims: The European Fisheries and Aquaculture Markets Case." *Food Policy* 104: 102141.

Meyners, M., S. R. Jaeger, and G. Ares. 2016. "On the Analysis of Rate-All-That-Apply (RATA) Data." *Food Quality and Preference* 49: 1–10.

Nes, K., F. Antonioli, and P. Ciaian. 2024. "Trends in Sustainability Claims and Labels for Newly Introduced Food Products Across Selected European Countries." *Agribusiness* 40, no. 2: 371–390.

Obst, K. 2014. "Phytochemical Characterization and Sensory Evaluation of Macropiper Excelsum." PhD diss., Technische Universität München.

Oku. 2024. "Kawakawa Teas. New Zealand". https://oku.co.nz/.

Peryam, D. R., and F. J. Pilgrim. 1957. "Hedonic Scale Method of Measuring Food Preferences." *Food technology* 11: 9–14.

Rasmussen, P. 2014. "*Pseudowintera* spp. (Horopito): A Monograph." *Australian Journal of Herbal Medicine* 26, no. 4: 150–154. https://search.informit.org/doi/abs/10.3316/informit.834580598794982.

Robert, P., and Y. Escoufier. 1976. "A Unifying Tool for Linear Multivariate Statistical Methods: The RV-Coefficient." *Journal of the Royal Statistical Society Series C: Applied Statistics* 25, no. 3: 257–265.

Roskruge, N. 2012. *Tahua-Roa: Food for Your Visitors: Korare, Maori Green Vegetables Their History and Tips on Their Use*. Institute of Natural Resources, Massey University.

Roskruge, N. 2014. *Rauwaru, the Proverbial Garden: Ngā-Weri, Māori Root Vegetables, Their History and Tips on Their Use*. Institute of Agriculture and Environment, Massey University.

Schunko, C., and C. R. Vogl. 2020. "Factors Determining Organic Consumers' Knowledge and Practices With Respect to Wild Plant Foods: A Countrywide Study in Austria." *Food Quality and Preference* 82: 103868.

Seisonen, S., K. Vene, and K. Koppel. 2016. "The Current Practice in the Application of Chemometrics for Correlation of Sensory and Gas Chromatographic Data." *Food Chemistry* 210: 530–540.

Spicecraft. 2025. "Kiwi Rub Seasoning." https://www.spicecraft.co.nz/products/kiwi-rubseasoning.

Taylor, A. J. 2002. "Release and Transport of Flavors in Vivo: Physicochemical, Physiological, and Perceptual Considerations." *Comprehensive Reviews in Food Science and Food Safety* 1, no. 2: 45–57.

Ti Ani. 2024. "Wild-Harvested Mountain Horopito Tea." https://tiani.co.nz/products/wild-harvested-mountain-horopito-tea.

Torrico, D. D., X. Nie, D. Lukito, S. Deb-Choudhury, S. C. Hutchings, and C. E. Realini. 2023. "Consumer Attitudes and Acceptability Toward Edible New Zealand Native Plants." *Sustainability* 15, no. 15: 11592. https://www.mdpi.com/2071-1050/15/15/11592.

Van Bussel, L. M., A. Kuijsten, M. Mars, and P. Van't Veer. 2022. "Consumers' Perceptions on Food-Related Sustainability: A Systematic Review." *Journal of Cleaner Production* 341: 130904.

Varela, P., and G. Ares. 2014. *Novel Techniques in Sensory Characterization and Consumer Profiling*. CRC Press.

von Meyer-Höfer, M., V. von der Wense, and A. Spiller. 2015. "Characterising Convinced Sustainable Food Consumers." *British Food Journal* 117, no. 3: 1082–1104.

Wang, C. M., X. Du, C. N. Nie, X. Zhang, X. Q. Tan, and Q. Li. 2022. "Evaluation of Sensory and Safety Quality Characteristics of "High Mountain Tea"." *Food Science & Nutrition* 10, no. 10: 3338–3354. https://doi.org/10.1002/fsn3.2923.

Wardle, P. 1985. "Environmental Influences on the Vegetation of New Zealand." *New Zealand Journal of Botany* 23, no. 4: 773–788.

Yang, J. E., and J. Lee. 2020. "Consumer Perception and Liking, and Sensory Characteristics of Blended Teas." *Food Science and Biotechnology* 29, no. 1: 63–74. https://doi.org/10.1007/s10068-019-00643-3.

Yu, P., A. S. L. Yeo, M. Y. Low, and W. Zhou. 2014. "Identifying Key Non-Volatile Compounds in Ready-to-Drink Green Tea and Their Impact on Taste Profile." *Food Chemistry* 155: 9–16. https://doi.org/10.1016/j.foodchem.2014.01.046.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: jfds70956-sup-0001-SuppMat.docx