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# The Effect of Sonication on Bubble Size and Sensory Perception of Carbonated Water to Improve Quality and Consumer Acceptability

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**Abstract:** Bubbles are important for carbonated beverage quality since smaller bubbles contribute to higher acceptability. Therefore, the effects and acceptability of the application of audible sound in carbonated water were studied using three brands and applying five frequencies for one minute each in ascending order. Six samples, two from each brand, were used for treatments: (i) control and (ii) sonication. Physicochemical measurements consisted of total dissolved solids (TDS), electric conductivity (EC), pH, bubble size, and bubble size distribution. A sensory session ($N$ = 30) was conducted using the Bio-Sensory application to assess acceptability and emotions using self-reported and biometric responses. Statistical analysis included: ANOVA ($\alpha = 0.05$) and principal component analysis (PCA) for quantitative data and Cochran Q test with pairwise comparisons ($p < 0.05$) for self-reported emotion responses. Results showed that the sonication effect for the sample with higher TDS, EC, and pH (SPS) reduced bubble size by 46%, while in those with lowest TDS, EC, and pH (IceS) caused an increase of 158% compared to the control. For samples with intermediate values (NuS), there were non-significant differences ($p > 0.05$) compared to the control. Acceptability was higher for samples with sonication for the three brands. Emotional self-reported responses were more positive for samples with sonication, showing significant differences ($p < 0.05$) for emotions such as "happy" and "pleased" during both sound and visual assessments. From PCA, a positive relationship between bubble size and liking of bubbles was found as well as for the number of medium bubbles and happy facial expression. The audible sound generated by ubiquitous sound systems may potentially be used by the industry, applying it to the bottled product to modify bubble size and improve quality and acceptability of carbonated beverages.

**Keywords:** audible sound; bubble size; emotions; acceptability

## 1. Introduction

Carbonated water is the beverage classified by either natural carbonation or gas injection categories depending on the source of the product. The first category corresponds to the water obtained from springs in which carbon dioxide ($CO_2$) is produced naturally [1], while gas injection corresponds to water from any source which is carbonated by incorporating $CO_2$ at high pressure [2]. The importance of carbonated water in the market relies on its rapid growth rate in terms of volume sales within the category of bottled beverages as it is selected as an alternative to still water and soft drinks. In Australia, this growth accounted for 32% of total volume sales between 2010–2015, which is comparable to still water growth of 39% within the same period [3]. Carbonated water is mostly consumed in countries such as Chile, Argentina, Netherlands, Uruguay, and Germany and is specially paired with meals [4]. Carbonated water is preferred by most consumers because it is seen as more enjoyable due to the fizzing sensation [5] and healthier than soft drinks by adults; moreover, children perceive fizziness to be more attractive [6].

Bubble-related parameters are the most important quality and sensory attributes in carbonated water due to the lack of other descriptors such as flavor and aromas, which makes consumers focus more on its appearance and mouthfeel [7,8]. Regarding bubble size, it has been reported that smaller bubbles in carbonated beverages such as beer and sparkling wine are usually preferred by consumers due to the longer foam stability [9,10]. It has been shown that in sparkling water, consumers have the same preference for small bubbles; however, consumer acceptability studies related to bubble size in carbonated water are limited. Authors such as Barker et al. [11] have concluded that consumers prefer smaller bubbles in carbonated water, but this study was conducted with 17 participants with only two samples, "normal" and small bubbles, which limited the validity of their conclusions.

There are a few published studies related to bubble size modification in carbonated water [11,12]. However, the methods presented in those studies involve gas injection to alter the size, which would not be applicable for carbonated waters from natural sources. Gonzalez Viejo et al. [13] have studied the effects of audible sound (low-frequency sonication) in beer both during fermentation and natural carbonation stages to improve foam-related parameters. The main result was a significant reduction in bubble size. However, the source of the effects was not investigated, which means that it did not specify whether the bubble size alteration was due to changes in yeast activity, to physical effects or both.

Therefore, this study aimed to assess the physical effects of low-frequency sonication on carbonated water bubbles. The physicochemical parameters, consumer acceptability and emotional self-reported and biometric responses to carbonated water samples from three different brands with two treatments: (i) control and (ii) using audible sound frequencies within the 20–75 Hz range, were also measured. The study consisted of measuring parameters such as total dissolved solids (TDS), electrical conductivity (EC), and pH as well as bubble size and bubble size distribution (small, medium and large bubbles) using computer vision algorithms. Furthermore, samples were assessed for acceptability and emotional responses using biometrics from consumers using a novel Bio-Sensory application (App; The University of Melbourne, Melbourne, VIC, Australia).

## 2. Materials and Methods

### 2.1. Samples Description

Samples used in this study consisted of two treatments: (i) control and (ii) treated with audible sound of three different commercial brands of carbonated water ($n$ = 6; Table 1). The sonication was applied to three 500 mL polyethylene terephthalate (PET) bottles from each brand at refrigeration temperature (4 °C) and consisted of treating the unopened bottles with five different frequencies, 20 Hz, 30 Hz, 45 Hz, 55 Hz, and 75 Hz, for one minute each [13]. As shown in Figure 1, the sonication treatment was applied using two sub-woofers Response CW2199 (Jaycar Electronics, Sydney, NSW, USA)—resistance: 8 Ω, RMS power: 225 W, diameter: 12′′ maximum decibels: 90 dB, maximum power: 450 W—connected to a DigiTech AA0479 amplifier (DigiTech, Sandy, UT, USA) and controlled with the Audio Function Generator application available in the App Store (Thomas Gruber) using an iPhone 5s (Apple Inc., Cupertino, CA, USA). All frequencies were applied in stereo mode using the same volume in both subwoofers and −4 dB of amplitude. There was a distance of 15 cm between the bottle and each subwoofer.

**Table 1.** Description and labels of samples used for the study.

| Brand | Image | Sample Denomination | Bottle Dimensions (Diameter/Height/Neck Diameter/Thickness) | $CO_2$ Source | TDS in Label | Label Control | Label Sonication Treatment |
|---|---|---|---|---|---|---|---|
| San Pellegrino |  | Sparkling natural mineral water | 22.0 cm/22.5 cm/11.5 cm/0.40 mm | Natural springs with natural $CO_2$ added | 854 ppm | SP | SPS |
| Nu Pure |  | Lightly sparkling water | 22.5 cm/22.0 cm/12.5 cm/0.39 mm | Natural springs | Not reported | Nu | NuS |
| Icelandic Glacial |  | Natural spring water | 21.0 cm/24.3 cm/11.8 cm/0.40 mm | Natural springs with added $CO_2$ | 62 ppm | Ice | IceS |

Abbreviations: TDS = Total dissolved solids, $CO_2$ = carbon dioxide.

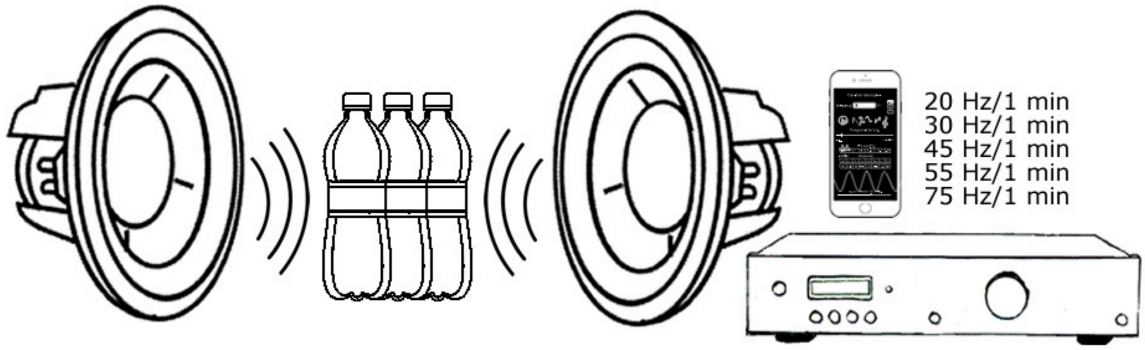



**Figure 1.** Set up of the application of audible sound waves to carbonated water samples.

Frequencies were selected from a range from 20 to 100 Hz by applying them to milk in a petri dish with dry thyme leaves as particles to observe movements. Videos were recorded and magnified using the Eulerian magnification algorithm [14] for movement detection with Matlab® R2019a (Mathworks, Inc., Natick, MA, USA). Frequencies that generated movement of the particles in different directions were chosen. These movements are shown in Figure 2. All frequencies were tested in stereo mode using the same volume in both subwoofers and −4 dB of amplitude.

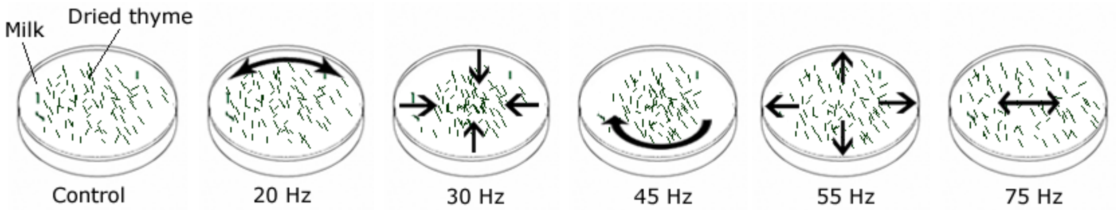



**Figure 2.** Selected frequencies for sonication and the direction of particle movements obtained. Movements were stationary for control; rotational in both directions for 20 Hz; grouping in the center for 30 Hz; rotational clockwise for 45 Hz; segregation movement for 55 Hz and horizontal bidirectional movement for 75 Hz.

### 2.2. Physicochemical Analysis

Duplicates of samples (two bottles of each) were assessed for TDS and EC using a Yuelong YL-TDS2-A digital water quality tester (Zhengzhou Yuelong Electronic Technology Co., Ltd., Zhengzhou City, Henan Province, China). Furthermore, the same samples were measured for pH using a pH-meter Benchtop pH/mV meter 860031 (Sper scientific direct, Scottsdale, AZ, USA), which was calibrated using buffer solutions of 4.0 and 7.0. The three measurements were conducted using 50 mL of carbonated water samples at 25 °C from remnant samples after opening for bubble analysis.

Samples were assessed for bubble-related parameters using computer vision algorithms. The method consisted on manually pouring the sample up to half of the capacity of a Greiner Bio-One Polystyrene petri dish 94 mm for standardization (part number 633179; Greiner Bio-One, Kremsmünster, Austria); the dish was placed on a small lightbox constructed using a light pad covered with a black box, and images were taken using an iPhone 5s. The same petri dish was used for all samples and was dried using a White Magic® cloth made of 72% polyester and 27% polyamide to remove any lint and avoid bias due to additional nucleation points for bubbles [15] that could be formed due to foreign matter or defects in the petri dish. All images were taken from the same height to get comparable measurements at the same scale. The images were taken 5 s after pouring to assess the bubbles formed initially and were assessed using a customized Matlab R2019a developed by the sensory group from The University of Melbourne, Australia. This algorithm is able to automatically detect the petri dish, crop the image, and recognize every single bubble from the binary image, which are then counted, measured for diameter and distributed according to size. Once the raw data for each bubble is obtained, bubbles are classified as small, medium, and large (Figure 3). Therefore, the parameters obtained from this method are: (i) average bubble diameter (AvgBubbSize), (ii) number of small bubbles (SmBubb; 0–25 pixels; 0.00–0.07 cm), (iii) number of medium bubbles (MedBubb; 26–53 pixels; 0.08–0.16 cm), (iv) number of large bubbles (LgBubb; 54–81 pixels; 0.16–0.24 cm), and (v) total number of bubbles.

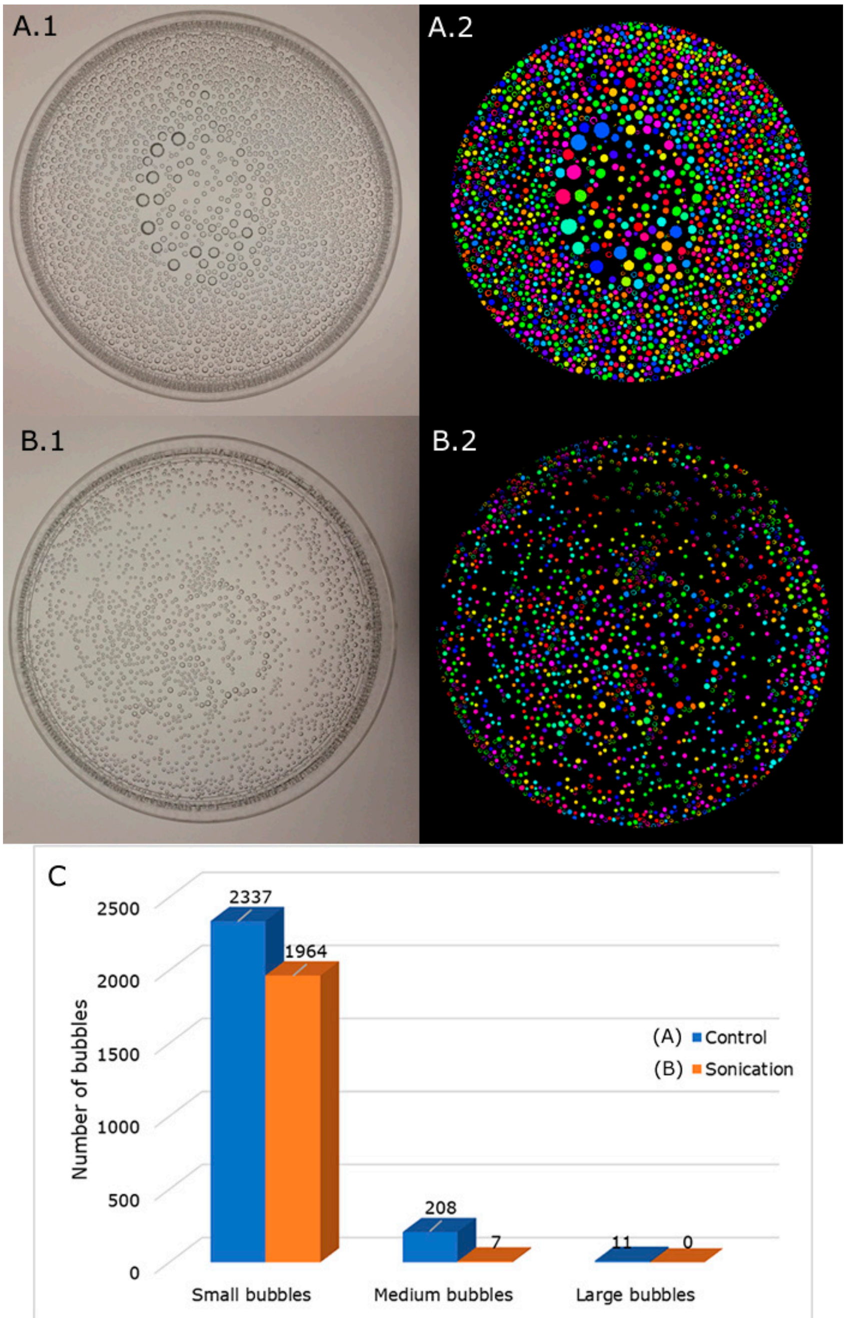



**Figure 3.** Bubble analysis of one replicate of (**A**) control (SP) and (**B**) sonication treatment (SPS) samples, where (**A.1**) and (**B.1**) are images taken using the lightbox, and (**A.2**) and (**B.2**) images processed using the algorithm to detect, count, and measure bubbles using Matlab® R2019a; different colors represent different bubble sizes. (**C**) shows the bubble size and bubble size distribution (small, medium, large bubbles) of both (**A**) and (**B**). SP and SPS are samples used, defined in Table 1.

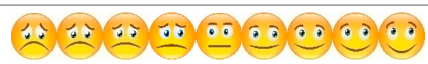
### 2.3. Sensory Evaluation

A total of $N = 30$ consumers was recruited from staff and students of The University of Melbourne (Ethics ID: 1545786.2). The number of participants was sufficient to find significant differences according to the Power analysis ($1 - \beta = 0.90$) performed using SAS® Power and Sample Size 14.1 software (SAS Institute Inc., Cary, NC., USA). The sensory session was conducted in the Sensory Laboratory of the Faculty of Veterinary and Agricultural Sciences of The University of Melbourne, which consists of 20 individual booths with uniform white light, each booth is equipped with a Samsung Galaxy View 18″ tablet PC (Samsung Group, Seoul, South Korea; Figure 4). The session was conducted at ambient temperature (24–25 °C), and 30 mL of samples were served in plastic cups at refrigeration temperature (4 °C) as it is the normal consumption condition. All samples ($n = 6$) were labeled with three-digit random codes and were served in random order to avoid bias from participants. Three bottles of each sample were used, and each bottle was used randomly for 10 participants. The sonication treatment was applied 2 h before the sensory session.

**Figure 4.** Participant in the booth during the sensory session using the integrated camera system and Bio-Sensory App.

To gather data from consumers, the Bio-Sensory application (App; The University of Melbourne, Melbourne, VIC, Australia) was used, which is able to display the questionnaire, randomize the samples, and automatically record videos of the participants while assessing the samples (Figure 4) [16]. The questionnaire consisted of three main assessments: (i) fizzing sound when opening the bottle, (ii) visual assessment, and (iii) mouthfeel/taste. The sound assessment (i) required the participants to wear wireless headphones (Home & Co., Kmart, Hoffman Estates, IL, USA) to listen to the fizzing sound of the sample when opening the bottle, which was pre-recorded and uploaded to the Bio-Sensory App, this recording was presented followed by the questions presented in Table 2. For the visual assessment (ii), videos from the pouring of the samples were included in the Bio-Sensory App, the pouring was done using a robotic pourer RoboBEER (The University of Melbourne, Melbourne, VIC, Australia) [17], and videos were followed by the questions in Table 2. For the last assessment (iii), samples were served to participants, and they were required to taste them for mouthfeel and tastes evaluation (Table 2).

**Table 2.** Questionnaire presented to consumers in the sensory session for each sample.

| Assessment | Question | Scale | Anchors/Options |
|---|---|---|---|
| **Sound** | Liking | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |
| | Face Scale | Continuous non-structured (9 cm) |  |
| | Emotions | Check all that apply | Happy */Sad */Surprised */Angry */Disgusted */Scared *+/Contempt ˆ/Neutral ˆ/Calm */Pleased */Satisfied */Loving */Joyful */Worried */Energetic */Active */Glad */Steady */Interested */Aggressive * |
| **Visual** | Liking of bubbles velocity | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |
| | Liking of bubble size | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |
| | Face Scale | Continuous non-structured (9 cm) |  |
| | Emotions | Check all that apply | Happy */Sad */Surprised */Angry */Disgusted */Scared *+/Contempt ˆ/Neutral ˆ/Calm */Pleased */Satisfied */Loving */Joyful */Worried */Energetic */Active */Glad */Steady */Interested */Aggressive * |
| **Taste/Mouthfeel** | Liking of taste | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |
| | Liking of mouthfeel | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |
| | Overall liking | Continuous non-structured (9 cm) | Dislike extremely–Like extremely |

* Emotion-terms obtained from EsSense Profile® [18]; *+ Synonym of fearful from EsSense Profile®; ˆ Emotion-terms obtained from FaceReader™.

The Bio-Sensory App was also used for biometrics; it was configured to record videos of participants during the sound and visual assessments. These videos were analyzed for facial expressions using FaceReader™ 8 software (Noldus Information Technology, Wageningen, Netherlands) to assess 13 parameters, which consist of eight emotions (i) happy, (ii) sad, (iii) disgusted, (iv) scared, (v) contempt, (vi) neutral, (vii) angry and (viii) surprised, two dimensions (ix) valence and (x) arousal, and head orientation in (xi) x (XHead), (xii) y (YHead) and (xiii) z (ZHead) axes.

### 2.4. Statistical Analysis

All quantitative data were analyzed for significant differences through an analysis of variance (ANOVA) using Fishers least significant difference (LSD) post-hoc test ($\alpha = 0.05$) using the SAS® 9.4 software (SAS Institute Inc., Cary, NC. USA.). Furthermore, a multivariate data analysis based on principal components analysis (PCA) was performed using an algorithm written in Matlab® R2019a to assess the relationships between the physicochemical, self-reported, and facial expressions from consumers. Cochran Q test and the Bonferroni–Dunn method [19] for the pairwise test were performed for frequencies of self-reported emotional responses from check all that apply (CATA) test to assess significant differences between samples for responses from both the sound and visual assessments using MedCalc v.19.0.3 software (MedCalc Software, Ostend, Belgium). Furthermore, a correspondence analysis was conducted for CATA frequencies using XLSTAT (Addinsoft, Long Island City, NY, USA) to assess associations between samples and emotions.

## 3. Results

### 3.1. Physicochemical Properties of Carbonated Water

There were non-significant differences ($p < 0.05$) between treatments for TDS, EC, and pH. However, there were significant differences between the three brands (Table 3). Samples SP had the highest value for the three parameters (TDS = 443, EC = 941, pH = 5.5), while Ice presented the lowest values (TDS = 48, EC = 101, pH = 4.5). The three brands had different pH, being SP the highest (5.5) and Ice the lowest (4.5). According to the manufacturer, Ice sample has a pH of 8.4, claiming to be alkaline water; however, the measured value was much lower, making it the most acidic from the three brands.

**Table 3.** Means and standard deviation (SD) of chemical data. Different letters denote significant differences between samples assessed using the Fishers least significant difference test with $\alpha = 0.05$.

| Sample | Total Dissolved Solids (ppm) | | Electrical Conductivity (µs cm$^{-1}$) | | pH | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| **SP** | 442.5 $^{a}$ | 13.28 | 941.0 $^{a}$ | 27.71 | 5.5 $^{a}$ | 0.00 |
| **Nu** | 70.5 $^{b}$ | 2.89 | 149.5 $^{b}$ | 6.35 | 4.9 $^{b}$ | 0.00 |
| **Ice** | 47.5 $^{c}$ | 0.58 | 101.0 $^{c}$ | 1.16 | 4.5 $^{c}$ | 0.06 |

Table 4 shows the results of the ANOVA for bubbles assessment. There were significant differences between samples for all bubble parameters. Regarding bubble size, SP mean (14.84 pixels) was significantly higher than SPS (10.18 pixels), and IceS (13.46 pixels) was significantly higher than Ice (5.22 pixels). However, Nu and NuS had no significant differences, being Nu the sample with the largest bubble size (15.47 pixels) from all samples. There were significant differences between all six samples for the total number of bubbles, with SP containing the largest amount of bubbles (2723) and NuS the lowest (1107). In terms of bubble size distribution, there were non-significant differences between SP and Ice for the number of small bubbles. Samples Ice, Nu, NuS, and SPS did not have large bubbles, while SP presented the largest number (17).

**Table 4.** Means and standard deviation (SD) of bubbles analysis. Different letters denote significant differences between samples assessed using the Fishers least significant difference test with $\alpha = 0.05$.

| Sample | Bubble Size (Pixels First Row/cm Second Row) | | Total Number of Bubbles | | Number of Small Bubbles | | Number of Medium Bubbles | | Number of Large Bubbles | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| **Ice** | 5.22 $^{e}$<br>0.02 | 2.64<br>0.01 | 2193.84 $^{c}$ | 138.73 | 2193.84 $^{b}$ | 138.73 | 0.00 $^{d}$ | 0.00 | 0.00 $^{c}$ | 0.00 |
| **IceS** | 13.46 $^{c}$<br>0.04 | 10.44<br>0.03 | 1953.53 $^{d}$ | 132.21 | 1768.03 $^{c}$ | 110.26 | 180.36 $^{b}$ | 19.96 | 5.14 $^{b}$ | 2.00 |
| **Nu** | 15.04 $^{ab}$<br>0.04 | 6.16<br>0.02 | 1403.39 $^{e}$ | 147.67 | 1315.83 $^{d}$ | 202.86 | 87.56 $^{c}$ | 55.19 | 0.00 $^{c}$ | 0.00 |
| **NuS** | 15.47 $^{a}$<br>0.05 | 7.28<br>0.02 | 1106.82 $^{f}$ | 60.42 | 1013.47 $^{e}$ | 117.85 | 93.35 $^{c}$ | 57.43 | 0.00 $^{c}$ | 0.00 |
| **SP** | 14.84 $^{b}$<br>0.04 | 12.57<br>0.04 | 2723.20 $^{a}$ | 157.75 | 2196.79 $^{b}$ | 132.29 | 509.06 $^{a}$ | 284.04 | 17.35 $^{a}$ | 5.99 |
| **SPS** | 10.18 $^{d}$<br>0.03 | 5.05<br>0.01 | 2238.26 $^{b}$ | 239.59 | 2234.03 $^{a}$ | 242.08 | 4.23 $^{d}$ | 2.49 | 0.00 $^{c}$ | 0.00 |

Small bubbles were considered within the range of 0–25 pixels (0.00–0.07 cm), medium bubbles within 26–53 pixels (0.08–0.16 cm) and large bubbles between 54–81 pixels (0.16–0.24 cm).

## 3.2. Sensory Evaluation of Carbonated Water

### 3.2.1. Self-Reported Responses of Consumer Acceptability of Carbonated Water

Figure 5 shows the means and results of the ANOVA of the self-reported responses from consumers for the different sensory descriptors. There were significant differences between samples for all attributes, except for liking of taste and mouthfeel. Samples Ice and IceS, and Nu and NuS presented significant differences in most of the descriptors; however, SP and SPS did not have significant differences for any descriptor. For all descriptors, samples with sonication treatment had higher liking and face scale scores than the control.

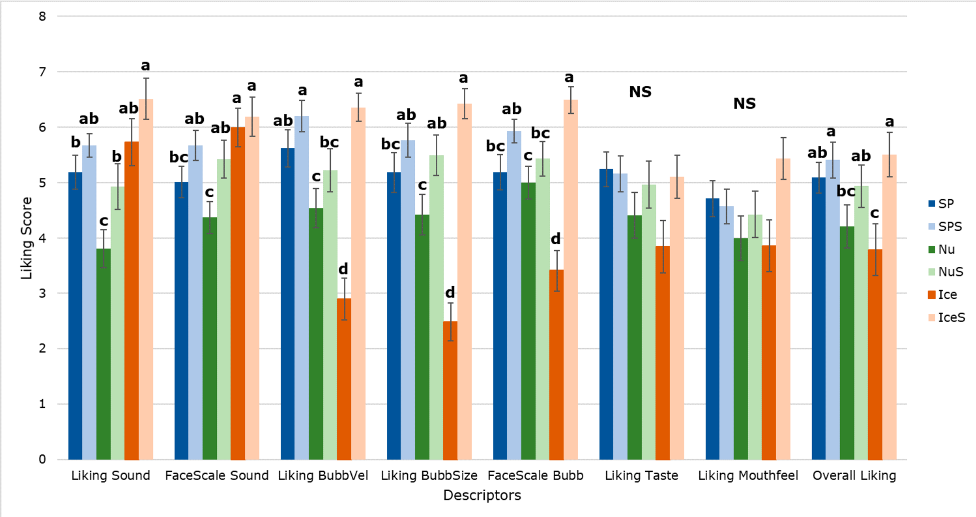



**Figure 5.** Means of the results from the self-reported responses of consumer acceptability of different sensory attributes. Error bars represent the standard error, and different letters denote significant differences between samples assessed using the Fishers least significant difference test with α = 0.05. NS = non-significant differences between samples, BubbVel = bubble velocity, BubbSize = bubble size, Bubb = bubbles. Table 1 describes the abbreviations of each sample.

### 3.2.2. Self-Reported Emotional Responses of Carbonated Water

Table 5 shows that nine out of 20 emotion-terms from the CATA question when assessing fizzing sound when opening the carbonated water bottle—Pleased, Active, Interested, Energetic, Happy, Neutral, Surprised, Joyful and Glad—presented significant differences ($p < 0.05$) between samples in the frequency of selection. IceS was the highest in the selection of positive terms such as Active, Interested, Energetic, Happy, Surprised, Loving, Joyful and Glad, and it presented no significant differences with Ice, but did present significant differences with Nu, which was the lowest in most of the terms above.

Figure 6 shows the correspondence analysis for the emotion-terms selection, factor 1 (F1) represented 50% of data, while F2 accounted for 25%, representing 75% of total data variability. In this figure, it can be observed that NuS and SP were more associated with terms such as Calm and Neutral, while SPS and Ice are more associated with Pleased, Energetic and Loving, and IceS was related mainly with Glad, Joyful and Interested. On the other hand, Nu, which is separated from the other samples, was related to negative terms such as Sad, Worried, and Contempt.

**Table 5.** Frequency of selection of the emotion-terms from the check all that apply sensory response for fizzing sound assessment. Different letters denote significant differences between samples assessed using Cochran Q and pairwise comparison tests [19].

| Emotion | SP | SPS | Nu | NuS | Ice | IceS |
|---|---|---|---|---|---|---|
| Pleased | 0.11 [ab] | 0.19 [ab] | 0.07 [b] | 0.16 [ab] | 0.25 [a] | 0.23 [ab] |
| Satisfied (NS) | 0.14 | 0.25 | 0.09 | 0.05 | 0.18 | 0.18 |
| Active | 0.12 [ab] | 0.16 [ab] | 0.07 [b] | 0.16 [ab] | 0.16 [ab] | 0.25 [a] |
| Interested | 0.11 [b] | 0.18 [ab] | 0.07 [b] | 0.14 [b] | 0.21 [ab] | 0.30 [a] |
| Energetic | 0.18 [ab] | 0.12 [ab] | 0.05 [b] | 0.18 [ab] | 0.18 [ab] | 0.23 [a] |
| Happy | 0.12 [b] | 0.19 [ab] | 0.07 [ab] | 0.16 [ab] | 0.14 [ab] | 0.25 [a] |
| Calm (NS) | 0.30 | 0.18 | 0.23 | 0.21 | 0.19 | 0.09 |
| Neutral | 0.18 [a] | 0.14 [ab] | 0.12 [ab] | 0.12 [ab] | 0.21 [ab] | 0.07 [b] |
| Sad (NS) | 0.00 | 0.00 | 0.04 | 0.02 | 0.02 | 0.02 |
| Surprised | 0.07 [ab] | 0.05 [ab] | 0.12 [ab] | 0.02 [b] | 0.05 [ab] | 0.16 [a] |
| Angry (NS) | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.00 |
| Disgusted (NS) | 0.02 | 0.02 | 0.09 | 0.00 | 0.00 | 0.02 |
| Scared (NS) | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Contempt (NS) | 0.04 | 0.04 | 0.11 | 0.07 | 0.04 | 0.02 |
| Loving (NS) | 0.04 | 0.04 | 0.02 | 0.05 | 0.04 | 0.05 |
| Joyful | 0.05 [b] | 0.11 [ab] | 0.02 [b] | 0.09 [ab] | 0.09 [ab] | 0.18 [a] |
| Worried (NS) | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.02 |
| Glad | 0.07 [ab] | 0.09 [ab] | 0.07 [ab] | 0.05 [b] | 0.09 [ab] | 0.19 [a] |
| Steady (NS) | 0.11 | 0.09 | 0.16 | 0.05 | 0.09 | 0.05 |
| Aggressive (NS) | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.02 |

NS = non-significant differences between samples.

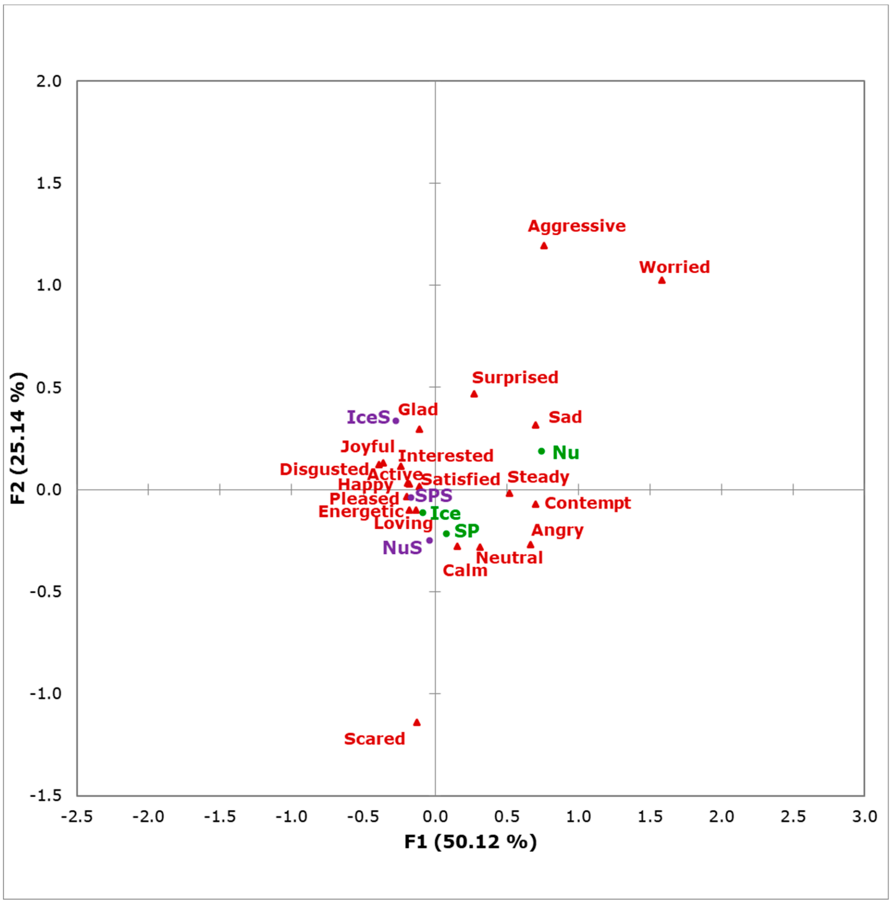



**Figure 6.** Correspondence analysis of the fizzing sound assessment showing the emotion terms in red and triangles, and the samples in green circles for the control and purple circles for the sonication treatments. Axes represent the contribution of factors 1 and 2 (F1 and F2).

Table 6 shows the ANOVA results of the CATA question for emotion terms from the visual assessment of the carbonated water samples. Nine out of 20 terms (Happy, Neutral, Calm, Pleased, Satisfied, Joyful, Active, Angry, and Disgusted) presented significant differences between samples. The term aggressive was not selected for any sample and, therefore, was removed from the results. IceS was highest for Happy and presented significant differences with the three control samples (SP, Nu, and Ice). Similarly, IceS was highest for Joyful and Active and was significantly different from control samples of Nu and Ice. On the other hand, Ice was the only sample that elicited the emotion Disgusted and the highest in Angry. Furthermore, similar to the sound assessment, Ice was the lowest in all positive emotions.

**Table 6.** Frequency of selection of the emotion-terms from the check all that apply sensory response for visual assessment. Different letters denote significant differences between samples assessed using Cochran Q and pairwise comparison tests [19].

| Emotion | SP | SPS | Nu | NuS | Ice | IceS |
|---|---|---|---|---|---|---|
| Happy | 0.14 [b] | 0.20 [ab] | 0.11 [b] | 0.18 [ab] | 0.05 [b] | 0.32 [a] |
| Neutral | 0.16 [ab] | 0.18 [ab] | 0.25 [a] | 0.18 [ab] | 0.18 [ab] | 0.05 [b] |
| Calm | 0.23 [ab] | 0.25 [ab] | 0.30 [a] | 0.27 [ab] | 0.09 [b] | 0.16 [ab] |
| Pleased | 0.30 [a] | 0.36 [a] | 0.18 [ab] | 0.30 [a] | 0.09 [b] | 0.27 [ab] |
| Satisfied | 0.23 [ab] | 0.30 [a] | 0.20 [ab] | 0.25 [ab] | 0.07 [b] | 0.23 [ab] |
| Joyful | 0.18 [ab] | 0.11 [ab] | 0.07 [b] | 0.14 [ab] | 0.07 [b] | 0.25 [a] |
| Energetic (NS) | 0.14 | 0.18 | 0.11 | 0.16 | 0.09 | 0.25 |
| Active | 0.16 [ab] | 0.16 [ab] | 0.09 [b] | 0.18 [ab] | 0.09 [b] | 0.27 [a] |
| Interested (NS) | 0.25 | 0.16 | 0.14 | 0.25 | 0.14 | 0.25 |
| Sad (NS) | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.00 |
| Surprised (NS) | 0.05 | 0.05 | 0.07 | 0.02 | 0.09 | 0.11 |
| Angry | 0.02 [ab] | 0.00 [b] | 0.00 [b] | 0.02 [ab] | 0.09 [a] | 0.00 [b] |
| Disgusted | 0.00 [b] | 0.00 [b] | 0.00 [b] | 0.00 [b] | 0.07 [a] | 0.00 [b] |
| Scared (NS) | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Contempt (NS) | 0.05 | 0.05 | 0.09 | 0.05 | 0.07 | 0.05 |
| Loving (NS) | 0.05 | 0.09 | 0.05 | 0.09 | 0.05 | 0.07 |
| Worried (NS) | 0.02 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 |
| Glad (NS) | 0.11 | 0.11 | 0.11 | 0.14 | 0.05 | 0.20 |
| Steady (NS) | 0.11 | 0.18 | 0.18 | 0.11 | 0.07 | 0.07 |

NS = non-significant differences between samples.

Figure 7 shows the correspondence analysis for the visual assessment in which F1 and F2 represent a total of 85% of data variability (F1 = 60.3%; F2 = 24.2%). It can be observed that Nu was more associated with terms such as Steady and Scared, while SPS and NuS were more related to Satisfied and Pleased and SP to Loving and Interested. IceS was more associated with Joyful, Happy, and Active. On the other hand, Ice is separated from all other samples and more associated with negative terms such as Disgusted, Worried, and Angry.

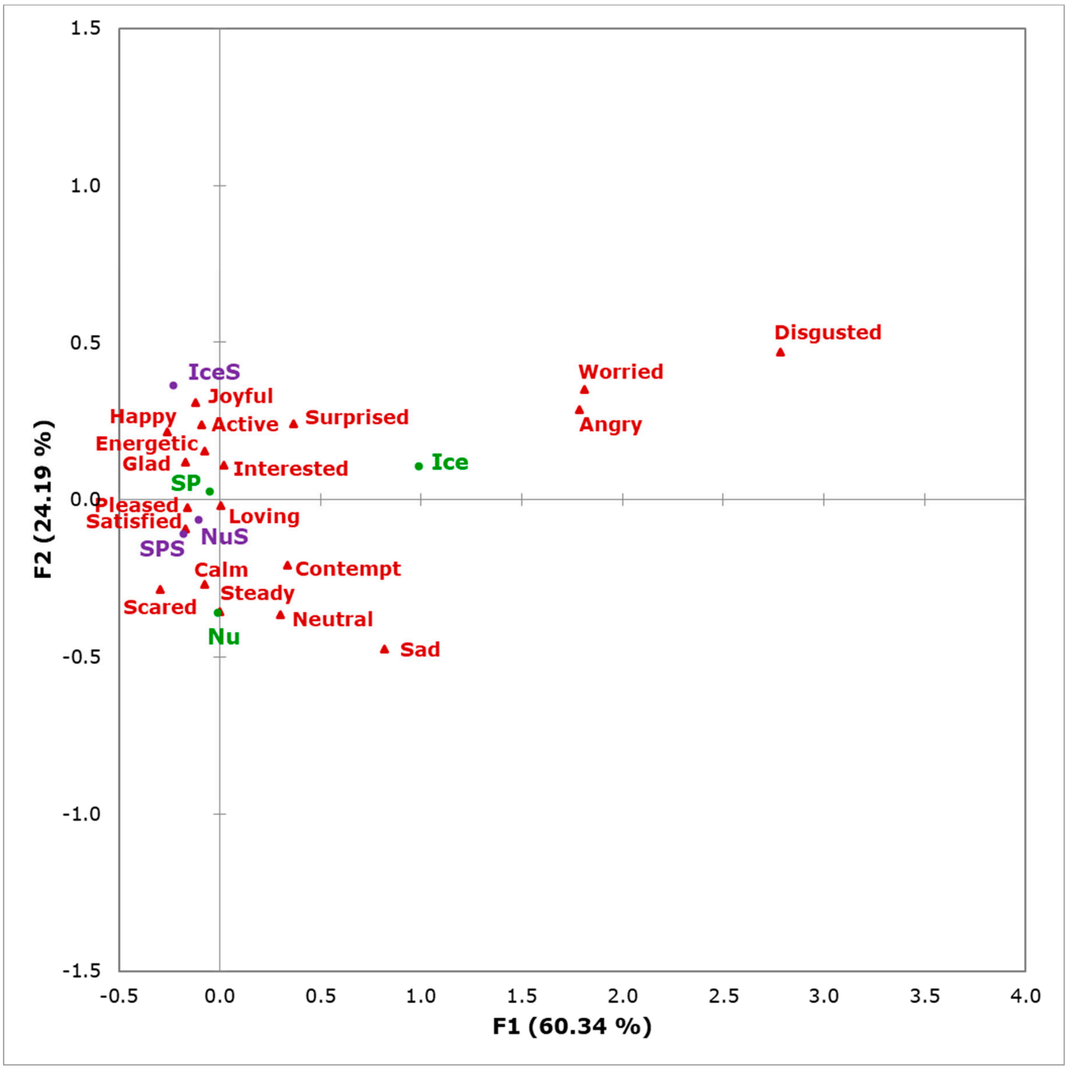



**Figure 7.** Correspondence analysis of the visual assessment showing the emotion terms in red triangles, and the samples in green circles for the control and purple circles for the sonication treatments. Axes represent the contribution of factors 1 and 2 (F1 and F2).

### *3.3. Multivariate Data Analysis*

Figure 8 shows the PCA using all sensory, facial expressions, and physicochemical responses. Principal components one and two explained a total of 74% (PC1 = 46%; PC2 = 28%). According to the factor loadings (FL) found in supplementary material (Table S1), PC1 was mainly represented by HappyFE (FL = 0.29) and Valence (FL = 0.28) on the positive side of the axis, and SadFE (FL = −0.25) and AngryFE (FL = −0.22) on the negative side. On the other hand, PC2 was mainly represented by DisgustedFE (FL = 0.33) and SurprisedFE (FL = 0.31) on the positive side and Liking BubbSize (FL = −0.31) and FaceScale Bubbles (FL = −0.32) on the negative side of the axis. It can be observed that AvgBubbSize was positively related to Liking BubbVel and overall liking, and these three descriptors were negatively related to SurprisedFE and ZHead. The number of medium bubbles was positively related to HappyFE and valence, while number of large bubbles had a positive relationship with valence and ContemptFE. Both medium and large bubbles had a negative relationship with SadFE and AngryFE. Number of small bubbles had a positive relationship with DisgustedFE and negative with AngryFE. Results from TDS and EC are positively related to arousal, while pH was positively related to Liking Sound. Samples SPS and IceS were more associated with Liking and FaceScale of sensory descriptors as well as AvgBubbSize, while NuS was more related to AngyFE and SadFE. SP was associated with Valence, ContemptFE and medium and large bubbles, while Ice was more related to SurprisedFE and ZHead. On the other hand, Nu is not positively associated with any parameters but is negatively related to pH, TDS, EC, and arousal.

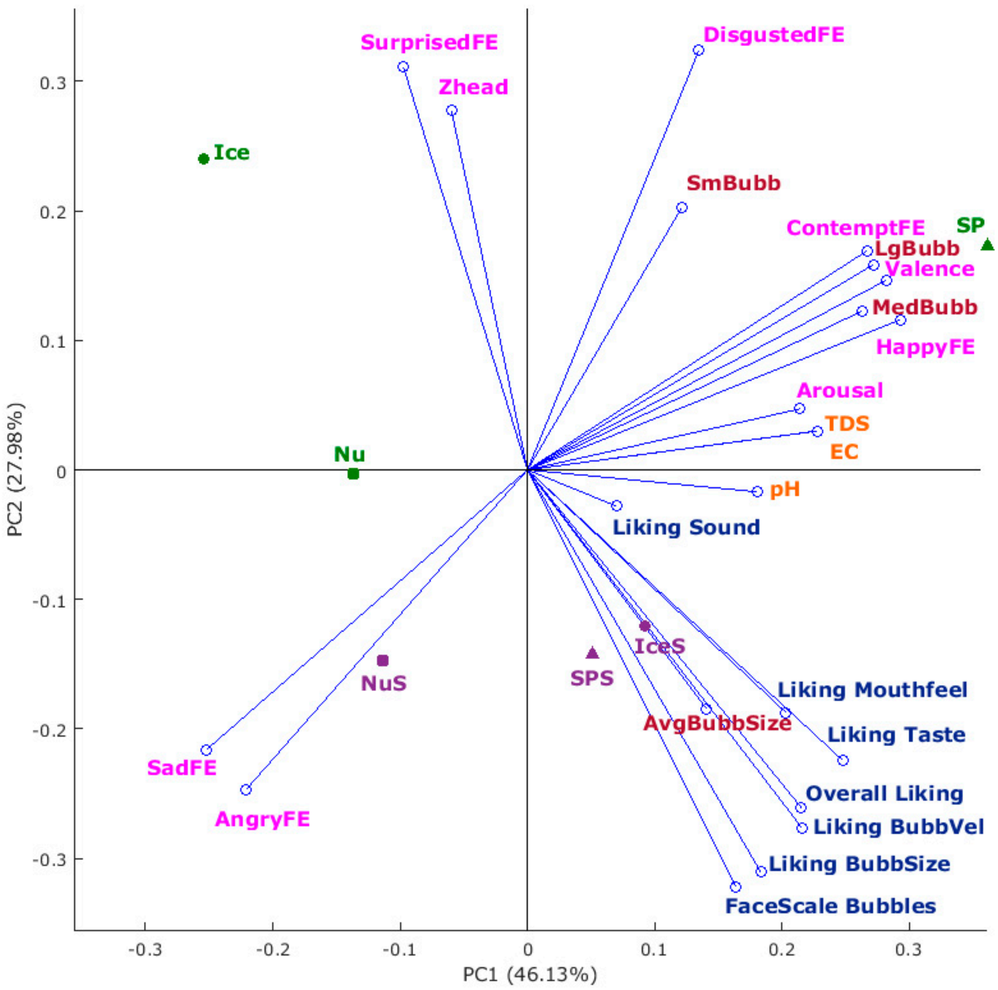



**Figure 8.** Biplot of the principal component analysis using all sensory, physicochemical, and facial expression responses. Abbreviations: PC = principal component, FE at the end of emotions = facial expression, SmBubb = number of small bubbles, MedBubb = number of medium bubbles, LgBubb = number of large bubbles, TDS = total dissolved solids, EC = electrical conductivity, BubbVel = bubble velocity, BubbSize = bubble size, AvgBubbSize = average bubble size and ZHead = head orientation in *z*-axis. Table 1 describes the abbreviations of each sample.

## 4. Discussion

### *4.1. Physicochemical Properties of Carbonated Water*

The TDS consists of the assessment of inorganic salts present in water; this parameter is used to assess drinking water quality [20]. Results from the measured TDS were compared with the information reported on the label. The SP sample measured value was much lower (442.5 ppm) than the one reported on the label (854 ppm). Likewise, the label of Ice sample stated a TDS of 62 ppm, but the measured value was lower (47.5 ppm). These differences were also reported by English [21] who found lower values of the samples. On the other hand, the Nu sample had a measured TDS of 70.5 ppm, but it does not report the mineral content in the label. Since electrical conductivity is a measure of the ions' concentration and is directly related to TDS, it is also used to assess mineralization of waters [22].

In a study by Liger-Belair et al. [23], they found that bubble size in low carbonated waters had an average of ~420 µm (14.2 pixels) after 5 s, which is the same time used in the present study. In medium carbonated waters, the average diameter at 5 s was ~560 µm (18.9 pixels) and in high carbonated waters ~1110 µm (37.4 pixels). Results from the average bubble size of all samples, except for Ice, coincide with the average size for the low carbonated waters in the aforementioned study. Ice had a bubble size of 5.2 pixels, which is even smaller than that reported by Liger-Belair et al., [23] for low-carbonated waters at time 0 s (~287 µm = 9.7 pixels). However, the diameter of Ice increased with sonication (IceS = 13.4 pixels) closer to the values of low carbonated waters.

On the contrary, for SP, the bubble size decreased with sonication (SP = 14.8 pixels; SPS = 10.2 pixels); however, no significant changes were found in bubble size of Nu and NuS. These differences in bubbles with the sonication treatment in the three brands may be due to other characteristics of the water such as the chemical composition (TDS, EC, and pH), which were different in the three samples. This may be explained due to the energy loss of a resonating bubble and its relationship with viscosity [24]. However, in terms of the total number of bubbles and the number of small bubbles, the sonication treatment significantly decreased the values compared with the control. For medium and large bubbles, these decreased significantly for SP when sonicated (SPS), increased for Ice with sonication (IceS), but no significant difference was found for Nu and NuS. The changes in bubble size distribution may be due to the effect of the pressure caused by the sonication treatment in the bottle due to the energy associated with the wavelength of audible sound waves, which although lower than ultrasound energy, it still alters the media and particles [25,26]. When the pressure in carbonated beverages is higher, the $CO_2$ solubility increases [27]. Therefore, the change in pressure caused by the application of soundwaves may be related to bubble size distribution because $CO_2$ is responsible for bubble formation and pressure is directly related with bubble size as this is given by the expansion or contraction of the gas inside the bubble explained by the ideal gas law [28].

### *4.2. Sensory Evaluation of Carbonated Water*

#### 4.2.1. Self-Reported Responses of Consumer Acceptability of Carbonated Water

Barker et al. [11] found that consumers prefer smaller bubbles in a study with 17 participants. However, in the present study, it was found that when bubbles are too small, consumers dislike the sample, as shown with Ice, which was the sample with the smallest average bubble size and had the lowest rating in descriptors such as face scale of bubbles, liking BubbVel, BubbSize, and overall liking. On the other hand, the samples with sonication treatment, SPS and IceS, which had an average bubble size in the middle of the range found in this study (range = 5–15 pixels; SPS = 10 pixels; IceS = 13 pixels) were the highest in liking of BubbVel, BubbSize, face scale Bubb and overall liking. In the fizzing sound assessment, there were improvements found between control and sonication treatment in liking and face scale responses for the three brands.

#### 4.2.2. Self-Reported Emotional Responses of Carbonated Water

Some studies have assessed different carbonated beverages such as sparkling water, sparkling wine, and beer just by presenting the fizzing sound when pouring the liquid, finding that consumers can assess the quality of the beverage based on this parameter only [29]. This, due to the smaller bubbles such as those in champagne producing a fizzing sound at a higher pitch than larger bubbles in a club soda water [30]. However, there are no known studies in which consumers emotions towards the fizzing sound when opening a bottle have been assessed. From Table 5 and Figure 6, it can be observed that in the case of the three brands, sonication treatment elicited more positive emotions than control, especially for Nu and Ice. This shows that sonication treatment also improves the fizzing sound of bottled carbonated water.

It has been reported that the visual assessment of foods and beverages is the most important because it gives the first impression to consumers. Especially, in carbonated beverages, bubbles visual assessment is important for consumers to assess the quality and acceptability [8,17]. There are no known studies in the consumers' emotional assessment of carbonated water from the visual perspective. However, a study in beer using biometrics showed that consumers are able to assess quality and acceptability by looking at videos of the pouring [17]. Results of self-reported emotions elicited from the visual assessment differ from the fizzing sound evaluation for specific terms; however, it has a similar trend as samples with sonication treatment had more positive terms selection, especially for Ice and Nu. When comparing emotion-terms selected from sound assessment for Ice, sound elicited more positive terms such as loving and energetic, but visual assessment had a higher selection of negative terms such as angry and worried. However, in Nu, the association with the selection of Steady coincided in both assessments (Figures 3 and 4).

### 4.3. Multivariate Data Analysis

From the PCA, it can be observed that taking all measurements, physicochemical, emotional and self-reported sensory responses, the sonicated samples SPS and IceS were more liked in all sensory attributes and elicited more positive responses from the face scale. Sample SP elicited higher valence and contempt (ComtemptFE) from the unconscious reactions of consumers. Ice, which was the least liked, elicited surprise (SurprisedFE) emotion from consumers and Nu was low in arousal. Contrary to other references that state that consumers approach when they are exposed to positive foods and avoid (retract) with negative foods [31], in this study it was found that consumers approach when they dislike the sample and retract when they like it. This trend was also found in a study assessing beer consumer acceptability using biometrics [32] and may be due to consumers feeling more comfortable and relaxed when they like a product, which makes them sit back [33]. Contrary to other studies that found that smaller bubbles are preferred [10,11,23], in this study, small bubbles elicited disgusted unconscious emotion (DisgustedFE), while medium bubbles were related with HappyFE and valence.

The sonication treatment presented in this study may be potentially used in the industry to improve the size and distribution of bubbles in carbonated beverages, which increase consumer acceptability and elicit more positive emotional responses. According to Hewson et al. [5], positive emotions such as enjoyment are within the main drivers for consumers to select carbonated water due to the fizziness, which elicits a pleasant sensation.

## 5. Conclusions

The application of sonication treatment using audible sound (20–75 Hz) showed to have a positive effect to improve the quality and consumer acceptability of carbonated water due to the effects of audible wavelengths which increase pressure within the bottle and, therefore, modifies bubble size during formation. This treatment increased the liking and elicited more positive emotional responses towards the fizzing sound, visual assessment, and overall liking. This would potentially be of interest to the industry to manipulate the bubble size of the finished product without altering the carbonation in the water, which is highly desired, especially for naturally carbonated waters. Further studies may be conducted to assess the time that the sonication effect lasts to define when the treatment should be applied and to evaluate the relationship between the TDS, EC, and pH of carbonated waters and the effects of sonication by using a larger number of samples with different values; this may also allow developing machine learning models to predict the bubble size and bubble size distribution using consumers biometric responses as inputs.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2306-5710/5/3/58/s1, Table S1: Factor loadings from the principal components analysis for both principal components one and two (PC1 and PC2).

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