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RESEARCH ARTICLE

Sweetness-enhancing effects of aromatic compounds in glucose aqueous solutions: sensory evaluation, electronic tongue detection, and exploratory molecular docking analysis

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Abstract

This study applied sensory evaluation and electronic tongue technology to assess the sweetness-enhancing effects of seven aromatic compounds, including ethyl acetoacetate, trans-2-hexen-1-ol, ethyl acetate, ethylhexanoate, phenethylalcohol, cinnamylalcohol, and phenylacetaldehyde, in 2.4% aqueous glucose solutions. The results indicated that these aromatic compounds enhanced the perceived sweetness of glucose solutions to varying degrees, with ethyl acetoacetate exhibiting the most significant sweetening effect (its sweetness value increased from 5.0 to 8.5, $p<0.05$), followed by ethylhexanoate (the sweetness value increased from 5.0 to 6.8, $p<0.05$). To gain preliminary molecular insights, molecular docking was employed to investigate the potential influence of these aromatic compounds on the interaction between glucose and sweet taste receptors. Docking simulations revealed the formation of hydrogen bonds and hydrophobic interactions between glucose and the sweet taste receptor, offering a tentative molecular interaction pattern that may partly explain the observed sweetness elevation in sensory tests.

Keywords

Aroma-taste interaction, aromatic compounds, electronic tongue, glucose, molecular docking, sensory evaluation

Introduction

As global health awareness continues to rise, reducing sugar intake has become a major focus in food research and product development. To address this challenge, the food industry has explored various sugar reduction strategies (Ismail et al. 1997). Currently, non-nutritive sweeteners such as sucralose, sodium saccharin, and aspartame are widely used due to their low- or zero-calorie properties (Grilo et al. 2023). Although these sweeteners can provide sweetness without significantly affecting blood glucose levels, their safety profiles and long-term health effects remain under active investigation (McConway 2023).

In addition to chemical sweeteners, aroma-induced sweetness enhancement has emerged as an alternative strategy for sugar reduction. Previous studies have demonstrated that certain aroma compounds can enhance perceived sweetness through perceptual cross-modal interactions between olfaction and taste, without increasing sugar content (Liu et al. 2021). Most existing research in this area has focused on sucrose-based systems, showing that aroma compounds such as nonanal, decanal, γ-caprolactone, cinnamylalcohol,

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and γ-decalactone can enhance the perceived sweetness of sucrose solutions (Barba et al. 2018; Yang 2024).

However, despite the extensive literature on aroma-induced sweetness enhancement in sucrose systems, the effects of aroma compounds on the sweetness perception of glucose remain poorly understood. Glucose is the core monosaccharide participating in human blood glucose metabolism and widely present in fruits, cereals and dairy products, which bears stronger physiological representativeness than disaccharide sucrose. Glucose features a simpler monosaccharide skeleton, different sweetness threshold; hence the cross-modal interaction rules summarized from sucrose matrices cannot be directly transferred to glucose systems. Up to now, few studies have quantitatively characterized the sweetening capacity of common food aromas in glucose solution or explored the potential intermolecular basis behind sensory changes, leaving insufficient theoretical guidance for glucose-oriented sugar reduction development.

The human sweet taste receptor is a class C G protein–coupled receptor composed of a heterodimer of T1R2 and T1R3 subunits, each containing a Venus flytrap domain (VFD), a cysteine-rich domain (CRD), and a seven-transmembrane domain (7TM) (Smith et al. 2021). While direct molecular interactions between sweeteners and these receptor domains have been extensively studied, aroma-induced sweetness enhancement is generally considered to arise primarily from perceptual cross-modal effects, rather than confirmed direct binding of aroma compounds to sweet taste receptors.

This study focuses on glucose components in food products and aims to investigate the effects of different aroma substances on the sweetening effect of glucose, which increases the relevant research of aroma-induced sweetness enhancement in glucose systems. The study first evaluated the sweetness-promoting performance of seven typical edible aromatic compounds in glucose solution via sensory evaluation and electronic tongue measurement. Based on the sensory evaluation and e-tongue analysis, the study further adapt sequential molecular docking to simulate the ternary interaction of aroma-glucose-T1R2/T1R3, and compare binding free energy and interacting amino residues with blank glucose group. Through this integrated multi-method approach, this study aims to reveal how aroma substances affect the sweetness perception of glucose and how these components act together on sweetness receptors, thus providing a scientific basis for flavor modification and sweetness enhancement in food products. This is of great theoretical and practical significance for the development of foods with better sensory properties.

Materials and methods

Aromatic compounds and experimental materials

Glucose, ethylacetoacetate, trans-2-hexen-1-ol, ethyl acetate, ethylhexanoate, phenethylalcohol, cinnamylalcohol, phenylacetaldehyde are of edible grade and were purchased from Shanghai Caicheng Industrial Co. Distilled water was purchased from Watson's Trademark Co. All samples were kept at room temperature.

Sensory evaluation and electronic tongue

Evaluation of sweetening of glucose solutions by aroma substances

The ten sensory evaluators (5 males and 5 females) were all from the School of Flavor and Fragrance Technology and Engineering, Shanghai University of Applied Sciences. The panel size is in accordance with ISO 8586-1:2022 (Sensory analysis - Selection, training and monitoring of assessors - Part 1: General guidance) and is widely adopted in food sensory evaluation studies on sweetness enhancement effects. All panelists received a total of 28 hours of standardized sensory training before the formal test, and the intraclass correlation coefficient (ICC) of sweetness scoring in pre-experiment repeatability verification reached 0.89, which meets the repeatability standard of sensory analysis. All panelists involved in the study did not exhibit any sensory deficiencies and possessed the ability to accurately identify the five basic flavors - sour, sweet, bitter, salty and umami. Two separate testing modes were set to independently regulate olfactory and gustatory perceptions: one group of tests was performed without nose clips to obtain integrated aroma-taste sensation, while the other group used medical nose clips to block orthonasal smell and only record pure gustatory perception. Prior to the formal evaluation, panelists were familiarized with the evaluation procedure and scoring criteria. All samples were marked with random three-digit numbers, the tasting order of samples was randomly rearranged for each assessor, and double-blind test control was adopted throughout the whole experiment. All samples were balanced in a 25 °C constant-temperature water bath for 30 min before tasting, with a single tasting volume of 10 mL for each sample. Between two adjacent sample evaluations, panelists rinsed their oral cavity with 20 mL room-temperature purified water and maintained a 60 s resting interval until residual taste disappeared completely before the next test. To minimize potential interference, panelists were instructed to avoid consuming spicy foods on the day of testing. This measure helped to prevent any possible interference or influence of spicy food on the sense of taste, and ensured the purity and objectivity of the taste assessment during the test (Xiao et al. 2024a). All sensory assessments were conducted under normal orthonasal and retronasal olfactory conditions without nose clips, so panelists could simultaneously receive both taste and aroma signals to simulate real oral eating perception.

Panelists were evaluated using a scale of sweetness values ranging from 0-10 (0: no sweetness, 10: very sweet), and a scale of comfort values ranging from 0-10 (0: very uncomfortable, 10: very comfortable). As a control, a 2.4% glucose solution was used as a reference sample. Its

sweetness and comfort scores were set at 5 as an internal calibration point, allowing panelists to evaluate relative changes in sweetness and comfort among samples within the same evaluation session.

This reference-based scoring approach was adopted to facilitate comparative assessment rather than to determine absolute sweetness intensity. Accordingly, the sensory evaluation was designed as an exploratory analysis focusing on relative sweetness enhancement effects under controlled conditions. The 2.4% glucose solution containing the aroma substance was then prepared by dissolving the aroma substance in water or propylene glycol and diluting it according to a predetermined concentration gradient.

The experiments were conducted in a fume hood under room temperature conditions to control the potential influence of environmental factors on the results. To ensure the reliability of the results and the anonymity of the sample evaluations, all samples were numbered by random numbers. This method reduces bias in the assessment process and ensures that each member's evaluation is based on the properties of the samples themselves and is not influenced by any external identifiers.

Electronic tongue

In this study, a TS-5000Z electronic tongue system (Insent, Japan) was used for sweetness evaluation. Only signals from the sweetness-specific sensor were chosen as core indicators to track variations in sweet intensity; the output signal of the sweetness sensor is potential difference with the unit of mV, which stands for the voltage gap between working electrode and reference electrode after flavor molecules adsorb on lipid polymer membranes, and higher positive mV values represent stronger sweet signals. Prior to measurement, the electronic tongue system was calibrated using standard solutions, and the validation was conducted by testing the standard solutions in triplicate. The relative standard deviation (RSD) of the sensor response values was less than 5%, which met the instrument performance verification requirements. After calibration and validation, the system was pre-equilibrated for 30 min to ensure signal stability before sample injection.

Three groups of liquid samples were prepared for detection: experimental samples were 2.4% glucose aqueous solutions with gradient aromatic concentrations; blank control was pure 2.4% glucose solution without aroma; aroma-only control was gradient aromatic aqueous solutions free of glucose, which could eliminate sensor signal interference caused by aroma molecules and distinguish genuine glucose sweetening effect. All prepared liquids were transferred into 40 mL beakers dedicated to electronic tongue testing. Samples were randomly coded to ensure traceability and minimize potential bias during measurement. A cycle number of 6 was applied, and each cycle included sensor rinsing, equilibration, signal acquisition and regeneration. The average of the 6 cycles was used for subsequent analysis to effectively improve the reproducibility of measurement data and reduce random instrumental errors.

The electronic tongue results were evaluated using the average sweetness sensor response value as a reference index, which was used for comparative assessment of relative sweetness changes among samples. This exploratory test only focused on comparing the variation trend of sweet signals corresponding to sensory scores, so only sweetness sensor data were collected without acquiring full multi-sensor spectrum; the research target was simple pairwise comparison of sweet intensity instead of overall sample classification. Due to the exploratory positioning of this research focusing on the change trend of sweetness-related signals, multivariate chemometric analyses including PCA, DFA and cluster analysis were not carried out in the current work. Relevant multivariate statistical analysis will be supplemented in follow-up in-depth research to further distinguish sample groups and enrich data interpretation dimensions.

Molecular docking

Molecular docking is a computational chemistry approach that simulates the placement of a ligand (small molecule) into the vicinity of the active site of a receptor (typically a protein) to predict potential binding modes. The receptor adopted in this work was the human T1R2/T1R3 sweet taste heterodimer protein built via homology modeling. The modeling template crystal structure belongs to the Venus flytrap domain (VFD) of human T1R2 subunit, which is the core binding pocket for sweet molecules (Wang and Li 2022; Bi et al. 2024). Before docking calculation, the rationality of the homologous protein structure was assessed by two standard validation indicators: Ramachandran plot and ERRAT quality factor, to eliminate unreasonable spatial conformations of amino acid residues. The homology modeling was based on the crystal structure of the T1R2/T1R3 Venus flytrap domain, and the stability and rationality of the modeled structure were verified by 100 ns molecular dynamics simulation. The validated model has been widely used in the study of sweet taste receptor-ligand interactions.

The SDF structural files of seven tested aromatic compounds were downloaded from the PubChem database, then converted into PDB format for docking input via open-source Open Babel chemical toolbox (Open Babel official website: http://openbabel.org/). Next, molecular docking work was carried out using AutoDockTools (ADT) version 1.5.6 and AutoDock Vina version 1.2.0, an open-source molecular docking program widely used to predict binding modes and affinities between small molecules and proteins. Docking was performed in AutoDockTools 1.5.6 and AutoDock Vina 1.2.0. The grid box centered at T1R2 VFD pocket was set as 40 Å × 40 Å with 0.375 Å spacing, exhaustiveness = 8 and energy cutoff = 3 kcal/mol; other parameters kept default.

In the docking procedure, aroma compounds were first docked to the sweet taste receptor using AutoDock Vina to generate aroma–receptor complex models. Subsequently,

glucose molecules were docked into the pre-established aroma–receptor complexes to explore potential changes in predicted glucose–receptor interaction patterns in the presence of aroma substances. The sequential docking (aroma first, then glucose) was an exploratory design: we hypothesized aroma ligands remodel pocket microenvironment to modulate glucose binding. This workflow only generates ternary complex models instead of reflecting physiological binding order. Classic sweet ligand and blank receptor controls were absent due to limited computational resources, and comparative docking will be supplemented in subsequent research. This sequential docking strategy was adopted as an exploratory, hypothesis-driven *in silico* approach, and was not intended to represent the actual ligand binding sequence nor to determine whether aroma compounds and glucose compete for the same binding site. Among the docking results, complex structures with lower binding energies and reasonable conformations were selected for further analysis (An et al. 2023).

Finally, the docking results were visualized in three dimensions using Pymol software (Yuan et al. 2017) to visualize the intermolecular interactions. Meanwhile, a two-dimensional interaction map was plotted using LigPlot+ software (Laskowski and Swindells 2011), which helps to analyze in detail the non-covalent interaction modes between ligand and receptor, such as hydrogen bonding, hydrophobic interactions, and so on.

Data and statistical analysis

Sensory measurement and electronic tongue detection were separately set with independent parallel replicates to distinguish technical repeats, and all operations followed unified standard operating procedures to guarantee data reproducibility. Prior to performing one-way ANOVA, Shapiro-Wilk test was adopted to verify the normality of all experimental datasets, and Levene's test was carried out to examine homogeneity of variances to meet the prerequisite of variance analysis. For sensory evaluation: each sample received 3 independent experimental sessions as biological repeats; within each session, every assessor completed one tasting as technical repeat, and all individual scores of the same sample were averaged before statistical analysis. Significant difference analysis of the experimental data was performed by using SPSSv26.0 (SPSS, Chicago, IL, USA). Significant difference analysis of sensory sweetness values were analyzed using one-way analysis of variance (ANOVA) by Duncan's test in order to assess whether the differences between the different treatments were statistically significant ($P < 0.05$). Origin software (OriginLab 2018) was used for visualization and graphing of data. All error bars displayed in Figs 1, 2 represent the standard deviation (SD) calculated from three parallel replicate experimental data.

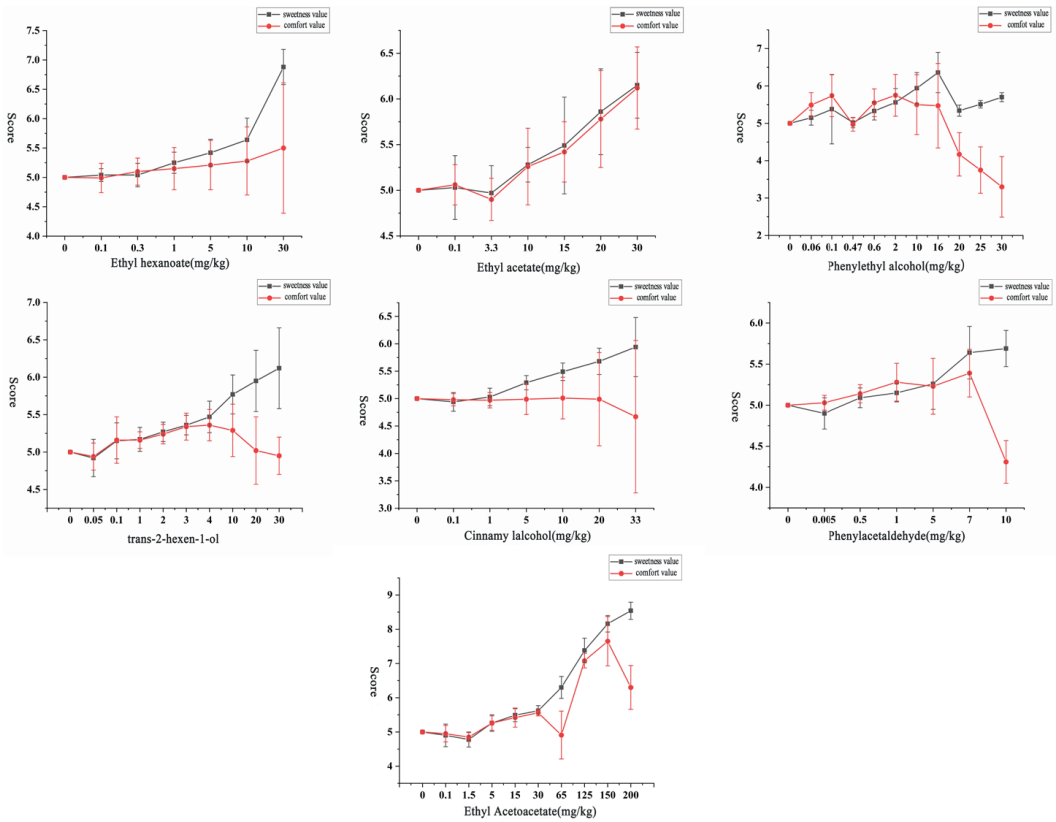

Figure 1. A–G. Depicts the average sweetness and comfort values of ethylhexanoate (**A**), ethylacetate (**B**), phenethylalcohol (**C**), trans-2-hexen-1-ol (**D**), cinnamylalcohol (**E**), phenylacetaldehyde (**F**), and ethylacetoacetate (**G**) in a 2.4% glucose solution. The black curve represents the average sweetness values, while the red curve indicates the average comfort values.

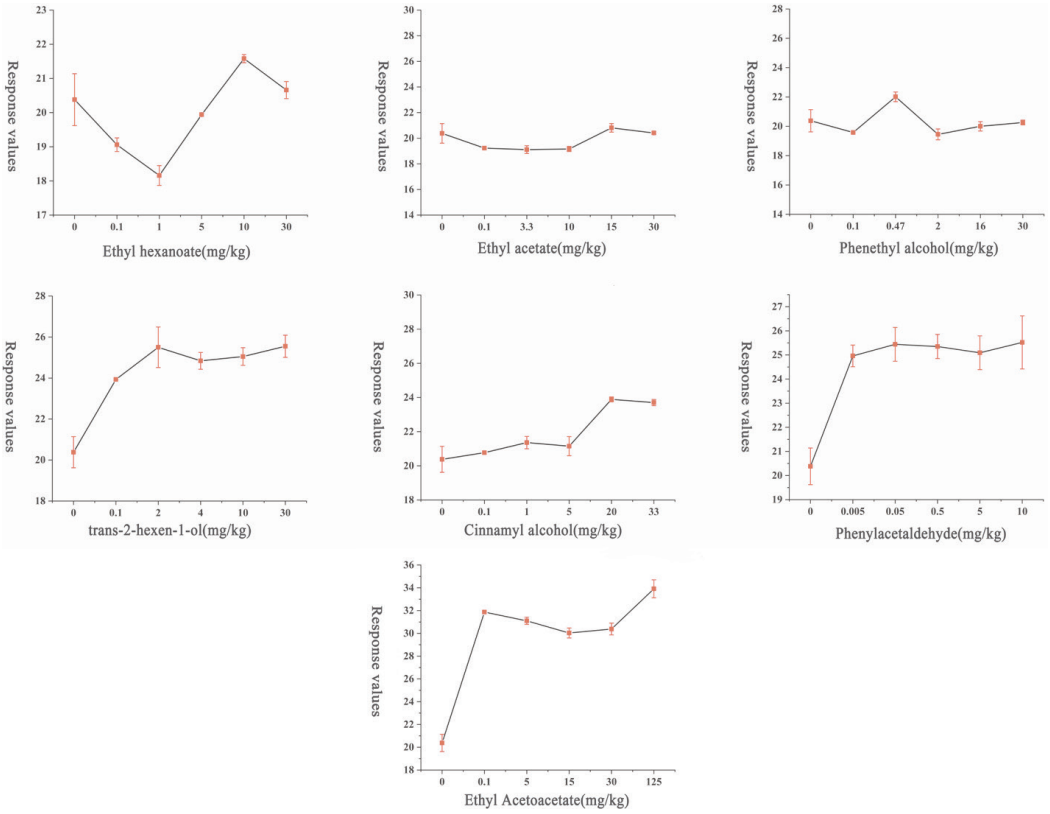

Figure 2. A–G. Represent the average sweetness response values of ethylhexanoate (**A**), ethylacetate (**B**), phenethylalcohol (**C**), trans-2-hexen-1-ol (**D**), cinnamylalcohol (**E**), phenylacetaldehyde (**F**), and ethylacetoacetate (**G**) in a 2.4% glucose solution.

Results and discussion

Sweetening evaluation of aroma substances

Currently, the assessment of sweetening effect mainly relies on artificial sensory evaluation. In such studies, aroma substances with known sweetening effects are selected, such as β-violetone (Yu et al. 2021). However, the concentration of the aroma substance has a significant effect on the sensory experience. Although moderate amounts of aroma substances can enhance sweetness perception, excessive concentrations may cause discomfort and affect the overall eating experience. Therefore, in addition to the sweetness evaluation, the comfort evaluation was also considered to ensure that the sweetening effect was achieved while the product still had a pleasant taste and odor.

Fig. 1 shows that the sweetness values of ethylhexanoate (0-30 mg/kg), ethylacetate (0-30 mg/kg), trans-2-hexen-1-ol (0-30 mg/kg), cinnamylalcohol (0-35 mg/kg), phenylacetaldehyde (0-10 mg/kg), and ethyl acetoacetate (0-200 mg/kg) generally increased with increasing concentration. For example, the sweetness value of ethylhexanoate increased significantly from 5.0 to 6.8 ($p < 0.05$) with gradual increase in its concentration (Fig. 1A), a change that reveals its potential for sweetness enhancement. Similarly, the sweetness value of ethyl acetate demonstrated an increasing trend with concentration, increasing gradually from 5.0 to 6.1 (Fig. 1B), although the increase was slightly lower than that of ethylhexanoate.

Particularly striking was the sweetness value of ethylacetoacetate, which significantly increased from 5.0 to 8.5 as the concentrationincreased (Fig. 1G), showing an excellent sweetening effect ($p < 0.05$). In addition, ethylacetoacetate also received high comfort ratings in sensory tests (Fig. 1G), which provides an additional advantage for its application in the food industry. It is noteworthy that the sweetness values of phenethylalcohol showed a nonlinear trend of increasing, then decreasing and then increasing within the concentration range of 0-30 mg/kg. This unique phenomenon may be closely related to its aroma threshold and sensory properties, suggesting that the sweetness perception of phenethylalcohol may be affected by its aroma properties in a specific concentration range. In addition, Xiao et al. (2024b) noted that fruity aroma substances in sweet oranges significantly enhanced the sweetness of sucrose solutions. These fruity aroma substances share similar aroma properties with sweet aroma and may therefore contribute to the enhancement of sweetness perception. Based on these findings, we hypothesize that these aroma substances are able to sweeten because they have aroma attributes similar to sweet aromas, such as fruity, floral, or umami aromas. For instance, ethyl acetate carries prominent fruity odor matching sweet sensory cues. This cross-sensory signal overlap aligns with the halo-dumping effect summarized

by Clark and Lawless (1994), a general sensory bias where untargeted flavor sensations are assigned to adjacent taste dimensions by panelists, which serves as one neutral auxiliary explanation for the observed sweetness rise rather than a definitive causal mechanism.

In order to evaluate the sweetening effect of these aroma substances more comprehensively, in addition to sensory evaluation, we also used the electronic tongue experiment. As an instrument that simulates human taste, the electronic tongue can provide objective data to help us understand the effect of aroma substances on sweetness perception more accurately. Notably, inconsistent changing trends were observed between sweetness values and comfort scores across multiple aroma groups. For ethyl hexanoate, trans-2-hexen-1-ol and phenylacetaldehyde, sweetness continuously rose with growing concentration, while comfort scores declined after reaching an optimal concentration point. This divergence arises from dual sensory influences: low-to-moderate concentrations produce harmonious fruit-flavor combinations that improve overall sensory comfort; once aroma concentration exceeds the acceptable sensory threshold, pungent, heavy or irritating odor notes dominate the oral sensation, creating unpleasant sensory experience even though sweet signals are further strengthened. The mismatch between sweetness and comfort highlights that aroma dosage must be strictly controlled when applying aroma-assisted sugar reduction.

Electronic tongue analysis

Electronic tongue technology, as an emerging chemical sensing system, has shown great potential and application in the field of taste analysis. It is capable of quickly and accurately assessing and analyzing the taste of food, beverages, and other chemical samples by mimicking the taste perception ability of the human tongue (Bai et al. 2022). An electronic tongue system usually consists of multiple sensors that have specific responses to the taste properties of different chemicals (e.g., sweet, sour, bitter, salty, and umami). By analyzing the response patterns of these sensors, the electronic tongue is able to recognize and differentiate between a variety of complex taste samples (Gong et al. 2016). First a 2.4% glucose solution was tested with a response value of 20.38. using this as a criterion, samples with readings above 20.38 mV were described to have higher sweet-related sensor response values.

Fig. 2 records the sweet-related sensor response values of seven aromatic compounds under serial concentration gradients. It should be emphasized that all voltage signals only reflect chemical adsorption on sensor membranes, which cannot be equated to real integrated sweet sensation felt by human assessors. Trans-2-hexen-1-ol, phenylacetaldehyde, cinnamyl alcohol and ethyl acetoacetate showed continuous upward sweet-related sensor signals as concentration rose, which is highly consistent with the rising sweetness score trend obtained from sensory evaluation. Notably, ethyl acetoacetate exhibited a relatively high sweetness response value at 125 mg/kg compared with other compounds (Fig. 2G), indicating a stronger sweetness-related signal under the present experimental conditions. In contrast, phenethylalcohol showed a non-monotonic response pattern, with the sweetness response value increasing at lower concentrations and decreasing at higher concentrations (Fig. 2C). This behavior suggests a concentration-dependent modulation of the electronic tongue response, rather than a simple linear relationship. Similarly, ethylhexanoate exhibited a biphasic response pattern, characterized by an initial decrease followed by an increase and stabilization at higher concentrations. Such response profiles may reflect sensor-specific response characteristics of the electronic tongue system at different concentration ranges. Ethyl acetate showed relatively stable sweetness response values across the tested concentrations, indicating a limited effect on sweetness-related sensor signals under the present experimental conditions (Fig. 2B).

However, it is important to recognize that the principles of electronic tongue and manual sensory evaluation are fundamentally different. E-tongue is mainly analyzed based on the potential response of the sensor to the chemical composition of the sample (Nery and Kubota 2016), whereas artificial sensory evaluation is more complex and involves a variety of psychological, neurobiological, and comfort factors. Combining sensory and electronic tongue data achieves more comprehensive and reliable evaluation of aroma-induced sweetness changes.

Docking of aroma substances, glucose, with sweetness receptors

In a molecular level study to investigate the effect of different aroma substances on the perception of glucose sweetness, first, each aroma substance was independently docked onto a sweetness receptor in order to form a stable aroma substance-sweetness receptor binary system complex. On the basis of the binary system complex, glucose molecules were further docked onto the formed aroma substance-sweetness receptor complex. Binding free energy was selected as the quantitative index for conformational screening; more negative calculated values correspond to more energetically favorable static binding conformations within computational models (Raghavendra et al. 2015). Docking results were evaluated based on the calculation of binding free energies, with lower binding free energies indicating more stable ligand-receptor binding and stronger interactions (Morris and Della 2021).

Table 1 summarizes the molecular docking results, illustrating the predicted changes in interaction characteristics between glucose and the sweet taste receptor upon the introduction of aroma substances. In the absence of aroma compounds, the predicted binding free energy between glucose and the sweet taste receptor was

Table 1. Binding energy, hydrogen bonding and hydrophobic interactions between glucose and sweet taste receptor after the addition of aromatic substances. The binding-free-energy values shown are predictive scores obtained from molecular docking simulations and are not experimentally measured binding free energies. All data are derived from ternary-complex models containing aromatic compound, glucose and sweet-taste receptor.

	Binding energy (kcal/mol)	Binds key amino acids with hydrogen bonds	Hydrophobic residue
Glucose	-5.108	LYS-65, ASP-142, SER-144, SER-165	ASN-143, TYR-215, ASP-278, SER-303
Ethylhexanoate	-7.345	LYS-65, SER-144, SER-165, ASP-278, GLU-302	ASN-143, ALA-166, SER-303
Ethylacetate	-7.124	LYS-65, SER-144, ASP-218, ASP-278, GLU-302	ASN-143, SER-165, TYR-215
Phenethylalcohol	-8.33	LYS-65, TYR-103, ASP-142, SER-144, SER-165, ASP-278	ASN-143, ALA-166, TYR-215, ASP-278, SER-303
Trans-2-Hexen-1-ol	-7.151	ILE-104, ASN-107, VAL-108	ASN-106, THR-149, LYS-155, PHE-159, THR-179
Cinnamylalcohol	-8.066	THR-214, TYR-215, SER-224, GLN-237, THR-239	GLU-238
Phenylacetaldehyde	-5.047	ARG-76, TYR-96, GLU-80, GLN-344, GLY-346	ASN-24, ASP-26, LEU-29, PRO-343, GLY-346
Ethylacetoacetate	-8.771	LYS-65, SER-165, ASP-278, GLU-302	Asp-142, Ser-303

−5.108 kcal/mol, indicating a favorable binding propensity. Binding free energy acts as a standard computational descriptor for ligand-protein interaction analysis, where more negative outputs reflect lower energy barriers for static complex formation *in silico* (Yu et al. 2023).

Following the introduction of different aroma substances, the docking results showed an overall decrease in the predicted binding free energy of glucose to the sweet taste receptor. For example, in the presence of ethylhexanoate, the predicted binding free energy decreased to −7.345 kcal/mol, while the addition of ethyl acetoacetate further reduced this value to −8.771 kcal/mol. The computational outputs reveal that aromatic ligands remodel the local microenvironment surrounding glucose within the simulated binding pocket, offering a structural basis to interpret the variation of sweet response recorded in tests. All structural configurations obtained via docking are static snapshots captured under fixed computational parameters. Analysis of the interaction patterns indicated that multiple hydrogen bonds could form between glucose and the sweet taste rec eptor, involving amino acid residues such as LYS-65, ASP-142, SER-144, and SER-165. The side chains of these residues were predicted to form hydrogen bonds with glucose, which may contribute to stabilization of the predicted ligand–receptor binding conformations. In addition, hydrophobic interactions involving residues including ASP-278, SER-303, TYR-215, and ASN-143 were observed, which may further support structural stabilization of the docked complexes.

It should be noted that these molecular docking results reflect potential binding propensities and interaction patterns, rather than receptor activation or downstream signal transduction efficiency. Therefore, the physiological relevance of these predicted interactions requires further experimental validation.

Fig. 3 provides a visual illustration of the putative interactions among aroma compounds, glucose, and the sweet taste receptor using 2D interaction diagrams and 3D docking poses. In representative docking poses, glucose was observed to form putative hydrogen-bond contacts with several receptor residues. For example, in the presence of phenethylalcohol, potential hydrogen-bond interactions were observed between glucose and residues including LYS-65, ASP-278, TYR-103, ASP-142, SER-165, and SER-144. These contacts indicate plausible interaction features at the ligand–receptor interface under the tested docking conditions.

Hydrophobic contacts were also observed in the ternary complex, involving residues such as SER-303, ASP-278, ASN-143, TYR-215, and ALA-166. These nonpolar interactions may be relevant to the local binding environment of the aroma compound–glucose–receptor assembly and provide structural clues that could be associated with the sweetening effect.

It should be emphasized that these interpretations are derived from docking-based static poses and are therefore hypothesis-generating rather than quantitative or causal evidence. Docking can suggest plausible interaction patterns but does not directly determine binding pathways, conformational dynamics, or signaling efficiency. Further validation (e.g., molecular dynamics simulations, free-energy calculations, and/or functional assays) would be needed to substantiate the proposed mechanisms. Overall, these docking observations offer molecular-level clues for how aroma compounds may modulate sweetness perception through potential interactions with the sweet taste receptor.

Conclusion

Sensory evaluation and electronic tongue tests were conducted to examine the sweetening capacity of seven aromatic compounds in glucose aqueous solutions. Firstly, it was observed that all these aroma substances could enhance the sweetness perception of glucose to a certain extent through the combined application of sensory evaluation and electronic tongue technology. After that, the interaction of the ternary system of aroma substances-glucose-sweetness receptor was deeply analyzed by molecular docking technique. Simulation results indicated that hydrogen bonding and hydrophobic

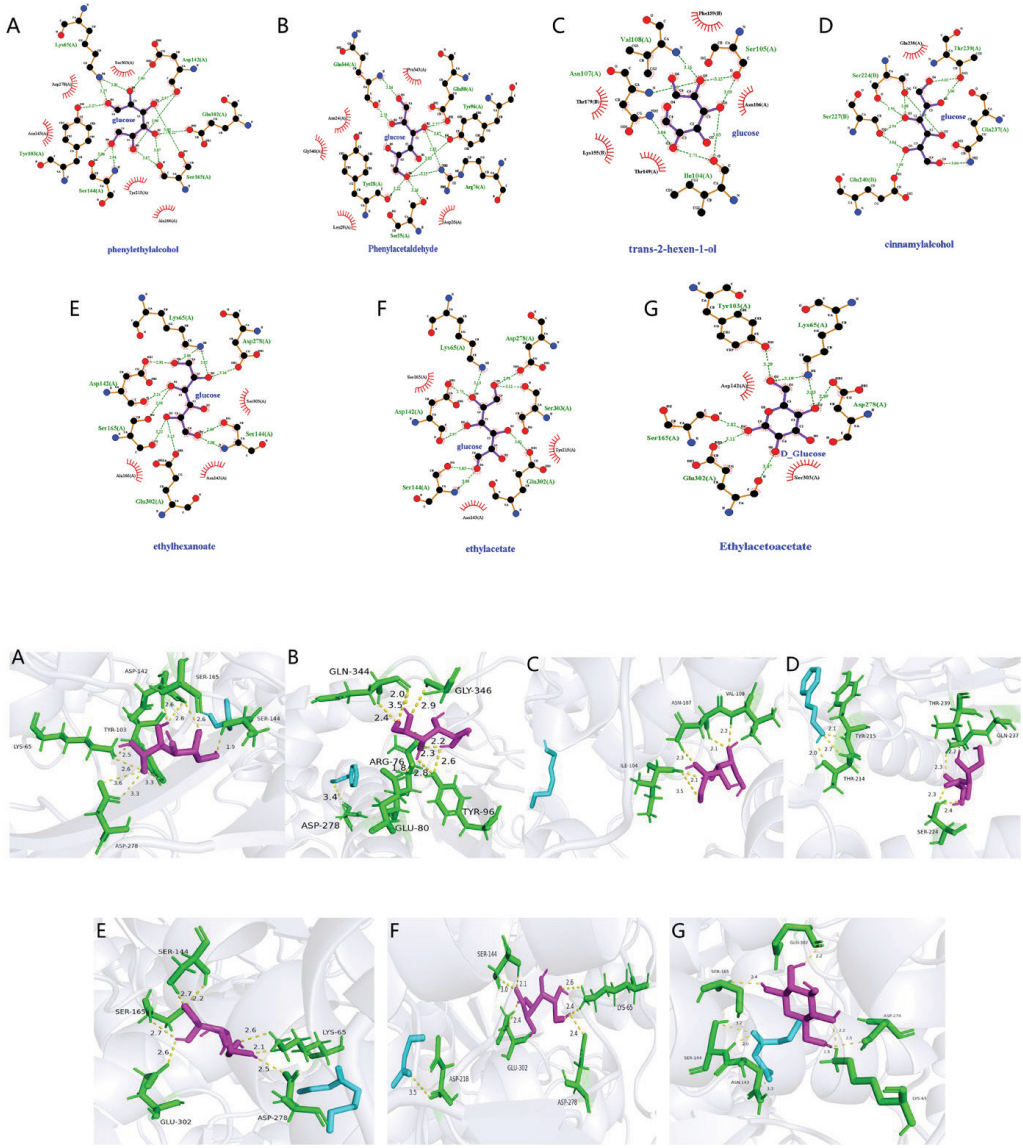

Figure 3. A–G. Represents the 2D and 3D diagrams of phenethylalcohol (**A**), phenylacetaldehyde (**B**), trans-2-hexen-1-ol (**C**), cinnamylalcohol (**D**), ethylhexanoate (**E**), ethylacetate (**F**), and ethylacetoacetate (**G**) interacting with glucose and sweet taste receptors. The 2D interaction diagrams were generated using LigPlot+ software, and the 3D docking conformations were visualized with PyMOL software. Blue indicates the aromatic substances, purple represents glucose, and green highlights the key amino acid residues involved in hydrogen bonding.

interactions serve as key structural forces for maintaining the stable conformation of the ternary complex in computational models. Docking simulations predicted lower binding free energy for glucose in ternary complexes with extra hydrogen and hydrophobic contacts, which offers tentative molecular clues for the observed sweetness elevation. These static computational findings cannot independently confirm receptor activation or in-vivo sweet signaling, and cellular functional tests are required to verify the full molecular mechanism. These findings provide predictive and exploratory insights into aroma–taste interactions at the molecular level, which may serve as a theoretical reference for future studies on sweetness modulation. Further validation in real food matrices and physiological systems is required before practical applications can be considered. Notably, the optimal sweetening performance of ethyl acetoacetate was observed only in simplified aqueous model solutions. Further verification in diverse real food matrices is required to support its practical flavor regulation application. Consistent with its exploratory research attribute, this study has several systematic limitations. First, sensory evaluation data were collected from a limited panel of assessors, which generates subjective sensory scoring characteristics. Second, all experiments were implemented in pure glucose aqueous systems without complex food components. Third, electronic tongue data only record sensor chemical response signals under instrumental detection conditions, reflecting instrumental response characteristics. Fourth, molecular mechanism analysis is exclusively based on static docking structural snapshots and *in silico* energy parameters, describing

molecular static binding features under theoretical calculation conditions. Future studies can focus on real food matrix verification and multi-dimensional physiological testing to further supplement the theoretical system of aroma-mediated sweetness modulation.

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Additional information

Conflict of interest
The authors have declared that no competing interests exist.

Ethical statement
No ethical statement was reported.

Artificial Intelligence (AI) use
The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.
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Data availability
All of the data that support the findings of this study are available in the main text.