An Acoustic Method for Flow Rate Estimation in Agricultural Sprayer Nozzles

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Abstract: The cost of current flow rate measurement devices is quite high compared to the cost of low-end microphones. This circumstance, together with the fact that common agricultural sprayers have more than 50 nozzles, makes the use of current flow rate measurement devices cost-prohibitive. That considered, this article examines, by proposing one particular method, the feasibility of using microphones as flowmeters for nozzle tips in agricultural sprayers. The proposed method consists of the following stages: (*i*) acquisition of the digital acoustic data sequence, (*ii*) signal preprocessing, (*iii*) frequency domain transformation using FFT analysis, (*iv*) in-band power calculation, (*v*) power normalization, and (*vi*) regression or curve fitting. This method was assessed in an in-lab sprayer test bench employing 11 commercial nozzle tips at several operating flow rates. The experimental results yielded, for all the tested nozzle tips, average absolute and relative Root Mean Square Error (RMSE) values always below 0.08 liters per minute (lpm) and 5%, respectively, while the overall mean absolute and relative RMSE values were lower than 0.05 lpm and 2.5%. The accuracies when employing a high-end microphone instead of a low-end one were slightly worse, with a relative accuracy difference around 30%. These results provide strong evidence of the feasibility of accurately estimating the nozzle tip flow rate in real time based on acoustic signals. Moreover, no significant improvements are to be expected by using a high-end microphone instead of a low-end one. However, there are still some issues that should be tackled in order to enable the application of this method in real agricultural settings.

Keywords: agricultural sprayer nozzle; flowmeter; acoustic signal; microphone; frequency analysis; cost-effective solution.

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1. Introduction

In the last few decades, agricultural sprayer technology has been continuously evolving toward the ability to accurately measure and control the flow rate of each individual nozzle on a spray boom [1, 2]. The recognition has been made that there can be significant variation between nozzles on a boom, and that the effects of vehicle turning maneuvers can be severely detrimental to achieve a uniform chemical application. By being able to control the flow rate of each individual nozzle, both a higher uniformity in turns and a more consistent application along straight paths can be achieved in the spread pattern of chemicals (pesticides, insecticides, fertilizers, and herbicides), which provides two distinct advantages. First, the reduction in the waste of chemicals would allow farmers to reduce the amount of chemicals used, thereby reducing production costs [3]. Second, in some applications the amount of chemicals to be dispatched is absolutely critical: when incorrect amounts are sprayed, either the chemicals will lack effectiveness because of under-application, or soil and crops will lose quality and yield, or they can be polluted and even irreversibly damaged, because of the over-application of chemicals [3-6].

To provide a finer resolution of control, solenoid-based electronic valves, controlled by *Pulse-Width Modulation* (*PWM*), have been employed in agriculture at the nozzle level [7, 8]. The practical implementations of nozzle-level PWM control have been limited to open-loop control, which implicitly relies on uniformity and consistency of all the components across the boom for control accuracy. Feedback control would be much more accurate, but it would require reliable, real-time flow measurements from each nozzle. There is no currently available flow metering technology that could provide suitable accuracy at reasonable cost and size for implementation at each nozzle. The goal of this study is to develop an acoustic-based flow measuring technology that would be appropriate for implementation at the individual nozzle level to facilitate feedback control.

Many published articles have addressed the sound generation of nozzles and orifices [9-11]. These studies have shown that the intensity and spectrum of the acoustic signal generated by nozzles and orifices change when the flow rate changes. Testud *et al.* [12, 13] investigated the sound generation by the presence of single-hole and multi-hole orifice plates along the pipe, showing that the characteristic whistling frequency of the emitted sound signal depends on the flow rate. Howe [14] showed that inner cavities in the pipe generate a sound signal whose acoustic intensity depends on the flow speed as a cubic function and whose cavity resonant tone frequency also depends on the speed of the stream flow. Druault *et al.* [15] also found a dependence of the acoustic signal spectrum on the flow rate due to the presence of a cavity along the pipe. Kobayashi *et al.* [16] studied, for an ocarina musical instrument, the dependence of the acoustic signal on the flow rate due to the presence of a cavity along the pipe.

Guided by the aforementioned research, the present study relies on the working hypothesis that flow rate changes through the sprayer nozzle tip will predictably change its generated acoustic signal both in intensity and frequency distribution. This hypothesis has already been proven valid in previous studies for taps or faucets [17, 18]. So far as the authors are aware, despite all the research advances, no prior progress has been made toward quantifying a relationship between the generated acoustic signal and the flow rate for sprayer nozzles. Thus, the proposal of this new acoustic flow rate estimation method is intended to become a point of inception for further research to gain more insight about flow rate estimation through acoustic signal processing.

The main goal of this article is to provide evidence supporting the feasibility of accurately estimating the flow rate of individual sprayer nozzles based on the acoustic signal measured close to the nozzle tip. To this end, four subobjectives can be highlighted: (*i*) the proposal of a new real-time flow rate estimation method based on the acoustic signal acquired by a nearby microphone, (*ii*) the assessment of this method's performance, (*iii*) the comparison of performance employing low-end versus high-end microphones, and (*iv*) the analysis of the influence of the nozzle-to-microphone distance on flow rate estimation.

This article will describe the aforementioned proposed flow rate estimation method and highlight the Materials and Methods employed to undertake the research in this study (Section 2), present the main results obtained from the assessment of this method (Section 3), and present a discussion of this study's findings and conclusions (Sections 4 and 5).

2. Materials and Methods

All tests in this study were performed in a well-adapted laboratory belonging to the Department of Biosystems and Agricultural Engineering at the University of Kentucky in Lexington, KY, USA.

2.1. Materials

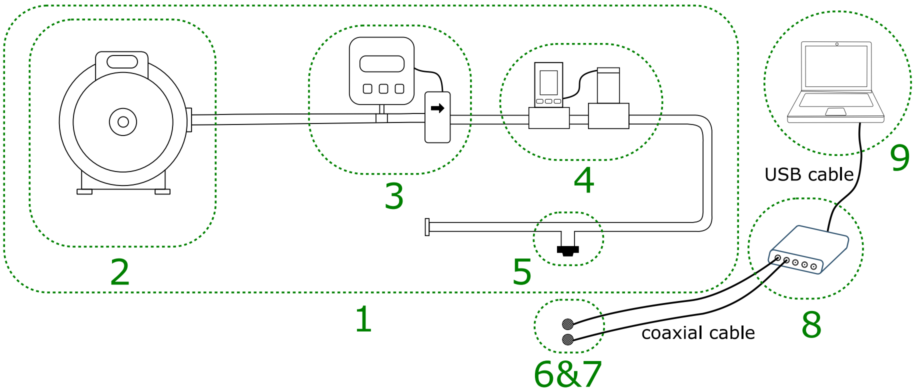
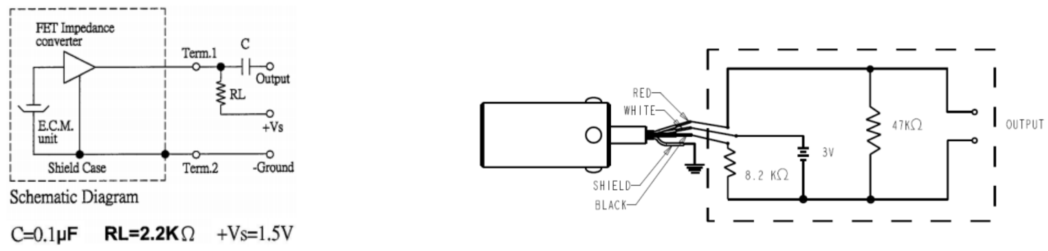


Figure 1. Schematic of the setup employed for conducting the experimental tests. The elements in the schematic are: (1) sprayer test bench, (2) water tank and supply pump, (3) accurate reference flowmeter, (4) flow controller, (5) nozzle mounting adapter and nozzle tips, (6&7) low-end and high-end microphones, (8) data acquisition module, and (9) laptop computer.

The experimental setup used to conduct the experiments in this study consisted of the following elements, where the item numbers in the list match the labels employed in Figure 1:

1. A laboratory sprayer test bench equipped with a water tank, a supply pump, hoses, pipes, a flowmeter, a flow controller, and one nozzle mounting adapter.
2. A 200-liter water tank and a supply pump, which was composed of a *Dayton® 5K117BD* industrial motor and an *Oberdorfer™ 101BM07MC* gear pump.
3. An *OMEGA Engineering Inc. FMG202-NPT* low-flow magnetic flowmeter, which was employed to measure flow rates during the recording experiments to provide ground truth reference for the evaluation of the proposed flow rate estimation method.
4. A *LCR-5LPM-D-100PSIG5V* liquid flow controller from *Alicat Scientific, Inc.*, which was employed to control the flow rate at which water flowed through the nozzle tip.
5. A *Wilger Combo-Rate Modular Nozzle Body* that was used to mount the nozzle tips.
6. A low-cost *CUI CMC-5044PF-A* electret microphone, plus preprocessing electronics. A very simple electronic circuit (Figure 2a), which was specified by the manufacturer, was used for impedance adaptation and high-pass filtering of the signal provided by the microphone.
7. A high-end *Knowles BL-21994-000* microphone, plus preprocessing electronics, which was used to check the results provided by the aforementioned low-end microphone. A very simple electronic circuit (Figure 2b) was used for powering this microphone and setting its proper operating point.
8. A *NI USB-4431* National Instruments (NI) data acquisition (DAQ) module, which was used to digitize the signals provided by both analog microphone sensors.
9. A *Dell Latitude E6400* laptop computer, which was employed to acquire and save the logged data coming from the data acquisition module. The connection between the laptop and the data acquisition system was made through a USB cable. The laptop was also employed to conduct the processing steps for the proposed flow rate estimation method, as explained in Section 2.2.

Eleven different agricultural nozzle tips were used in the experiments. These tips were chosen among the most commonly used tips from two mainstream manufacturers: *TeeJet®* [19] and *Wilger Industries Ltd* [20]. Specifically, from *TeeJet®*, the following set of nozzle tips was used: *AITT110-03*, *AIX110-03*, *TG-03*, *Turbo TTVP110-03*, *TwinJet 80-03*, *XRC80-04*, and *XRC80-06*. From *Wilger Industries Ltd*, the following *COMBO-JET®* nozzle tips were used: *ER80-03*, *MR80-04*, *MR80-06*, and *MR80-08*. The chosen set of nozzle tips is considered representative enough, covering most of the mainstream agricultural spraying applications, since they all present features differing in spray pattern (flat fan, twin flat, and cone spray), droplet size (fine, medium, and coarse), spray fan angle (80º and 110º), and flow rate operating range.



(**a**) (**b**)

Figure 2. Schematic of the preprocessing electronic circuits for the: (**a**) *CUI CMC-5044PF-A* microphone, and (**b**) *Knowles BL-21994-000* microphone.

2.2. Methods

The main processing stages performed in this study can be conceptualized as follows (Figure 3): (*i*) data acquisition (Section 2.2.1); (*ii*) preprocessing (Section 2.2.2); (*iii*) FFT analysis (Section 2.2.3); (*iv*) in-band power calculation (Section 2.2.4); (*v*) power normalization (Section 2.2.5); (*vi*) regression or curve fitting (Section 2.2.6)); and (*vii*) evaluation (Section 2.2.7). The first six stages correspond to actual stages of the proposed flow rate estimation method, while the last one was aimed at assessing the accuracy of this method. Figure 3 summarizes the main processing stages and contains an overview of the methods, which are explained in greater detail in the remainder of this subsection.

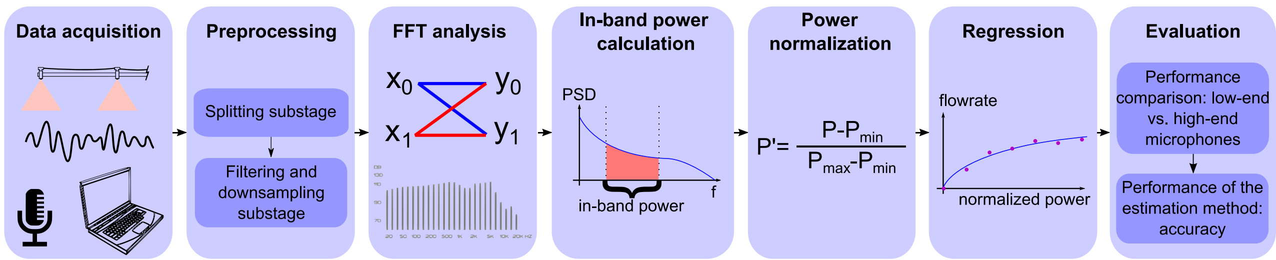


Figure 3. Overall block diagram summarizing the main processing stages performed in this study.

2.2.1. Data acquisition

Acoustic data were experimentally obtained from around the nozzle by using the aforementioned sprayer test bench. Both the low-end (*CUI CMC-5044PF-A*) and high-end (*Knowles BL-21994-000*) microphones were used to measure the acoustic signal simultaneously. The location of the microphones used for these recordings was as depicted in Figure 4. After several trial and error tests, this location was considered the best for optimizing the overall method performance. Two analog input channels of the National Instruments DAQ system, one for each microphone, were employed using the *NI LabView* software running on the aforementioned laptop.

The acquisition experiments involved setting up a constant flow rate through the nozzle. Once the flow rate had been stabilized, 61-second-long recordings were simultaneously taken with both microphones using a sampling frequency of 100 kHz. Eleven different nozzle tips, previously mentioned in Section 2.1, were tested. For each nozzle tip, several flow rates were used, all within or close to the operating range recommended by the manufacturer in the respective product datasheet. For each nozzle tip at each tested flow rate, two recordings were taken: one for training purposes and the other for testing purposes. The training data were used to determine the parameters of the subsequent processing stages of the estimation method. The testing data were used to assess the performance of the method using these parameters.

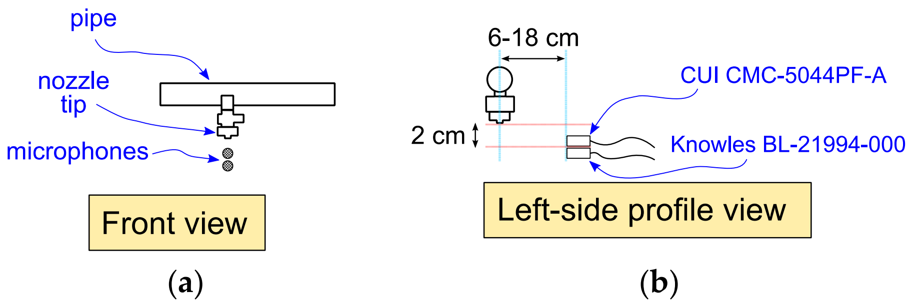


Figure 4. Location of the microphones with respect to the nozzle tip: (**a**) front view, and (**b**) left-side profile view.

2.2.2. Preprocessing

The preprocessing stage consisted of two substages: (*i*) the splitting substage, and (*ii*) the filtering and downsampling substage. This stage was applied to each of the aforementioned 61-second-long acquired signals, i.e., for all the recordings.

In the splitting substage, the complete 61-second-long sequence was divided into 122 epochs of 0.5 seconds each. In order to achieve a real-time flow rate estimation, this time was empirically considered as the minimum epoch size able to prevent the loss of meaningful information from the acoustic signal. Thus, the subsequent stages are still able to accurately compute flow rates from this split signal.

In the filtering and downsampling substage, a digital IIR elliptic low-pass filter with a cutoff frequency of 4 kHz was applied to the split signal to avoid spectral aliasing in the subsequent downsampling stage. This cutoff frequency was chosen since all frequencies of interest for this method lie in a band below 2 kHz, as will be further detailed in Section 2.2.4. After the filtering, the signal was also downsampled by a factor of $M = 10$, to reduce its original length, thus avoiding unnecessary processing overload in terms of computational complexity. In this way, every 0.5 seconds the subsequent FFT analysis stage receives as input the preprocessed data from one of these 0.5-second-long epochs, consisting of $N = 5{,}000$ samples. By doing so, the whole flow rate estimation method is able to update the provided measurement twice every second.

2.2.3. FFT analysis

In this stage the *Discrete Fourier Transform* (DFT) of each of the epochs was calculated using the *Fast Fourier Transform* (FFT) algorithm. Assuming that $x[n]$, with $n \in \mathbb{Z}$ and $n \in [0, N-1]$, denotes the discrete-time signal associated with each epoch output from the previous stage, its DFT transform, $X[k]$, is computed using Equation (1):

$$X[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-i \cdot 2\pi \cdot k \cdot n / N}, \text{for } k = 0, \dots, N-1 \quad (1)$$

After this step, the *Power Spectral Density* (PSD) was calculated using Equation (2):

$$PSD[k] = 2 \cdot \frac{X[k] \cdot X^*[k]}{N \cdot f_s} \quad (2)$$

where $f_s = 10{,}000$ Hz is the effective sampling frequency after the downsampling by a factor of ten, N is the length of the discrete signal $X[k]$, and the asterisk symbol denotes the complex conjugate of a complex number.

2.2.4. In-band power calculation

After having computed the PSD from the frequency spectrum via the FFT transform, the in-band power contained between 1,450 and 1,950 Hz was calculated by using the trapezoidal integration rule (Equation (3)). This frequency band was chosen after being considered the most suitable for the subsequent flow rate estimation. The process that led to this choice was a trial and error approach constrained by the early observation of the frequency spectrum of the acoustic signal coming from the nozzle tip.

$$P = \sum_{k=725}^{974} \frac{PSD[k] + PSD[k+1]}{2} \cdot 2\ \text{Hz} \quad (3)$$

In Equation (3), $k = 725$ and $k = 974$ are, respectively, the indexes corresponding to the 1,450 and 1,948 Hz frequencies, since the employed frequential resolution was 2 Hz.

2.2.5. Power normalization

The output from the previous stage, namely the unnormalized in-band power, became the input to this stage. The normalization process consisted of applying a linear mapping so that the output of this stage, P_{norm}, i.e. the normalized in-band power, was a value bounded between 0 and 1. The zero and one values correspond, respectively, to the minimum and maximum tested flow rates of the particular nozzle tip assessed. Additionally, during the training phase in this stage, the values of P_{min} and P_{max} were obtained, once again individually for each assessed nozzle tip, as the mean in-band power of the 122 epochs for the minimum flow rate and for the maximum flow rate, respectively. The normalized power, P_{norm}, was calculated from the unnormalized power, P, using the following linear mapping (Equation (4)):

$$P_{norm} = \frac{P - P_{min}}{P_{max} - P_{min}} \quad (4)$$

2.2.6. Regression or curve fitting

After computing the normalized in-band power, for the training data for which the actual flow rate was known, the flow rate versus the normalized in-band power was plotted. Using a sixth root function, as shown in Equation (5), the parameters k_1 and k_2 were adjusted for each assessed nozzle tip to better fit the empirical training data points by means of a transformed linear regression using the least squares approach. The fitted data curve was later used for flow rate estimation with the new testing data so that the output of this stage was an estimate of the volumetric flow rate measured in liters per minute (lpm).

The aforementioned sixth root function employed in this stage was:

$$x = (k_1 + k_2 \cdot P_{norm})^{1/6} \quad (5)$$

where x denotes the flow rate output, P_{norm} is the normalized in-band power coming from the previous stage, and k_1 and k_2 are constants determined during the curve fitting stage with the training data set.

For calibration purposes, whenever the nozzle tip or nozzle-to-microphone distance changes, all the stages described between Section 2.2.1 and Section 2.2.6 should be conducted again while the actual flow rate is measured simultaneously with an accurate flowmeter. In this way, a new different curve is fitted in order to be used for later estimation.

2.2.7. Evaluation

After having undertaken all the previous stages, the performance of the proposed method was assessed. For each nozzle tip, after performing the corresponding training phase, the method accuracy was evaluated for the testing data set. The evaluation stage consisted of using as input new acoustic signals and evaluating how accurate the method was in providing an estimate of the actual flow rate, which was measured concurrently with the accurate flowmeter. The absolute and relative *Root Mean Square Error* (RMSE), the maximum absolute error, and the 95% interpercentile range, as well as visual inspection, were used as performance metrics for evaluation.

The absolute and relative RMSE, the maximum absolute error, and the 95% interpercentile range values were calculated for all the aforementioned testing data experiments, i.e. one for each tested nozzle tip at several constant flow rates, as shown in Equations (6) to (9):

$$\text{Absolute } RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - x_{GT})^2} \tag{6}$$

$$\text{Relative } RMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - x_{GT})^2}}{x_{GT}} = \frac{\text{Absolute } RMSE}{x_{GT}} \tag{7}$$

$$\text{maximum absolute error} = \max_{1 \le i \le N}\{|x_i - x_{GT}|\} \tag{8}$$

$$95\% \text{ interpercentile range} = 97.5th \text{ percentile} - 2.5th \text{ percentile} \tag{9}$$

where x_i is the estimated flow rate value obtained by the proposed method at the *i-th* epoch, x_{GT} is the ground truth reference value provided by the accurate flowmeter, and $N = 122$ denotes the number of epochs for each experiment at a constant flow rate.

The assessment of the method, using the metrics previously introduced, consisted of three main evaluation experiments: (*i*) one for the accuracies of all tested nozzle tips, (*ii*) another for the influence of the quality of the measuring microphone, and (*iii*) a last one for the dependency on the location of the microphone.

In the first evaluation experiment, just the low-end microphone (*CUI CMC-5044PF-A*) was employed and it was located 6 cm from the nozzle tip (Figure 4). In this experiment, all 11 nozzle tips were tested and compared for several flow rates lying within or close to their manufacturer recommended operating ranges.

In the second evaluation experiment, both the high-end (*Knowles BL-21994-000*) and low-end (*CUI CMC-5044PF-A*) microphones were used, once again placed 6 cm from the nozzle tip (Figure 4). In order to report simpler results, three representative and commonly used nozzle tips were selected for comparison: *TeeJet® XRC80-04*, *Wilger COMBO-JET® MR80*-04, and *TeeJet® AIX110-03*. In addition to the aforementioned performance metrics, the correlation coefficients between the estimated flow rate discrete-time sequences for both the high-end and low-end microphones were computed. This value was used as a measurement of the coherence between the estimates provided by both microphones.

In the third evaluation experiment, once again just the low-end microphone (*CUI CMC-5044PF-A*) was employed, but several recordings were taken varying the nozzle-to-microphone separation distances to 6, 12, and 18 cm. In order to report simpler results, just one of the most commonly used nozzle tips was selected for comparison: *Wilger COMBO-JET® MR80-04*. The aforementioned performance metrics were computed for the recordings at these three separation distances in order to assess the influence of the distance on the method accuracy.

3. Results

For the sake of clarity, the main results of this study are presented in three separate subsections corresponding to each of the aforementioned evaluation experiments (Section 2.2.7). First, the estimation accuracy for all the tested nozzle tips was assessed. Second, the influence of the quality of the measuring microphone was evaluated. Last, the dependency on the location of the microphone was examined.

3.1. Accuracy Results for Different Nozzle Tips

In this subsection, the accuracy results obtained with the 11 aforementioned nozzle tips (Section 2.1) are reported while using the low-end microphone (*CUI CMC-5044PF-A*).

Figure 5 depicts the flow rate discrete-time sequences estimated by the proposed method applied to four acquired, representative acoustic signals for each of the 122 0.5-second-long epochs. It can be seen that the proposed method makes real-time flow rate estimation possible, since the flow rate can be updated every 0.5 seconds, thus allowing for quick updates as the flow rate changes.

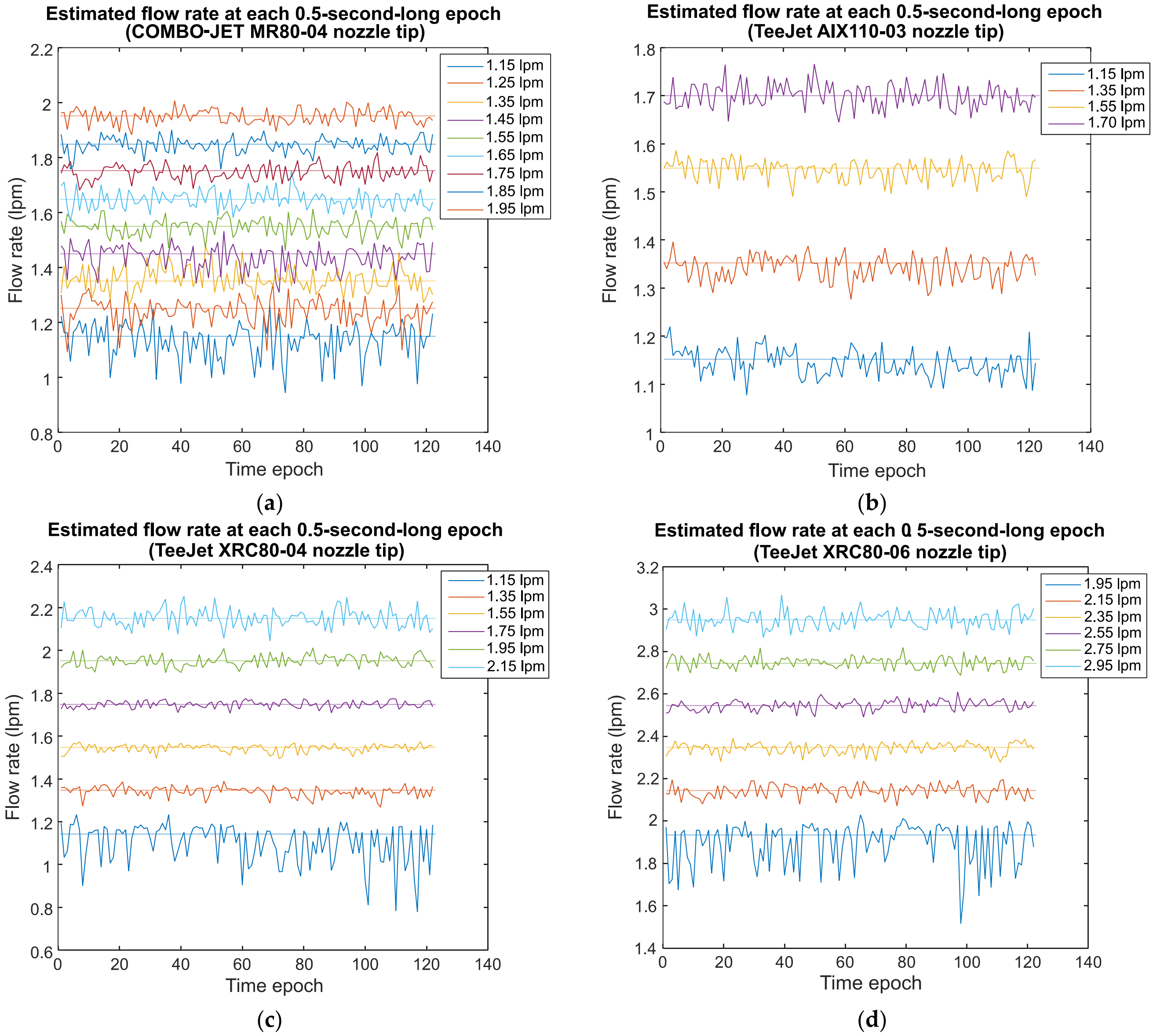


Figure 5. Flow rate estimation results for each of the 122 0.5-second-long epochs while the flow rate was kept constant and the low-end microphone (*CUI CMC-5044PF-A*) was 6 cm from the nozzle tip. (**a**) *Wilger COMBO-JET® MR80-04* nozzle tip. (**b**) *TeeJet® AIX110-03* nozzle tip. (**c**) *TeeJet® XRC80-04* nozzle tip. (**d**) *TeeJet® XRC80-06* nozzle tip.

Table 1 reports the accuracies for all 11 tested nozzle tips. It can be seen that the average values for the absolute RMSE, the maximum absolute error, and the 95% interpercentile range of the error are always below 0.08, 0.32 and 0.31 liters per minute (lpm), respectively. Computing the relative RMSE, found by dividing the absolute RMSE by the actual flowrate, an average error always lower than 5% was obtained for every single nozzle. These facts provide strong evidence of the usefulness of the here-proposed flow rate estimation method, which led to high accuracies for all tested nozzle tips.

Table 1. Accuracy results of the proposed flow rate estimation method for the tested nozzle tips and flow rates using the low-end microphone (*CUI CMC-5044PF-A*).

Nozzle tip employed	Actual flow rate (lpm)	Absolute RMSE (lpm)	Relative RMSE (%)	Maximum absolute error (lpm)	95% interpercentile range (lpm)
Wilger COMBO-JET® MR80-04	1.15	0.0689	5.991	0.2065	0.2550
	1.25	0.0487	3.896	0.1570	0.2201
	1.35	0.0455	3.370	0.1291	0.1695
	1.45	0.0462	3.186	0.1407	0.1626
	1.55	0.0318	2.052	0.0887	0.1353
	1.65	0.0331	2.006	0.1028	0.1228
	1.75	0.0280	1.600	0.0688	0.1053
	1.85	0.0280	1.514	0.0925	0.1150
	1.95	0.0262	1.344	0.0667	0.1010
	Average	**0.0396**	**2.773**	**0.1170**	**0.1541**
Wilger COMBO-JET® MR80-06	1.92	0.0921	4.797	0.3008	0.2914
	2.12	0.0434	2.047	0.1267	0.1699
	2.31	0.0511	2.212	0.1188	0.1804
	2.49	0.0406	1.631	0.0935	0.1578
	2.68	0.0413	1.541	0.1128	0.1594
	2.87	0.0446	1.554	0.1043	0.1757
	Average	**0.0439**	**2.297**	**0.1205**	**0.1618**
Wilger COMBO-JET® MR80-08	2.57	0.1221	4.751	0.4658	0.4277
	2.77	0.0382	1.379	0.1207	0.1475
	2.96	0.0539	1.821	0.1493	0.2271
	3.16	0.0463	1.465	0.1297	0.1898
	3.34	0.0483	1.446	0.1095	0.1699
	3.53	0.0490	1.388	0.1474	0.2004
	3.72	0.0451	1.212	0.1111	0.1818
	3.92	0.0436	1.112	0.1233	0.1796
	4.12	0.0575	1.396	0.1704	0.2148
	Average	**0.0560**	**1.775**	**0.1697**	**0.2154**
TeeJet® AIX110-03	1.15	0.0289	2.513	0.0726	0.1094
	1.35	0.0263	1.948	0.0733	0.0956
	1.55	0.0220	1.419	0.0602	0.0815
	1.70	0.0255	1.500	0.0658	0.0931
	Average	**0.0257**	**1.845**	**0.0680**	**0.0949**
TeeJet® Turbo TTVP110-03	1.15	0.0239	2.078	0.0634	0.0980
	1.35	0.0316	2.340	0.0695	0.1232
	1.55	0.0349	2.252	0.0937	0.1418
	1.73	0.0545	3.150	0.1409	0.2231
	Average	**0.0362**	**2.455**	**0.0919**	**0.1465**

TeeJet® AITT110-03	1.55	0.1337	8.626	0.6491	0.5191
	1.75	0.0568	3.246	0.1639	0.2324
	1.95	0.0433	2.221	0.1195	0.1708
	Average	**0.0779**	**4.697**	**0.3108**	**0.3074**
TeeJet® TG-03	1.55	0.0750	4.839	0.1830	0.3041
	1.75	0.0668	3.817	0.1664	0.2697
	1.95	0.0598	3.067	0.1675	0.2411
	2.15	0.0435	2.023	0.1320	0.1603
	2.35	0.0451	1.919	0.1397	0.1862
	Average	**0.0580**	**3.133**	**0.1577**	**0.2323**
TeeJet® TwinJet 80-03	1.15	0.0267	2.322	0.0806	0.1010
	1.35	0.0277	2.052	0.0664	0.1033
	Average	**0.0272**	**2.187**	**0.0735**	**0.1022**
Wilger COMBO-JET® ER80-03	0.95	0.0651	6.853	0.2139	0.1990
	1.15	0.0162	1.409	0.0611	0.0586
	1.35	0.0232	1.719	0.0623	0.0912
	1.55	0.0621	4.006	0.2014	0.2357
	Average	**0.0416**	**3.497**	**0.1347**	**0.1461**
TeeJet® XRC80-06	1.95	0.1168	5.990	0.4338	0.3296
	2.15	0.0306	1.423	0.0789	0.1089
	2.35	0.0252	1.072	0.0729	0.0969
	2.55	0.0236	0.925	0.0595	0.0851
	2.75	0.0269	0.978	0.0682	0.0978
	2.95	0.0405	1.373	0.1158	0.1557
	Average	**0.0446**	**1.960**	**0.1427**	**0.1437**
TeeJet® XRC80-04	1.15	0.1065	9.261	0.3709	0.3372
	1.35	0.0254	1.881	0.0823	0.0924
	1.55	0.0189	1.219	0.0557	0.0638
	1.75	0.0163	0.931	0.0439	0.0595
	1.95	0.0257	1.318	0.0613	0.1019
	2.15	0.0423	1.967	0.1063	0.1644
	Average	**0.0386**	**2.763**	**0.1228**	**0.1310**

3.2. Accuracy Comparison of High-End versus Low-End Microphones

In this subsection, a performance comparison between low-end and high-end microphones is tackled for the proposed flow rate estimation method. In order to simplify the comparison of the results from the two different microphones, only three representative nozzle tips were selected: *TeeJet® XRC80-04*, *Wilger COMBO-JET® MR80*-04, and *TeeJet® AIX110-03*. As previously noted, the same experiments were simultaneously recorded with both microphones for a more unbiased accuracy comparison between them.

Figure 6 shows a comparison of the estimated flow rate discrete-time sequences for all 122 0.5-second-long epochs with both microphones for the *TeeJet® XRC80*-04 nozzle tip. A very high similarity is observed for the highest flow rates, while small discrepancies appear for the lowest flow rates. This plot is a proof of the high coherence between the measurements provided by both microphones, which highlights the consistency of the here-proposed method with almost no dependence on the employed microphone.

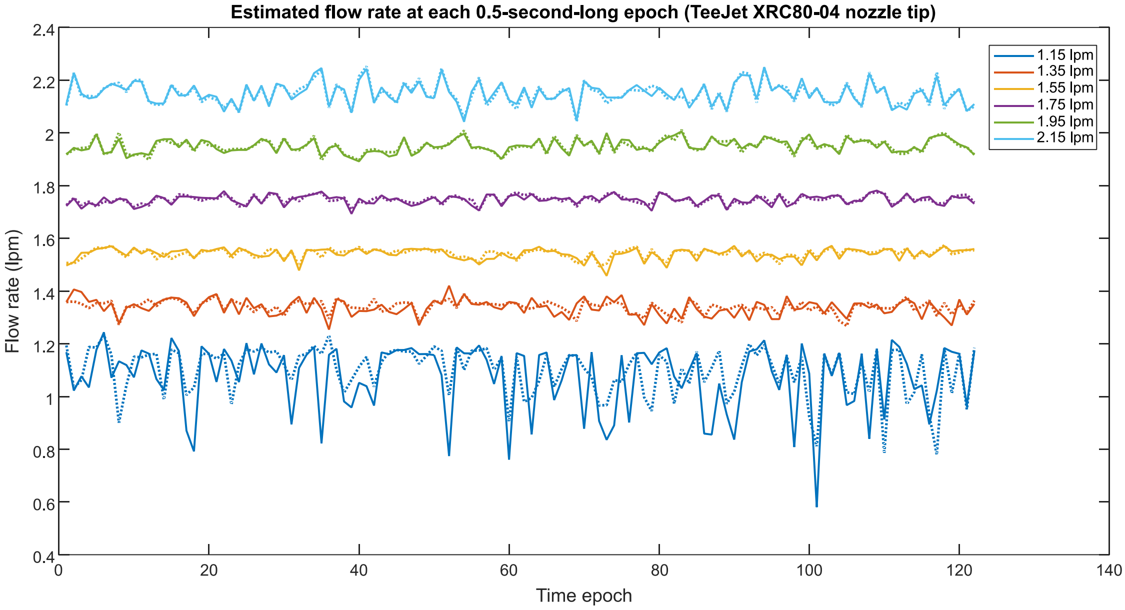


Figure 6. Comparison of the flow rate estimation results for each of the 122 0.5-second-long epochs while the flow rate was kept constant and the microphones were 6 cm from the *TeeJet® XRC80-04* nozzle tip. The solid and dotted lines represent the results for the high-end microphone (*Knowles BL-21994-000*) and the low-end microphone (*CUI CMC-5044PF-A*), respectively.

Table 2, Table 3, and Table 4 show the results obtained while using the high-end microphone (*Knowles BL-21994-000*) instead of the low-end one (*CUI CMC-5044PF-A*). A comparison between the performance for the *TeeJet® XRC80-04* nozzle tip in Table 1 and Table 2 reveals that the high-end microphone does not outperform the low-end microphone. In fact, the accuracies were slightly worse for the high-end microphone. The same conclusion can be reached by comparing the results for the *Wilger COMBO-JET® MR80-04* and *TeeJet® AIX110-03* nozzle tips in Table 1 with the results in Table 3 and Table 4, respectively. This fact proves that highly accurate results can be achieved with a low-end microphone, with no significant improvements expected when using a high-end one. Another remarkable result is that moderate (0.40-0.59) to very strong (0.80-1.00) correlations are observed between the measurements provided by both microphones. This fact clearly highlights the existence of a significant coherence between the measurements provided by both devices.

Table 2. Accuracy results of the proposed flow rate estimation method for the *TeeJet® XRC80-04* nozzle tip employing the high-end microphone (*Knowles BL-21994-000*).

Actual flow rate (lpm)	Absolute RMSE (lpm)	Maximum absolute error (lpm)	95% interpercentile range (lpm)	Correlation coefficient
1.15	0.1467	0.5696	0.4300	0.6065
1.35	0.0334	0.0958	0.1214	0.6574
1.55	0.0223	0.0920	0.0779	0.8284
1.75	0.0182	0.0568	0.0698	0.8880
1.95	0.0254	0.0579	0.0926	0.9531
2.15	0.0415	0.1077	0.1633	0.9700
Average	**0.0479**	**0.1633**	**0.1592**	**0.8172**

Table 3. Accuracy results of the proposed flow rate estimation method for the *Wilger COMBO-JET® MR80-04* nozzle tip employing the high-end microphone (*Knowles BL-21994-000*).

Actual flow rate (lpm)	Absolute RMSE (lpm)	Maximum absolute error (lpm)	95% interpercentile range (lpm)	Correlation coefficient
1.15	0.1274	0.2119	0.3314	0.4103
1.25	0.0786	0.1821	0.2429	0.5084
1.35	0.0746	0.1878	0.2574	0.4996
1.45	0.0842	0.1941	0.2522	0.5489
1.55	0.0723	0.1787	0.2881	0.6093
1.65	0.0645	0.1799	0.2373	0.6910
1.75	0.0512	0.1796	0.2014	0.6188
1.85	0.0442	0.1308	0.1796	0.6114
1.95	0.0516	0.1346	0.2071	0.6583
Average	**0.0721**	**0.1755**	**0.2442**	**0.5729**

Table 4. Accuracy results of the proposed flow rate estimation method for the *TeeJet® AIX110-03* nozzle tip employing the high-end microphone (*Knowles BL-21994-000*).

Actual flow rate (lpm)	Absolute RMSE (lpm)	Maximum absolute error (lpm)	95% interpercentile range (lpm)	Correlation coefficient
1.15	0.0439	0.1179	0.1887	0.4996
1.35	0.0311	0.1038	0.1178	0.5084
1.55	0.0290	0.0785	0.1030	0.7467
1.70	0.0282	0.0687	0.1154	0.8020
Average	**0.0331**	**0.0922**	**0.1312**	**0.6392**

3.3. Accuracy Comparison for Different Nozzle-to-Microphone Distances

In this subsection, an accuracy comparison of the proposed method for different nozzle-to-microphone separation distances is provided while using the low-end microphone (*CUI CMC-5044PF-A*).

Table 5 shows the accuracies for the *Wilger COMBO-JET® MR80-04* nozzle tip at different distances: 6, 12, and 18 cm. Figure 7 shows the absolute RMSE of the estimation for different flow rates at the three tested distances. In general, a gradual degradation of the accuracy can be observed as distance is increased. This degradation is higher for the lowest flow rates, probably due to the fact that the generated signal has less intensity and the acoustic noise floor masks the signal of interest. Nevertheless, this degradation is almost negligible for the rest of the higher flow rates, as long as the distances are kept close enough.

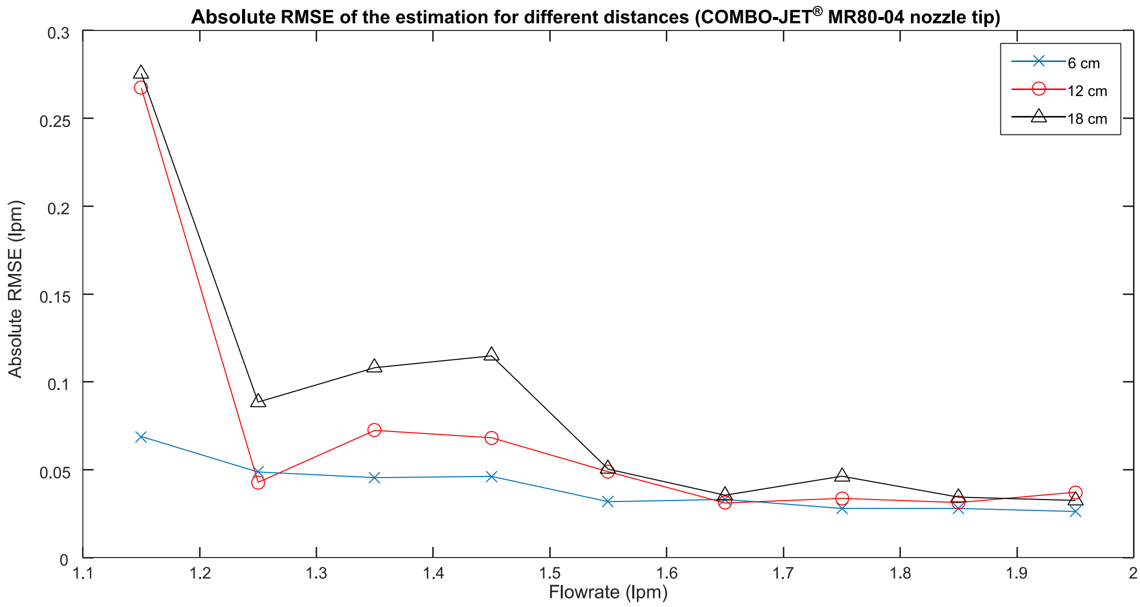


Figure 7. Comparison of the absolute RMSE estimation accuracy at several flow rates for different nozzle-to-microphone distances using the *Wilger COMBO-JET® MR80-04* nozzle tip and the low-end microphone (*CUI CMC-5044PF-A*).

Table 5. Accuracy results for the *Wilger COMBO-JET® MR80-04* nozzle tip using the low-end microphone (*CUI CMC-5044PF-A*) at different distances.

Distance from nozzle tip to microphone	Actual flow rate (lpm)	Absolute RMSE (lpm)	Maximum absolute error (lpm)	95% interpercentile range (lpm)
	1.15	0.0689	0.2065	0.2550
	1.25	0.0487	0.1570	0.2201
	1.35	0.0455	0.1291	0.1695
	1.45	0.0462	0.1407	0.1626
6 cm	1.55	0.0318	0.0887	0.1353
	1.65	0.0331	0.1028	0.1228
	1.75	0.0280	0.0688	0.1053
	1.85	0.0280	0.0925	0.1150
	1.95	0.0262	0.0667	0.1010
	Average	**0.0396**	**0.1170**	**0.1541**
	1.15	0.2674	0.6120	0.6815
	1.25	0.0428	0.1699	0.1382
	1.35	0.0724	0.1761	0.2682
	1.45	0.0682	0.1704	0.2696
12 cm	1.55	0.0489	0.1682	0.1617
	1.65	0.0311	0.1042	0.1278
	1.75	0.0337	0.1185	0.1302
	1.85	0.0313	0.0860	0.1127
	1.95	0.0372	0.1140	0.1543
	Average	**0.0703**	**0.1910**	**0.2271**
18 cm	1.15	0.2755	0.5863	0.7789
	1.25	0.0885	0.3251	0.2738

1.35	0.1081	0.2134	0.2964
1.45	0.1148	0.2178	0.3070
1.55	0.0503	0.2163	0.2206
1.65	0.0355	0.1008	0.1369
1.75	0.0463	0.1435	0.1704
1.85	0.0344	0.0896	0.1359
1.95	0.0325	0.1034	0.1435
Average	**0.0873**	**0.2218**	**0.2737**

4. Discussion

This article investigates the feasibility of using microphones as flowmeters for nozzle tips in agricultural sprayers. For this end, a flow rate estimation method is proposed for each individual nozzle tip by processing the generated acoustic signal acquired by a microphone located near the nozzle. The main finding that can be drawn from this article is that accurate real-time flow rate estimation for individual nozzle tips can be achieved by employing acoustic signal processing.

Seven major findings can be highlighted from this study: (*i*) the nozzle-generated acoustic signal contains enough information to enable accurate flow rate estimation by applying signal processing techniques; (*ii*) the proposed method can be used to estimate the flow rate of individual nozzles in a low-cost way with a high accuracy in a laboratory environment; (*iii*) the flow rate estimation becomes less accurate when operating outside the flow range recommended by the nozzle manufacturer; (*iv*) the proposed method can be used to estimate the flow rate in real time with a demonstrated update frequency of 2 Hz; (*v*) consistent results can be obtained when using a low-end microphone instead of a more expensive high-end microphone; (*vi*) the frequency band between 1,450 Hz and 1,950 Hz provided the best results; and (*vii*) the nozzle-to-microphone distance is not critical for the method to work accurately, but specific calibrations are required for each distance.

The first finding is that the nozzle-generated acoustic signal contains enough information to enable accurate flow rate estimation. This general conclusion can be derived from the particular results achieved with the proposed method. It is evident that the generated acoustic signal contains information related to the flow rate through the nozzle tip, and many processing techniques can be proposed for this end. Similar conclusions regarding this relationship have been found in previous studies. Jacobs *et al.* [17] already proved that the sound of water flowing through a tap can be used to estimate the actual flow rate. Kakuta *et al.* [18] demonstrated that a condenser microphone can be used as a vibration sensor in pipelines in order to measure flow rates. Evans *et al.* [21] also employed flow-induced mechanical vibrations in the pipe, acquired with an accelerometer, to estimate flow rates. Nevertheless, the present article complements the aforementioned studies by addressing sprayer nozzles where the flow is actually exiting a closed system in a controlled manner.

The second finding is that the proposed method can be used to estimate the flow rate of individual nozzles in a low-cost way with a high accuracy in a laboratory environment. The results presented in Section 3, mainly Table 1, support this finding, since for all the tested nozzles the average absolute and relative RMSE values are always below 0.08 lpm and 5%, respectively. Moreover, for flow rates lying within the manufacturer recommended operating ranges, the absolute and relative RMSE values are even lower, bounded below 0.05 lpm and 2.5%, respectively. Comparing these results with the ones obtained by Jacobs *et al.* [17], significantly better absolute accuracies and slightly better relative accuracies are achieved with the here-proposed method. However, it is worth noting that both studies are not quite comparable due to the nozzle tips versus faucets or taps are and also flow rate ranges are very different in both articles. The flow rate estimation accuracies obtained with the proposed acoustic method are close enough to some of the traditionally used flowmeters, whose relative RMSE errors can reach 4% [22, 23]. Moreover, it is commonly agreed, in mainstream agricultural spraying applications, that any flow rate variability among nozzles below XXX% is acceptable for enabling precision agriculture spraying of chemicals.

Thus, the values obtained for relative RMSE error, all bounded below 5%, pose evidences of the validity of this measurement method to meet this requirement when used for flow rate control. It should be noted that these studies were conducted in a relatively controlled laboratory environment; thus, the reproducibility of these accuracies in real agricultural settings has yet to be verified.

The third finding is that the flow rate estimation becomes more difficult, i.e. the errors increase, for either very low or very high flow rates, when operating outside the flow range recommended by the nozzle manufacturer. This behavior can be noticed in Table 1 for almost every single nozzle. One possible explanation for this behavior is the fact that the spray deposition pattern and output droplet size distribution of the nozzles changes appreciably outside of the manufacturer recommended range, which will consequently change the acoustic signature. The higher difficulty in estimation could also be due to the acoustic signals being more similar in these extreme cases. This effect is even more noticeable for low flow rates due to the inherently lower intensity of the nozzle-generated signal. This lower intensity leads to the acoustic noise floor being relatively stronger with respect to the signal of interest, thus making the estimation more difficult. Nevertheless, it has been checked that, in the recommended operating flow rate ranges given by the nozzle manufacturers, the proposed method presents satisfactory accuracies. No similar findings about lower estimation capabilities for extreme flow rates have been detected in previous studies, to the best of the authors' knowledge. Further studies should be conducted to provide more insight regarding the reasons behind this behavior.

The fourth finding is that the proposed method can work in real time. This method, when executed in post-processing in MATLAB®, requires less than five seconds to process the 61-second-long recordings for 10 flow rates, where the reported times were obtained in the aforementioned laptop (*Dell Latitude E6400*). This execution time, less than 0.01 seconds for each single epoch, shows the feasibility of performing all the necessary tasks between the acquisitions of two consecutive epochs, which is 0.5 seconds. It is worth remarking that no explicit code optimization was done and the computational efficiency of the method could be further improved for real-time operation.

The fifth finding is that consistent results, with neither significant improvements nor detriments, can be obtained when using a high-end or a low-end microphone. The results presented in Section 3.2 prove that the high-end microphone does not outperform the low-end microphone. Furthermore, the measurements provided by both are coherent (Figure 6), since moderate (0.40-0.59), strong (0.60-0.79) or very strong (0.80-1.0) positive correlations were found (Table 2, Table 3, and Table 4). The fact that the proposed method is highly independent of microphone quality makes it fiscally feasible to replicate flow sensors across a large boom with many nozzles.

The sixth finding is that the frequency band between 1,450 Hz and 1,950 Hz provided the best accuracies. Several bandwidths were tested, and a bandwidth of 500 Hz was found to be the best because it gave acceptable accuracies and was narrow enough to avoid excessive wideband interferences. Looking over the frequencies from 0 Hz to 50 kHz, the band from 1,450 Hz to 1,950 Hz contained more information than any other related to the flow rate.

The seventh finding is that the method accuracy does not depend too much on the nozzle-to-microphone distance. The results in Figure 7 and Table 5 show a tendency of a slow but progressive accuracy degradation as distance is increased. Only distances over 6 cm were tested in order to prevent the microphones from getting wet and thus being damaged. Moreover, since specific calibrations are required for each distance, it is worth noting that the proposed method will require strict control of microphone location while operating.

The major strength of the proposed method is the low-cost of its design, requiring for its deployment only a low-end microphone and a microcontroller-based computing platform. Another strength of the proposed estimation method is that it can work in real time.

Nevertheless, there are also some limitations to this work. Each nozzle tip requires its own calibration since no singular curve could be fitted accurately for all nozzle tips. Moreover, since the flow rate estimation method is dependent on the nozzle-to-microphone distance, as acoustic power decreases with distance, a new calibration process is mandatory when this distance is varied.

However, a simple straightforward calibration can be used in this case, requiring just the determination of the in-band power for highest and lowest flow rates for the normalization stage.

The low-cost sensing method evaluated in this study will bring tremendous benefits to the agricultural chemical application industry. It will be fiscally feasible to replicate this sensor at every nozzle along a large spray boom to facilitate monitoring and closed-loop control of flow rate from each individual nozzle tip. This will greatly increase the accuracy of placement of chemicals in the field and will prevent much of the errors and inconsistencies currently observed in field application equipment.

Future research related to this article could tackle the evaluation, and almost certainly improvement, of this method in real agricultural settings. More research on how to avoid acoustic interferences in real agricultural settings is needed as well. It is expected that interferences in real agricultural settings, e.g. acoustic noise generated by machinery and wind, can affect the performance of this method. The authors of this paper are currently undertaking new studies in this line of research.

Further studies are also required to gain more insight into where the sound enabling flow rate estimation comes from. Five possible sources for the generated acoustic signal have been identified while performing the experiments of this study: (*i*) turbulences generated by cavities inside the pipe-nozzle interface, (*ii*) droplet formation in the nozzle-air interface, (*iii*) acoustic radiation generated by mechanical vibrations of the nozzle or the pipe, (*iv*) residual elasticity of the nozzle tip outlet that makes its vibration dependent on the flow rate, which acts as an excitation force, (*v*) finite compressibility of the liquid, and (*vi*) cross section changes and presence of orifice plates along pipes or the nozzle. This article does not focus on identifying which of these sources have a predominant effect in the observed acoustic signature, but the authors of this paper are working on a follow-up study investigating the sound generation process for nozzle tips by using *Computational Fluids Dynamics* (*CFD*) simulations.

5. Conclusions

The results from this study support the feasibility of accurately estimating, in real time, the flow rate through agricultural sprayer nozzles based on the acoustic signal recorded in close proximity to them. While employing the proposed method, satisfactory accuracies with relative RMSE values below 5% are obtained under laboratory conditions. In addition, the quality of the microphone device has been proven to have little influence on the overall accuracy of this method. Furthermore, the distance from the nozzle tip to the microphone has not been shown to be overly influential, but the shortest distance does generally provide the most accurate results. Nevertheless, the results achieved in this article should be confirmed through field tests in agricultural environments. Deeper theoretical insight into acoustic signal generation in nozzle tips and its relationship with flow rate is also needed.

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Author Contributions: Timothy S. Stombaugh conceived the original idea; Timothy S. Stombaugh, Víctor Martínez-Martínez and Ruben Ruiz-Gonzalez designed the experiments; Ruben Ruiz-Gonzalez performed the experiments; Ruben Ruiz-Gonzalez and Víctor Martínez-Martínez proposed the acoustic estimation method and analyzed the experimental data under the supervision and guidance of Jaime Gomez-Gil and Timothy S. Stombaugh; all four coauthors collaboratively wrote the paper. All authors have approved the final version of this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DAQ: *Data AcQuisition*
DFT: *Discrete Fourier Transform*
FFT: *Fast Fourier Transform*
IIR: *Infinite Impulse Response*
lpm: *liters per minute*
PSD: *Power Spectral Density*
PWM: *Pulse-Width Modulation*
RMSE: *Root Mean Square Error*
USB: *Universal Serial Bus*

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