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Human Perception-Calibrated Electronic Tongue for Quantitative Bitterness Prediction and Characterization of Sucrose-Induced Sensor Response Modulation

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Abstract

Electronic tongue signals can provide objective measures of taste-related responses, but their quantitative correspondence with human perceptual intensity remains insufficiently characterized. This study developed a psychophysically calibrated electronic tongue framework for quantitative bitterness evaluation and sucrose-induced sensor response modulation. Concentration-dependent responses to quinine hydrochloride, berberine hydrochloride, and iso-α-acid followed logarithmic relationships, with coefficients of determination of 0.983, 0.910, and 0.984, respectively. By integrating these instrumental relationships with psychophysically derived sensory bitterness references, compound-specific conversion models were established to translate electronic tongue signals into psychophysically derived bitterness reference values. Validation using additional electronic tongue measurements yielded mean absolute percentage errors of 6.02%, 10.76%, and 7.14%, respectively. Electronic tongue responses to the three bitter compounds exhibited varying trends under 0%, 2%, and 8% sucrose backgrounds, suggesting compound-dependent effects of sucrose on sensor responses. The proposed framework provides a quantitative link between electronic tongue responses and psychophysically derived bitterness reference values, with potential applications in sucrose-containing systems.

Keywords: electronic tongue; bitterness perception; psychophysics; sensory–instrumental calibration; sweetness–bitterness interaction

1. Introduction

Bitterness is one of the five basic taste modalities and plays an important role in food perception, dietary behavior, and the recognition of potentially harmful substances [1]. In foods, functional products, and oral pharmaceuticals, however, excessive bitterness is often associated with reduced palatability and consumer acceptance, making effective bitterness evaluation and control important for product development and optimization [2]. Importantly, bitterness is ultimately a perceptual response rather than a direct reflection of bitter compound concentration [3]. Human sensitivity to bitter compounds varies considerably across substances and follows characteristic psychophysical processes, from initial detection at the sensory threshold to discrimination of concentration differences and subsequent changes in suprathreshold intensity [4]. Consequently, the same change in chemical concentration may not necessarily produce an equivalent change in perceived bitterness [5].

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Accurate characterization of bitterness therefore requires quantitative assessment of human perceptual intensity, providing a sensory-relevant basis for bitterness evaluation, formulation optimization, and the development of objective taste assessment approaches [6].

Human sensory evaluation remains the most direct approach for assessing bitterness, as it captures the perceptual response elicited by bitter stimuli [7]. Sensory and psychophysical methods, including threshold determination, difference testing, and intensity scaling, have been widely used to characterize bitterness sensitivity and quantify perceived intensity [8,9]. However, sensory evaluation is inherently influenced by individual variability and panel performance and generally requires trained assessors, standardized procedures, and substantial time, which can limit its efficiency for routine or high-throughput applications. Complementary objective approaches have therefore been developed, including chemical analysis [10], receptor- or cell-based assays [11], and various taste-sensing technologies [12]. These methods can provide reproducible information on bitter compounds or their biological and physicochemical responses, but the measured outputs are not necessarily equivalent to perceived bitterness intensity [13]. Consequently, there remains a need for objective and efficient approaches that can not only characterize bitterness-related responses but also provide quantitative information that is meaningfully linked to human perception.

Among the instrumental approaches developed for taste evaluation, electronic tongues have attracted considerable attention because of their rapid response [14], good reproducibility, and potential for objective and high-throughput analysis [15]. Inspired by the human gustatory system, electronic tongues employ arrays of cross-sensitive sensors to characterize taste-related physicochemical information and have been extensively applied to the evaluation of basic tastes, food products, pharmaceuticals, and taste-masking formulations. In particular, potentiometric taste-sensing systems based on lipid/polymer membranes can selectively respond to different taste qualities through changes in membrane potential resulting from electrostatic and hydrophobic interactions between taste compounds and sensing membranes [16]. For bitterness evaluation, sensor responses associated with the adsorption of bitter compounds have shown concentration-dependent characteristics and have been used to discriminate bitter substances, estimate bitterness intensity, and evaluate bitterness-masking effects [17]. These characteristics make electronic tongues particularly promising as complementary tools to human sensory evaluation for objective characterization of bitterness.

Despite these advances, translating electronic tongue responses into human-perceptible bitterness remains challenging. Electronic tongue outputs reflect compound-specific interactions with sensing membranes and are expressed as instrumental response values, whereas human bitterness intensity is governed by psychophysical relationships between stimulus concentration and perception [18]. Previous studies have demonstrated correlations between electronic tongue responses and sensory bitterness and have developed regression-based approaches for bitterness estimation [19]. However, a quantitative framework that explicitly links concentration-dependent instrumental responses with psychophysically characterized human bitterness intensity remains insufficiently established. Such a framework would allow electronic tongue signals to be interpreted on a perceptually meaningful scale, extending their role from instrumental signal characterization toward quantitative prediction of human bitterness. Moreover, bitterness in foods rarely occurs in isolation, and interactions with other taste stimuli may alter bitterness-related responses. Although electronic tongue systems have been applied to taste interactions and bitterness-masking effects, including those involving sweet substances [20], systematic characterization of how different sucrose backgrounds modulate concentration-dependent electronic tongue responses across chemically distinct bitter compounds remains limited. Addressing these issues is therefore important for extending electronic tongue-based bitterness evaluation

from single-compound systems toward more perceptually and compositionally complex taste environments.

To address these gaps, the present study aimed to develop a human perception-calibrated electronic tongue framework for quantitative bitterness evaluation and to further investigate its applicability to sucrose and bitterness interactions. The overall research framework is illustrated in Figure 1. First, the detection threshold and Weber fraction of berberine hydrochloride were determined, and its concentration-dependent sensory bitterness function was established to complement the previously established psychophysical reference data for quinine hydrochloride and iso-α-acid [1]. Second, concentration-dependent electronic tongue responses were characterized for quinine hydrochloride, berberine hydrochloride, and iso-α-acid. By integrating these instrumental response functions with psychophysically characterized human sensory bitterness data, compound-specific bitterness conversion models were established to translate electronic tongue signals into psychophysically derived bitterness reference values. The predictive performance of the models was subsequently evaluated using additional electronic tongue measurements at four predefined bitterness reference levels for each compound. Finally, electronic tongue responses to ten concentration levels of each bitter compound were examined under 0%, 2%, and 8% sucrose backgrounds to characterize sucrose-induced modulation of bitterness-related instrumental responses. Collectively, this framework extends electronic tongue-based bitterness evaluation from instrumental signal characterization toward quantitative prediction within a psychophysical reference framework and characterization of sensor responses in sucrose-containing solutions.

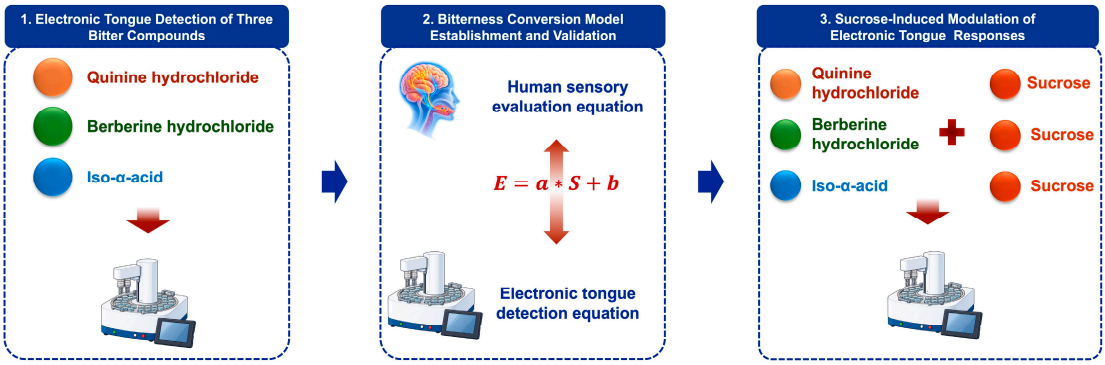


Figure 1. Overall research framework of the present study.

2. Materials and Methods

2.1. Materials

Iso-α-acid mixture was purchased from Labor Veritas AG (Zurich, Switzerland). Quinine hydrochloride and berberine hydrochloride were purchased from Aladdin Reagent Co., Ltd. (Shanghai, China). Ultrapure water with resistivity of 18.2 MΩ·cm was obtained from a Millipore system.

2.2. Psychophysical Characterization of Sensory Bitterness

2.2.1. Sensory Panel

The sensory panel comprised 30 experienced assessors (15 males and 15 females, aged from 20 to 35 years old), who were selected and trained according to the Chinese national standard (GB/T 16291.1-2012: Sensory analysis—General guidance for the selection, training and monitoring of assessors—Part 1: Selected assessors) [21]. All assessors received two weeks of training (once per day), covering the following aspects:

(1) Familiarization with sensory terminology, including absolute and difference thresholds;

(2) Discrimination of the basic taste qualities, with all assessors required to correctly complete the identification tests;

(3) Training in the triangle test method and paired comparison test method;

(4) Evaluation of taste intensity, with a relative error of below 10% between repeated assessments at the same concentration.

Assessors were instructed to refrain from smoking and consuming food for at least 30 min before each sensory evaluation session. Each assessor performed a single evaluation for each test condition, without repeated sensory measurements.

The study involving human participants was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Zhejiang Gongshang University (approval No. 24131201). All human sensory experiments were designed and performed at the sensory evaluation laboratory of the School of Food Science and Biotechnology, Zhejiang Gongshang University, as a single-center study under this ethics approval. Written informed consent was obtained from all participants before enrolment. Participants were informed of the study procedures, data confidentiality, the voluntary nature of participation and their right to withdraw from the study at any time without penalty.

2.2.2. Determination of Absolute and Difference Thresholds

The absolute and difference threshold data for sucrose, iso-α-acid, and quinine hydrochloride were obtained from our previous study [1]. The absolute thresholds were 0.173%, 0.00018%, and 0.00025% (w/v) for sucrose, iso-α-acid, and quinine hydrochloride, respectively. Based on the corresponding difference thresholds, the Weber fractions were calculated as 18.43%, 11.09%, and 21.24%, respectively. The corresponding thresholds for berberine hydrochloride were determined in the present study using the same sensory evaluation procedures established in that study. The iso-α-acid used in the present study was the same commercial product as that used in our previous study.

Absolute and difference thresholds were determined from the total responses of 30 panelists, yielding a single group-level threshold estimate for each condition rather than individual threshold estimates. Consequently, between-panelist standard deviations were not calculated.

2.2.3. Establishment of the Sensory Bitterness Reference Scale

Following determination of the absolute and difference thresholds, successive perceptually distinguishable bitterness levels were established for each bitter compound according to the Weber–Fechner law. Based on our previous study [22], the absolute threshold was assigned a sensory bitterness reference value of 1, and each subsequent just-noticeable difference was assigned an increment of 1. These levels were established using previously determined difference thresholds and subsequent concentration increments calculated from the corresponding Weber fractions. Thus, the reference scale started at 1 and increased progressively without a predefined fixed upper limit, rather than representing a conventional 0–10 sensory rating scale. The corresponding concentrations were calculated from the absolute threshold and Weber fraction to establish compound-specific concentration–sensory bitterness relationships. The reference values selected for model calibration and validation were within the ranges of these derived relationships, as presented in the corresponding tables. Importantly, although 30 assessors participated in the threshold determination experiments, the resulting bitterness reference values were mathematically derived from the psychophysical threshold parameters rather than obtained as direct intensity ratings from individual assessors. Therefore, these values do not represent the mean, median,

or mode of individual sensory ratings, and conventional standard errors or confidence intervals associated with such ratings are not applicable.

2.3. Electronic Tongue Detection and Response Modeling of Bitter Compounds

A series of solutions with progressively increasing concentrations was prepared for each of the three bitter compounds, including quinine hydrochloride, berberine hydrochloride, and iso-α-acid. Electronic tongue measurements were performed using a TS-5000Z taste sensing system (Intelligent Sensor Technology, Inc., Atsugi, Japan) [23] following the standard measurement protocol described by Woertz [24]. The BT0, AN0, and C00 sensors were used for quinine hydrochloride, berberine hydrochloride, and iso-α-acid, respectively. Prior to sample measurements, all sensors underwent conditioning and self-diagnostic procedures according to the standard protocol. Each sample was measured in triplicate ($n = 3$), and all measurements were retained without outlier exclusion. The corresponding CPA1 (change in membrane potential caused by adsorption) values were obtained directly from the instrument software without additional mathematical transformation and extracted as characteristic response signals [25].

For each bitter compound, scatter plots were constructed using concentration as the independent variable (X) and the mean CPA1 response as the dependent variable (Y). Each data point represented the mean of three replicate electronic tongue measurements, with the corresponding standard deviation used to indicate measurement variability. The concentration-dependent electronic tongue responses were fitted using logarithmic functions ($Y = a \ln(X) + b$), where X represents bitter compound concentration and Y represents the CPA1 response. The fitting was performed by applying linear regression to the natural logarithm of concentration using the mean CPA1 values from six concentration levels ($n = 6$) for each bitter compound.

2.4. Establishment of the Bitterness Conversion Models

To establish quantitative relationships between electronic tongue responses and psychophysically derived bitterness reference values, six predefined bitterness reference levels were selected for each bitter compound. The numerical reference scale was derived from the absolute threshold and Weber fraction, with level 1 corresponding to the absolute threshold and each subsequent level representing one additional just-noticeable difference (JND). The corresponding concentrations were calculated using the compound-specific concentration–bitterness relationships established in Section 2.2.3 and are provided in Table S1. The resulting concentrations were then substituted into the corresponding concentration–electronic tongue response functions to obtain the calculated characteristic CPA1 responses. For each bitter compound, the six pairs of electronic tongue responses and psychophysically derived bitterness reference values were plotted as scatter plots, with the characteristic CPA1 response as the independent variable (X) and the bitterness reference value as the dependent variable (Y).

The bitterness conversion models were established using linear regression ($S = aE + b$), where S represents the psychophysically derived human sensory bitterness reference value, E represents the electronic tongue response signal (CPA1), and a and b are the regression coefficients. Regression analyses were performed using Microsoft Excel (Version 16.114; Microsoft Corporation, Redmond, WA, USA) with the ordinary least-squares method.

2.5. Validation of the Bitterness Conversion Models

To validate the predictive performance of the established bitterness conversion models, four predefined sensory bitterness levels, ranging from weak to very strong bitterness, were selected for each bitter compound. The concentration corresponding to each predefined

bitterness level was first calculated using the previously established concentration–sensory bitterness function. Solutions of quinine hydrochloride, berberine hydrochloride, and iso-α-acid were then prepared at the calculated concentrations and independently measured using the electronic tongue. The characteristic CPA1 responses obtained from the corresponding sensors were entered into the respective bitterness conversion models to predict bitterness reference values. Predictions were performed using Microsoft Excel for Mac with the previously established linear conversion models (S = aE + b). The resulting S values were subsequently compared with the corresponding psychophysically derived bitterness reference values. The predicted bitterness intensities were subsequently compared with the corresponding reference sensory bitterness intensities. Prediction accuracy was evaluated using the absolute relative error (ARE) for each bitterness level and the mean absolute percentage error (MAPE) across the four validation levels for each bitter compound.

2.6. Electronic Tongue Responses to Bitter Compounds Under Different Sucrose Backgrounds

To investigate whether the electronic tongue could characterize sucrose-induced modulation of bitterness-related responses, three sucrose backgrounds (0%, 2%, and 8%, *w*/*v*) were established for quinine hydrochloride, berberine hydrochloride, and iso-α-acid. For each bitter compound, nine concentration levels were selected under each sucrose background based on the previously established relationships between sucrose concentration and sensory bitterness reported in our previous study [1]. Specifically, these concentration series represented the concentrations of each bitter compound required to elicit equivalent sensory bitterness intensities under the three sucrose backgrounds. The resulting bitter compound solutions prepared in 0%, 2%, and 8% sucrose were subsequently measured using the electronic tongue. CPA1 (BT0), CPA1 (AN0), and CPA1 (C00) were used as the characteristic responses for quinine hydrochloride, berberine hydrochloride, and iso-α-acid, respectively. For each bitter compound and sucrose background, concentration-dependent response curves were constructed with bitter compound concentration as the independent variable (X) and the corresponding characteristic CPA1 response as the dependent variable (Y). The resulting concentration–response functions were compared across the three sucrose backgrounds to characterize sucrose-dependent changes in electronic tongue responses and their correspondence with the previously established modulation of human sensory bitterness.

2.7. Statistical Analysis

Logarithmic regression analysis was performed to characterize the concentration-dependent electronic tongue responses of the three bitter compounds, using bitter compound concentration as the independent variable and the corresponding characteristic CPA1 response as the dependent variable. The goodness of fit was evaluated using the coefficient of determination (R^2). To establish the bitterness conversion models, linear regression analysis was conducted using the calculated characteristic CPA1 responses as the independent variable and the corresponding psychophysically derived sensory bitterness intensities as the dependent variable. The resulting regression coefficients were used to construct compound-specific conversion models. Model prediction accuracy was evaluated by comparing the predicted sensory bitterness intensities with the corresponding reference values at four predefined validation levels for each bitter compound. The absolute relative error (ARE) was calculated for each validation level, and the mean absolute percentage error (MAPE) was calculated across the four validation levels to quantify the overall prediction error. For the sucrose-background experiments, concentration-dependent electronic tongue response curves were fitted separately for each bitter compound under 0%, 2%, and 8%

sucrose conditions, and the resulting response patterns were compared to characterize sucrose-induced changes in instrumental responses.

The logarithmic regression models were used to characterize concentration-dependent electronic tongue responses within the investigated concentration ranges. The resulting regression statistics were interpreted as measures of model fit and parameter estimation within these ranges, rather than evidence of model applicability beyond the tested conditions.

3. Results

3.1. Psychophysical Characterization of Berberine Hydrochloride Bitterness

The absolute threshold of berberine hydrochloride was determined to be 0.00447% (w/v), with a Weber fraction of 7.9%. Based on these parameters, the concentration–bitterness reference relationship was expressed as:

$$C = 0.00447 \times 1.079^{(S-1)} \quad (1)$$

where C represents the berberine hydrochloride concentration (%) and S represents the psychophysically derived bitterness reference value. This relationship was used to calculate the concentrations corresponding to the selected bitterness reference levels for subsequent conversion model development.

3.2. Concentration-Dependent Electronic Tongue Responses of Bitter Compounds

The electronic tongue exhibited distinct concentration-dependent responses to the three bitter compounds (as shown in Figure 2). The CPA1 (BT0) response increased progressively with increasing quinine hydrochloride concentration, while CPA1 (AN0) showed a similar concentration-dependent increase for berberine hydrochloride. In contrast, the CPA1 (C00) response became progressively more negative as the concentration of iso-α-acid increased.

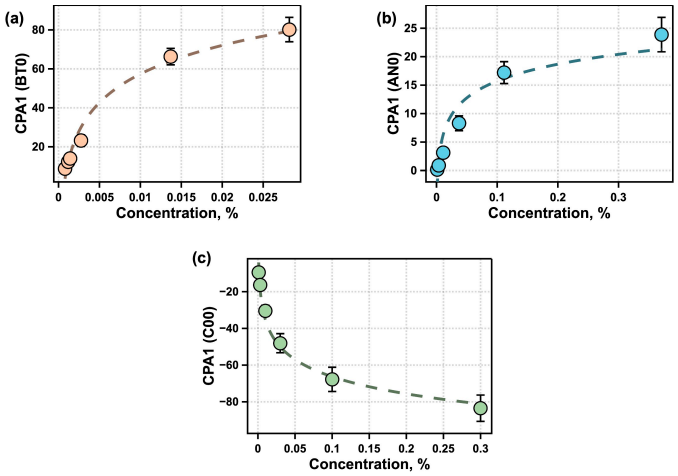


Figure 2. Concentration-dependent electronic tongue responses to three bitter compounds. (**a**) CPA1 (BT0) response to quinine hydrochloride as a function of concentration. (**b**) CPA1 (AN0) response to berberine hydrochloride as a function of concentration. (**c**) CPA1 (C00) response to iso-α-acid as a function of concentration. Dashed lines represent the logarithmic fitting curves. Data are presented as mean ± SD (n = 3).

Logarithmic fitting, performed by linear regression of the natural logarithm of concentration against the corresponding CPA1 response, adequately described the concentration-dependent electronic tongue responses of the three bitter compounds, with R^2 values of 0.983, 0.910, and 0.984 for quinine hydrochloride, berberine hydrochloride, and iso-α-acid, respectively (Table 1).

Table 1. Fitting curves of the electronic tongue response to three bitter compounds.

Bitter Compounds	Fitting Equation	Equation Parameters				R^2	*p*-Value
		a	SE (a)	b	SE (b)		
Quinine hydrochloride	$E^* = a \times \ln(C^▲) + b$	21.19	1.40	154.97	8.17	0.983	0.00011
Berberine hydrochloride		4.27	0.67	25.54	2.93	0.910	0.00313
Iso-α-acid		−13.51	0.87	−97.40	3.93	0.984	0.00010

E^* means the response signal of the electronic tongue. $C^▲$ means the concentration of the bitter compound (%).

3.3. Establishment of Bitterness Conversion Models

Based on the six predefined sensory bitterness levels, compound-specific relationships between the characteristic electronic tongue responses and psychophysically derived bitterness were established for the three bitter compounds (as shown in Figure 3).

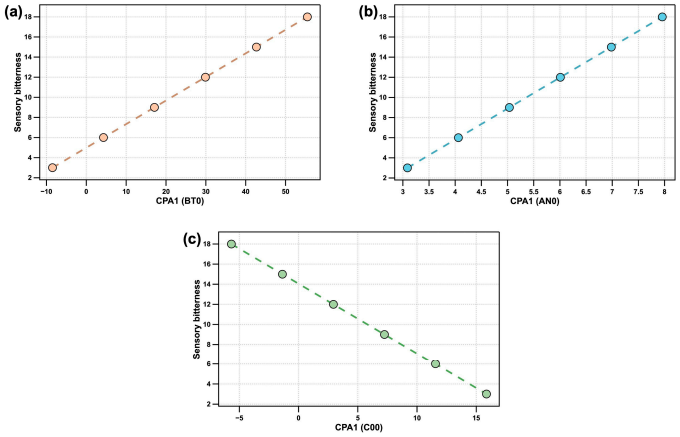


Figure 3. Relationships between electronic tongue responses (CPA1) and psychophysically derived bitterness reference values for three bitter compounds. (**a**) Relationship between CPA1 (BT0) and sensory bitterness for quinine hydrochloride. (**b**) Relationship between CPA1 (AN0) and sensory bitterness for berberine hydrochloride. (**c**) Relationship between CPA1 (C00) and sensory bitterness for iso-α-acid. Dashed lines indicate the linear regression fits used to establish the bitterness conversion models.

The psychophysically derived bitterness reference values increased linearly with CPA1 (BT0) for quinine hydrochloride and CPA1 (AN0) for berberine hydrochloride, whereas an inverse linear relationship was observed for CPA1 (C00) with iso-α-acid. The conversion equations for quinine hydrochloride, berberine hydrochloride, and iso-α-acid are presented in Table 2. These linear relationships, arising from the logarithmic concentration dependence of both the electronic tongue responses and the Weber–Fechner-based bitterness reference values, provide quantitative conversion equations linking CPA1 responses to psychophysically derived bitterness reference values.

Table 2. Conversion model linking electronic tongue signals to psychophysically derived bitterness.

Bitter Compounds	Conversion Equation	Equation Parameters	
		a	b
Quinine hydrochloride	$S^* = a \times E^▲ + b$	0.24	4.99
Berberine hydrochloride		3.08	−6.51
Iso-α-acid		−0.70	14.05

S^* means the psychophysically derived bitterness value. $E^▲$ means the response signal of the electronic tongue.

It should be emphasized that these conversion relationships were algebraically derived from the previously established concentration-dependent functions rather than independently fitted using experimental observations. Consequently, their linearity reflects the mathematical compatibility of the two functions and should not be interpreted as independent evidence of predictive accuracy. The predictive performance of the conversion models was evaluated separately using electronic tongue measurements at additional concentration levels.

3.4. Validation of the Bitterness Conversion Models

The predictive performance of the established bitterness conversion models was evaluated using four predefined sensory bitterness levels for each bitter compound (as listed in Table 3). For quinine hydrochloride, the predicted bitterness intensities were 4.99, 21.24, 37.84, and 45.19 at reference sensory bitterness intensities of 5, 20, 35, and 50, respectively, with ARE (Absolute Relative Error) values ranging from 0.11% to 9.63% and a MAPE (Mean Absolute Percentage Error) of 6.02%. For berberine hydrochloride, the predicted bitterness intensities were 4.30, 18.35, 38.52, and 55.37, with ARE values ranging from 8.27% to 13.98% and a MAPE of 10.76%. For iso-α-acid, the predicted bitterness intensities were 14.82, 27.73, 40.72, and 66.19 at reference sensory bitterness intensities of 15, 30, 45, and 60, respectively, with ARE values ranging from 1.18% to 10.31% and a MAPE of 7.14%. Overall, the predicted bitterness reference values showed close agreement with the corresponding psychophysically derived reference values across the validation levels, with MAPE values ranging from 6.02% to 10.76% among the three bitter compounds. Recent studies have highlighted the importance of integrating electronic tongue measurements with human sensory evaluation. For example, Huang [23] combined TS-5000Z electronic tongue measurements with sensory evaluation and chemical analysis to characterize taste differences among dairy products. Building on this approach, the present study established a quantitative conversion between electronic tongue responses and psychophysically derived bitterness reference values, providing a framework for interpreting instrumental responses in relation to human taste perception.

Table 3. Validation results of the conversion model.

Bitter Compounds	Psychophysically Derived Bitterness	Electronic Tongue Response Signal	Electronic Tongue Predicted Bitterness	ARE*	MAPE▲
Quinine hydrochloride	5	0.02	4.99	0.11%	6.02%
	20	69.16	21.24	6.21%	
	35	139.80	37.84	8.12%	
	50	171.05	45.19	9.63%	
Berberine hydrochloride	5	3.51	4.30	13.98%	10.76%
	20	8.07	18.35	8.27%	
	35	14.62	38.52	10.06%	
	50	20.09	55.37	10.73%	
Iso-α-acid	15	−1.11	14.82	1.18%	7.14%
	30	−19.63	27.73	7.56%	
	45	−38.26	40.72	9.52%	
	60	−74.80	66.19	10.31%	

ARE*, absolute relative error; MAPE▲, mean absolute percentage error.

It should be noted that both the electronic tongue responses and the Weber–Fechner-based bitterness reference scale exhibit logarithmic relationships with concentration. Therefore, the linear relationship between these two variables is mathematically expected and should not be interpreted as independent evidence of predictive accuracy. Rather, this mathematical compatibility provides the basis for establishing a quantitative conversion be-

tween electronic tongue signals and psychophysically derived bitterness values. Although the conversion models were evaluated using independently measured electronic tongue responses, the corresponding sensory reference values were derived from previously established psychophysical relationships rather than independently obtained intensity ratings. Future studies will incorporate direct sensory intensity assessments using a 15-cm line scale to further evaluate the predictive performance and generalizability of the proposed models.

3.5. Electronic Tongue Responses to Bitter Compounds Under Different Sucrose Backgrounds

Electronic tongue responses to the three bitter compounds under different sucrose backgrounds are presented in Figure 4. The concentration series of each bitter compound under the 0%, 2%, and 8% sucrose conditions were selected based on experimentally measured human bitterness intensity data, with the aim of characterizing electronic tongue responses at concentrations corresponding to different perceived bitterness levels. Consequently, the tested bitter compound concentrations were not identical across the sucrose backgrounds. For quinine hydrochloride, CPA1 (BT0) responses generally increased with increasing bitter compound concentration under all three sucrose conditions, although variations were observed among the response curves (Figure 4a). Similarly, berberine hydrochloride exhibited concentration-dependent increases in CPA1 (AN0) responses, with differences in the response patterns among the sucrose conditions (Figure 4b). In contrast, iso-α-acid showed increasingly negative CPA1 (C00) responses with increasing bitter compound concentration under all three sucrose backgrounds (Figure 4c). Logarithmic regression analysis further characterized these concentration-dependent relationships, with the corresponding regression equations and R^2 values presented in Table S2. Although variations in sensor responses were observed among the sucrose backgrounds, the differences cannot be attributed solely to sucrose concentration because the bitter compound concentrations were not matched across conditions. Overall, these results demonstrate that the electronic tongue retained concentration-dependent responses to all three bitter compounds under different sucrose backgrounds.

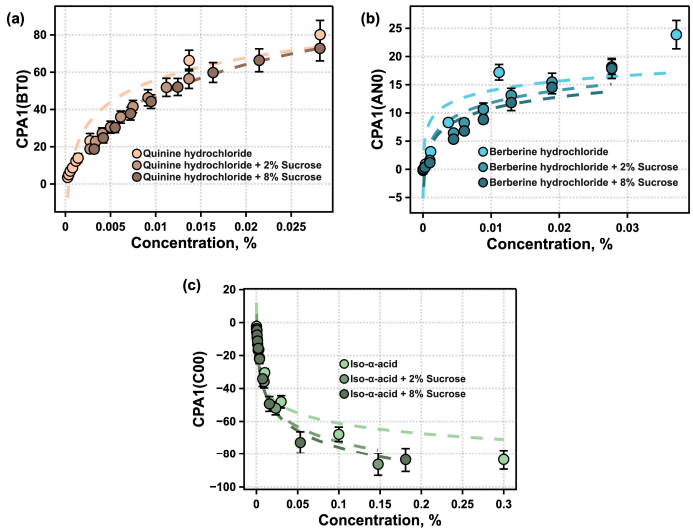


Figure 4. Concentration-dependent electronic tongue responses to three bitter compounds under different sucrose backgrounds. (**a**) CPA1 (BT0) responses to quinine hydrochloride under 0%, 2%, and 8% sucrose backgrounds. (**b**) CPA1 (AN0) responses to berberine hydrochloride under 0%, 2%, and 8% sucrose backgrounds. (**c**) CPA1 (C00) responses to iso-α-acid under 0%, 2%, and 8% sucrose backgrounds. Data are presented as mean ± SD (n = 3). Dashed lines indicate the fitted concentration–response curves.

4. Discussion

4.1. Linking Electronic Tongue Responses with Human Bitterness Perception

The present study established a quantitative connection between electronic tongue responses and human bitterness perception by integrating instrumental concentration–response relationships with psychophysically characterized sensory bitterness. The three bitter compounds exhibited distinct but systematic concentration-dependent electronic tongue responses, with logarithmic relationships observed for CPA1 (BT0), CPA1 (AN0), and CPA1 (C00) in response to quinine hydrochloride, berberine hydrochloride, and iso-α-acid, respectively, yielding R^2 values of 0.983, 0.910, and 0.984. Importantly, the present framework did not rely solely on direct statistical correlations between instrumental signals and sensory scores. Instead, human bitterness perception was first defined on a psychophysical reference scale based on absolute thresholds and Weber fractions, and this sensory reference was subsequently linked to the concentration-dependent electronic tongue responses. This approach resulted in compound-specific linear relationships between characteristic CPA1 responses and psychophysically derived bitterness reference values, despite the different response directions and sensitivities of the three sensors. Compared with previous electronic tongue approaches relying primarily on instrumental responses or empirical sensor–sensory correlations, the present study introduces a psychophysically defined reference scale that enables compound-specific sensor signals to be expressed on a common bitterness scale. Although this approach provides a more explicit perceptual basis for interpreting electronic tongue responses, its predictive advantage over conventional methods requires further validation. Moreover, the current conversion models were established using single-compound aqueous solutions, and their applicability to complex mixtures and real food matrices remains to be investigated.

4.2. Predictive Performance and Applicability of the Bitterness Conversion Models

A critical step in translating electronic tongue measurements into perceptually meaningful information is determining whether the established conversion relationships remain applicable to samples not directly used for model construction. Unlike conventional electronic tongue approaches that primarily rely on instrumental responses or empirical sensor–sensory correlations, the present study employed psychophysically derived bitterness reference values for model calibration. Four additional bitterness levels spanning weak to very strong bitterness were prepared and measured for each bitter compound, and the experimentally obtained CPA1 responses were converted into predicted bitterness reference values. The resulting MAPE values were 6.02% for quinine hydrochloride, 10.76% for berberine hydrochloride, and 7.14% for iso-α-acid. This out-of-calibration evaluation is particularly important because the perfect linearity of the conversion relationships arises from their mathematical construction and therefore cannot independently demonstrate predictive performance. The differences in prediction errors among the three compounds, particularly the higher MAPE observed for berberine hydrochloride, further indicate that model performance remains compound-dependent. Nevertheless, these prediction errors were calculated against psychophysically derived reference values rather than independently measured human bitterness intensity ratings, and the models were evaluated only in single-compound aqueous solutions. Therefore, further validation using direct human sensory intensity measurements and more complex food matrices is required to establish their broader predictive applicability. Furthermore, extending the proposed approach to additional bitter compounds will be necessary to evaluate the generalizability of the compound-specific calibration strategy.

It should also be acknowledged that the conversion models were constructed using only six concentration levels for each bitter compound. Therefore, the model performance

statistics should be interpreted cautiously, as the limited number of calibration points may affect the robustness of the established relationships. Future studies should employ larger concentration series and independent validation datasets, including direct human sensory intensity measurements, to further evaluate model robustness and predictive reliability.

4.3. Effects of Sucrose Backgrounds on Electronic Tongue Responses to Bitter Compounds

Beyond single-compound bitterness prediction, the present study further investigated electronic tongue responses to three bitter compounds under different sucrose backgrounds. The characteristic sensor responses exhibited varying patterns under 0%, 2%, and 8% sucrose conditions, with differences depending on the bitter compound. For quinine hydrochloride, CPA1 (BT0) responses showed relatively limited variations among the three sucrose backgrounds, whereas CPA1 (AN0) responses to berberine hydrochloride and CPA1 (C00) responses to iso-α-acid exhibited differences in their concentration–response relationships. Importantly, the concentration series under each sucrose background were established based on experimentally measured human bitterness intensity data, resulting in different bitter compound concentrations across the sucrose conditions. Therefore, the observed variations cannot be attributed solely to sucrose concentration, as the bitter compound concentrations were not matched across conditions. Nevertheless, concentration-dependent response patterns were maintained under all three sucrose backgrounds, indicating that the sensors retained their responsiveness to the bitter compounds. A recent study by Kanaga [26] investigated sweetener-related taste changes in black tea using an impedance-based electronic tongue combined with sensory evaluation, highlighting the importance of distinguishing instrumental responses from human taste perception. Although human sensory measurements were used to establish the concentration series in the present study, the observed sensor response variations cannot be directly interpreted as evidence of sucrose-induced bitterness suppression. Further experiments using matched bitter compound concentrations, together with corresponding human sensory evaluations, are needed to clarify the effects of sucrose on electronic tongue responses and their relationship with perceived bitterness.

5. Conclusions

This study developed a psychophysically calibrated electronic tongue framework for translating instrumental responses into psychophysically derived bitterness reference values. By integrating concentration-dependent electronic tongue responses with psychophysically derived bitterness reference scales, compound-specific bitterness conversion models were established for quinine hydrochloride, berberine hydrochloride, and iso-α-acid. Independent electronic tongue measurements demonstrated close agreement between predicted and reference bitterness values, supporting the feasibility of quantitative prediction within the established psychophysical framework. Moreover, the electronic tongue retained concentration-dependent responses to all three bitter compounds under different sucrose backgrounds, although the response patterns varied among the tested conditions. These findings extend the potential application of electronic tongue measurements from single-compound solutions to sucrose-containing formulations. The proposed framework provides a methodological basis for sensory-relevant instrumental evaluation of bitterness, although further validation using matched bitter compound concentrations and independent human sensory measurements is required to establish its broader applicability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/chemosensors14110254/s1, Table S1: Selected bitterness reference levels and corresponding calculated concentrations for the three bitter compounds; Table S2: Logarithmic regression models of electronic tongue responses to three bitter compounds under different sucrose concentrations.

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