Evaluation of syringes as a substitute for precision glassware in quantitative experiments in high school education

American Journal of Education and Learning
Vol. 10, No. 1, 23-33, 2025
e-ISSN:2518-6647

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ABSTRACT

This study aims to address the lack of resources in public education systems in many countries, including Brazil, by evaluating the use of plastic syringes as a cost-effective and safer alternative to traditional glassware for quantitative Chemistry experiments in high schools. The precision, accuracy, and suitability of plastic syringes as teaching aids for preparing solutions were assessed. Syringes of different volumes and brands were calibrated by determining the mass of water contained and delivered. The quality of the syringes, used as TC and TD devices, was demonstrated through the absorbances of diluted solutions from a dye stock solution. A statistical evaluation was conducted to measure the precision and accuracy of disposable plastic syringes. The study found that disposable plastic syringes with volumes of 1, 5, and 10 mL (as TD devices) and 60 mL (as TC devices) exhibited good precision and accuracy, with relative standard deviations lower than 1% and error percentages smaller than 3.5%. This indicates that plastic syringes are a viable option for performing quantitative experiments. The use of plastic syringes presents an appealing alternative for creating inexpensive and safer quantitative experiments for high school students. This approach can enhance the acquisition of knowledge in Chemistry without the high costs and potential physical risks associated with traditional glassware.

Keywords: *Accuracy, Low-cost experiments, Precision, Volumetric glassware.*

DOI: 10.55284/ajel.v10i1.1271
Citation | Lisboa, A. C. S., Silva, A. F. de S., & Oliveira, A. F. de. (2025). Evaluation of syringes as a substitute for precision glassware in quantitative experiments in high school education. *American Journal of Education and Learning, 10*(1), 23–33.

Funding: This research is supported by the National Council for Scientific and Technological Development (CNPq,: Conselho Nacional de Desenvolvimento Científico e Tecnológico) (Grant number: 405828/2022-5), FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais) (Grant number: RED-00144-22) and UFV-CISAB-ZM (Universidade Federal de Viçosa- Consórcio Intermunicipal de Saneamento Básico da Zona da Mata) (Grant number: 315/2023).
Institutional Review Board Statement: Not applicable.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
History: Received: 26 September 2024/ Revised: 21 November 2024/ Accepted: 12 December 2024/ Published: 1 January 2025
Publisher: Online Science Publishing

Highlights of this paper

- This study evaluates plastic syringes as a cost-effective and safer alternative to traditional glassware for quantitative Chemistry experiments in high schools.
- The precision and accuracy of commercial plastic syringes are comparable to those of glassware, making them suitable for chemical experiments in both high schools and universities.
- The introduction of plastic syringes opens up possibilities for a new set of chemical experiments, providing an affordable and safer option for educational settings.

1. INTRODUCTION

Chemistry is a discipline that can be difficult to understand, leading to disinterest by many students (Cardellini, 2012). Its extensive content and the typical difficulty in relating theory to everyday life make the participation of students in presential laboratory activities very important to enhance the teaching and learning process. Wrenn and Wrenn (2009) discussed the improvement of scientific understanding and reasoning through the integration of theory and practice in several learning methods. The implementation of presential laboratory activities in high school chemistry teaching is not straightforward in developing countries, including Brazil. There is a widespread lack of resources in public education systems, resulting in an insufficiency of teaching materials and equipment, such as glassware (Quive et al., 2021). Besides, there is the issue of safety that arises when young people handle glassware (Benderly, 2010). To minimize costs and to improve students' daily lives, many laboratory experiments that have been proposed employ reagents that are everyday products such as vinegar, sodium bicarbonate, iodine solution, and potassium permanganate, among others (Quive et al., 2021; Yitbarek, 2012). However, a limitation in conducting quantitative experiments is that they require the use of precision measurement equipment, typically glassware, to ensure satisfactory results and enable a more informed discussion that can enhance the acquisition of knowledge by the students. These procedures in chemistry laboratories require volumetric flasks, volumetric pipettes, and micropipettes, among others. The preparation of a solution requires equipment items with defined volumes in which the material of interest is contained. The precise measurement and quantitative transfer of defined volumes of pure liquids and solutions are performed using equipment such as glass volumetric pipettes and micropipettes, which deliver a precise volume and can be classified as TD ("to deliver") type devices (Kenkel, 2002).

The volumetric flask, which contains a well-defined volume of solution, can be classified as a TC ("to contain") type glassware. In some cases, it can also be used to deliver a defined volume but with less precision.

Table 1 shows the nominal volumetric capacities and the corresponding tolerances for commonly used commercially available volumetric flasks, volumetric pipettes, and micropipettes.

Table 1. Nominal volumetric capacities and tolerances of different TC and TD type glassware.

To contain (TC)	To deliver (TD)		
Volumetric flasks [1]	Volumetric pipettes [2]	Fixed-volume micropipettes [3]	Variable-volume micropipettes [4]
Nominal volume * ± tolerance /mL	Nominal volume ** ± tolerance /mL	Nominal volume *** /µL	Nominal volume ‡ ± tolerance /µL
5 ± 0.025	1 ± 0.008	10	(5-50) ± 0.4
25 ± 0.025	2 ± 0.01	50	(50-100) ± 1.2
50 ± 0.06	5 ± 0.015	100	(100-250) ± 6
100 ± 0.100	25 ± 0.03	250	(250-1000) ± 6
250 ± 0.150	50 ± 0.05	500	(1000-5000) ± 60
500 ± 0.0250	100 ± 0.08	-	-
1000 ± 0.400	-	-	-
2000 ± 0.600	-	-	-

Source: * Class A, International Organization for Standardization ISO 1042 (1998); ** Class A, International Organization for Standardization ISO 648 (2008); ***Measurement errors range from 0,2 to 1% for 100 to 1000 µL (Lippi et al., 2011) ‡ International Organization for Standardization ISO 8655-2 (2022).

Precision glassware used routinely in laboratories, such as volumetric flasks and volumetric pipettes, can present relative measurement errors lower than 0.4% for volumes smaller than 25 mL. Micropipettes, which allow the measurement of volumes from 0.2 µL to 10 mL, can present measurement errors of around 1-10% International Organization for Standardization ISO 8655-2 (2022).

In the health area, the commercially available plastic syringes that are used have a purpose different to that of glassware since their precision and accuracy must enable the administration of drugs and other substances in defined quantities for activity in living beings, usually humans and domestic animals (Figure 1). The volumetric specifications (Table 2) and tolerances (Table 3) of these items are based on the values established according to the Associação Brasileira de Normas Técnicas ABNT - NBR ISO 7886-1 (2020) standards.

Figure 1. Disposable syringes (Luer lock and luer slip models) of different capacities, without needles.

Table 2. Scale graduations and residual volumes for plastic syringes of different nominal capacities, according to the ABNT NBR ISO 7886-1/2020 standards.

Nominal capacity /mL	Main scale graduation /mL	Scale subdivision /mL	Maximum residual volume /mL	Scale length /mm
1	0.1	0.01	0.07	55
5	1.0	0.1	0.07	36
10	2.0	0.2	0.10	44
20	5.0	1.0	0.15	52
60	10.0	1.0	0.20	75

Table 3. Tolerance values for plastic syringes with different nominal capacities, defined by ABNT according to NBR ISO 7886-1/2020 standards.

Syringe nominal capacity (V) /mL	Tolerance for quantity smaller than half the nominal capacity	Tolerance for quantity equal to or greater than half the nominal capacity
V < 2	± 1.5% V ± 2% of the expelled volume	± 5% of the expelled volume
2 ≤ V < 5		
5 ≤ V < 10	± 1.5% V ± 1% of the expelled volume	± 4% of the expelled volume
10 ≤ V < 20		
20 ≤ V < 30		
30 ≤ V < 50		
V ≥ 50		

This study aims to evaluate the precision and accuracy of plastic syringes for preparing solutions in schools, as an alternative to traditional glass volumetric pipettes and flasks. If successful, plastic syringes would offer cost savings and lower risk to students.

2. EXPERIMENTAL

All the aqueous solutions were prepared using type 2 water obtained from a Millipore system (Burlington, USA). The syringes used, obtained from local stores, were as follows: 1 mL syringe with resolution (smallest division) of 0.01 mL (Solidor, China) (denoted brand 1); 5 mL syringe with resolution of 0.1 mL (SR, Paraguay) (brand 2); 10 mL syringe with resolution of 0.2 mL (Descarpack, India) (brand 3); 60 mL syringe with resolution of 1.0 mL (Descarpak, India) (brand 4). Six syringes of each nominal volume were used. The 60 mL syringe was used as a TC device, while the others were used as TD devices.

The general procedure for calibrating the TD syringes involved firstly weighing an empty acrylic flask (capped and numbered) with capacity of 23 mL. The desired volume of water was transferred to the flask, followed by reweighing. For each syringe, aliquots of half the nominal syringe volume (with six repetitions) and the entire nominal volume (also with six repetitions) were transferred. The procedure is illustrated schematically in Figure 2.

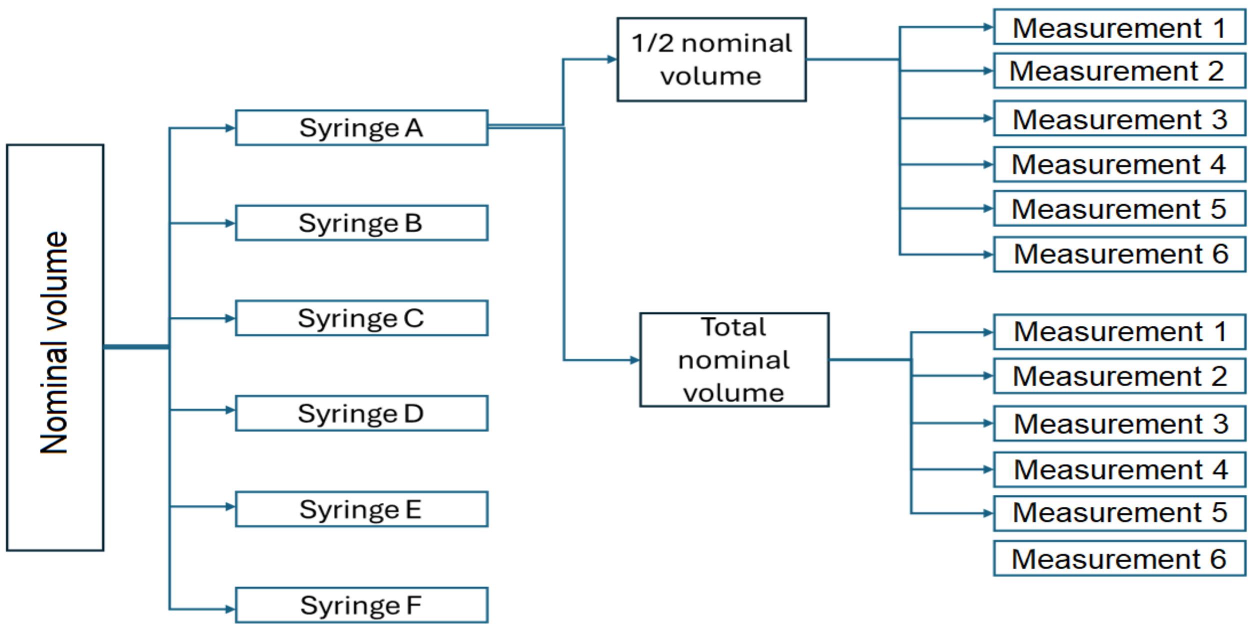


Figure 2. Schematic diagram of the procedure for the calibration tests using the syringes with nominal volumes of 1, 5, and 10 mL. The same procedure performed for syringe A was adopted for syringes from B to F.

For the 60 mL syringe, used as a TC device (substituting a volumetric flask), the volume was obtained by directly weighing the syringe, empty and with the desired volume of water. The water mass values were then used to calculate the volumes, considering the temperature of the water and its corresponding density (Haynes, 2014).

The dilution procedure employed a 3-way valve (Descarpack), shown in Figure 3a, to which the 60 mL syringe (TC) and the 1 mL syringe (TD) were connected for the volume to be transferred. Figure 3b shows a photograph of the setup.


(a)


(b)

Figure 3. (a) 3-way valve for transfer of the desired volume into the 60 mL syringe; (b) Photograph of the setup.

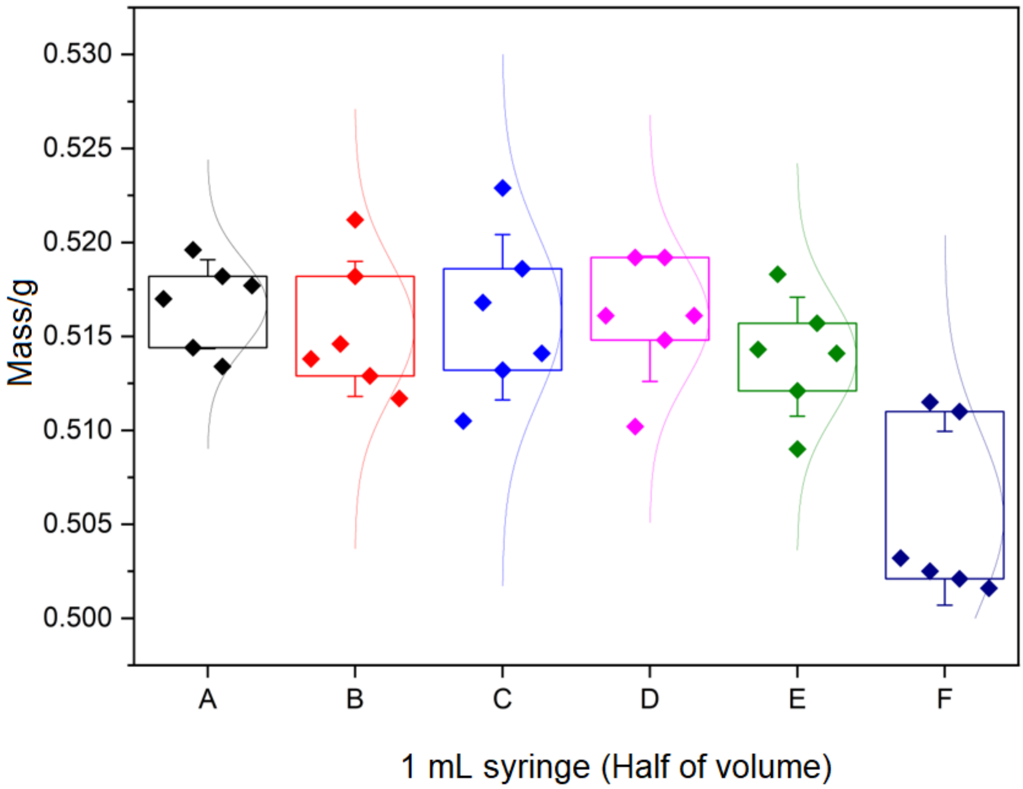
The calibration procedure using the acrylic flasks was repeated for the same volumes transferred using an adjustable micropipette capable of delivering volumes from 200 to 1000 µL (model Finipipette F1, Thermo). The procedure using the 50 mL volumetric flask was the same as for the 60 mL syringe.

Evaluation of error propagation for the use of the TC and TD format syringes was performed using a stock solution of gentian violet at a nominal concentration of 0.049 mol/L. A 1 mL aliquot of this solution was transferred to the 60 mL syringe, with the volume completed to 50 mL with water. From this intermediate solution with a nominal concentration of 9.80×10^{-4} mol/L, volumes of between 200 and 600 µL (measured using a 1 mL syringe) were transferred to a 60 mL syringe, obtaining a total solution volume of 50 mL. The same procedure was performed using a variable-volume micropipette (200-1000 µL) and a 50 mL volumetric flask.

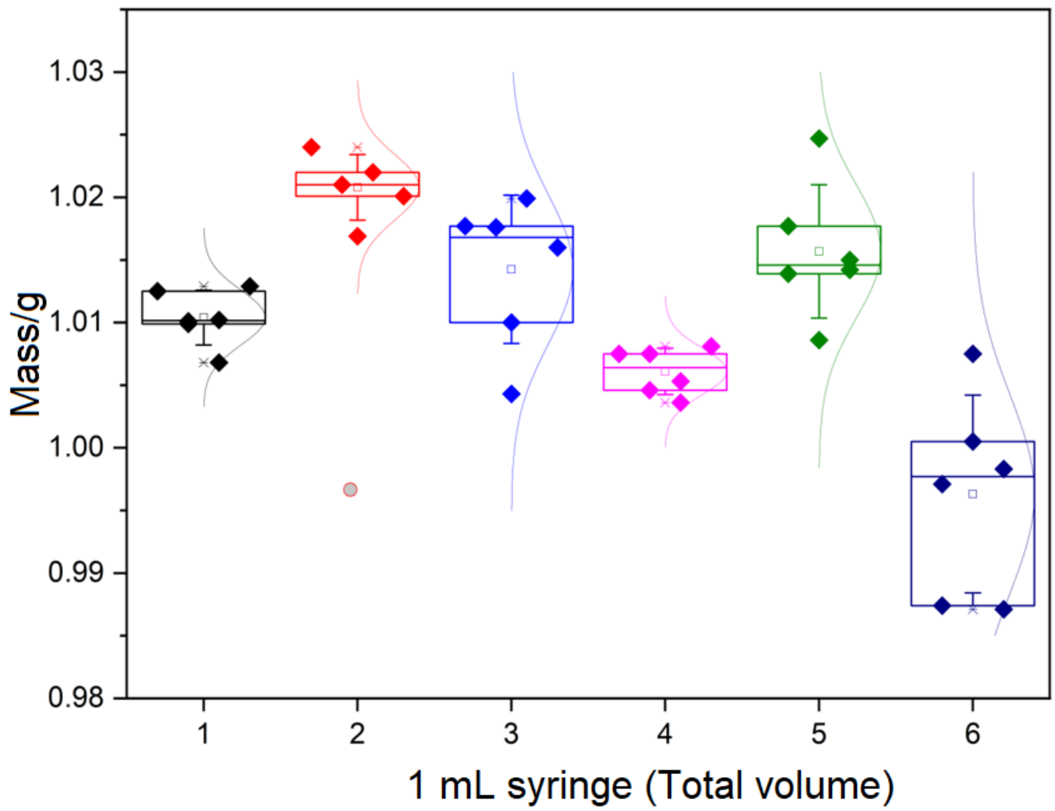
For all the prepared solutions, visible spectra were acquired using a USB2000 spectrophotometer (Ocean Optics), with a tungsten filament lamp and a glass cuvette with a 10 mm path length. For both experimental conditions, analytical curves were obtained using the maximum absorption wavelength of 583.4 nm. Data processing employed an Excel spreadsheet (Microsoft Corporation, 2024) and OriginPro software (OriginPro, 2024).

3. RESULTS AND DISCUSSION

As an example of the results obtained in the evaluation of the volumes released by the syringes, Figure 4 shows the individual values of the masses released for the 1 mL syringes, using half the nominal volume (0.5 mL) and the entire nominal volume. A box plot and a normal distribution model curve are overlaid for each set of data.



A



B

Figure 4. Mass distributions for the release of (A) half the nominal volume and (B) the entire nominal volume of the 1 mL syringes.

Note: The curves represent the normal distribution models. The box plots show the 25%, 50%, and 75% percentiles. The bars indicate the estimated standard deviations.

The graphs in Figure 4 show the data dispersion and the values grouped with frequency between 25 and 75% (box plots), where the sizes of the estimated standard deviation bars can be compared to the quartiles and the normal frequency distributions obtained by nonlinear regression. Figure 4A shows similar behaviour for most data sets, considering the mean values and the data dispersion indicated by the standard deviations. An exception was syringe F (Figure 4A), for which there were two groups of points, with dispersion and mean distinct from the results for the other syringes.

The Grubbs' test for outliers was applied for each set of 6 measurements obtained for the syringes (A, B, ..., F) of a given nominal volume. Details of the test are provided in Appendix 1. As an example of the procedure, an outlier was observed for the nominal volume of 1 mL, shown in Figure 4B as a grey dot, which was not included in the calculations.

The application of one-way analysis of variance (ANOVA) (Anderson, 1987) to each of the groups of measurements (at the half-nominal and nominal values) revealed a significant difference between the means (with at least one meaning being different from the others). An ad hoc test showed that only syringe F presented a significant difference about the others, confirming the previous analysis of the data shown in Figure 4A.

Table 4 shows the calculated delivered volumes, their relative standard deviations (%RSD), and the relative difference of mean volume from nominal value for the different syringes.

Table 4. Calculated volumes of water delivered by the different syringes.

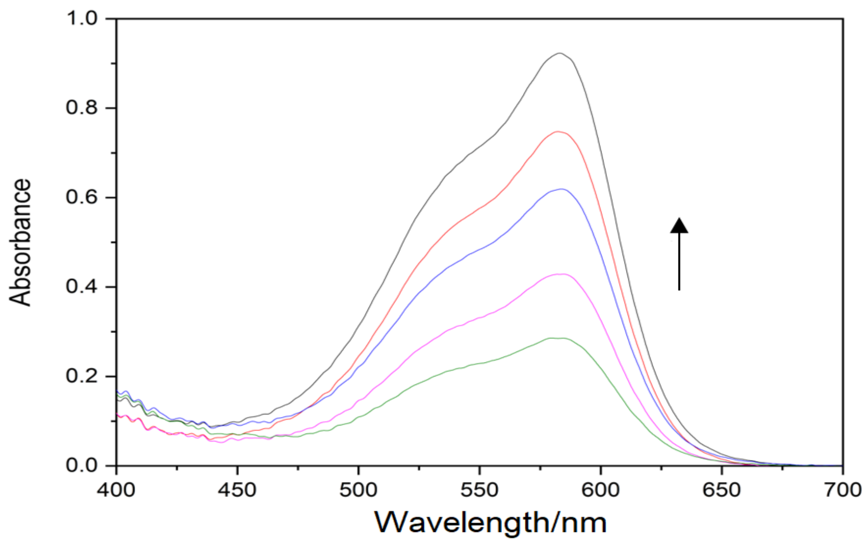
Syringe brand	Nominal volume /mL	Theoretical volume transferred /mL	Calculated volume* /mL	%RSD**	% error ***
Brand 1	1	0.5	0.5139 ± 0.0037	0.72	2.8
	1	1.0	1.0099 ± 0.0064	0.63	1.0
Brand 2	5	2.5	2.570 ± 0.012	0.47	2.8
	5	5.0	4.914 ± 0.016	0.34	-1.7
Brand 3	10	5.0	4.979 ± 0.028	0.57	-0.4
	10	10.0	9.925 ± 0.016	0.16	-0.7

Note: * Considering the density of water at the temperature of the experiment. Values shown as mean ± standard deviation (n = 6).

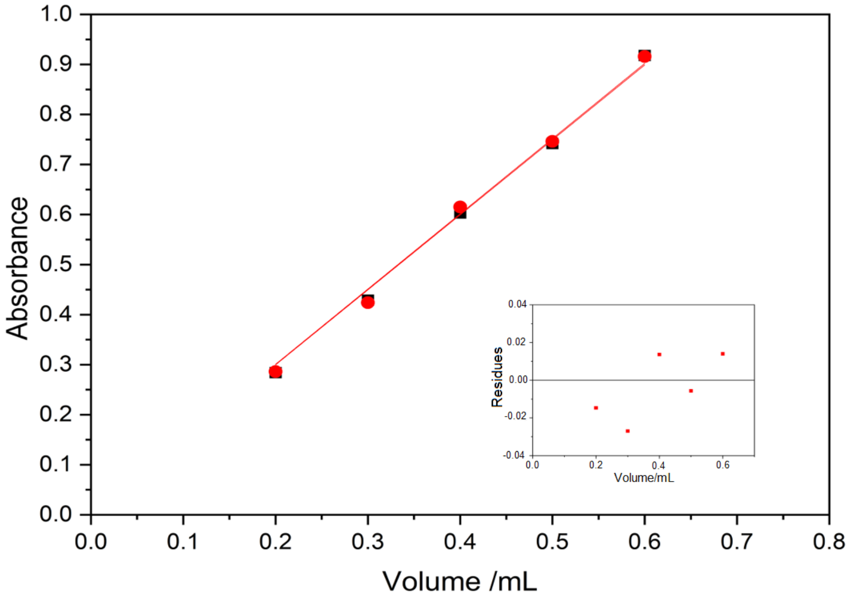
** $\%RSD = \frac{\text{standard deviation}}{\text{mean}} . 100$

*** $\% \, error = \frac{(mean - nominal\ volume)}{nominal\ volume} . 100$

One-way ANOVA was applied to each set of 6 measurements obtained for the different syringes (A, B, ..., F) with a nominal volume of 1 mL to determine whether the mean for any data set was significantly different from the others. In all cases, the p-value was greater than 0.24, showing that the volume released was the same for the different syringes. The precisions obtained for the different volumes and syringes were compared with the tolerance values established for pipettes and volumetric flasks, presented in Table 1. Considering the accuracy of the syringes, the mean values obtained at half the nominal volume of the 1 mL syringe differed from the reference value (0.5 mL) by between +0.88% and +3.2%, while the differences for the total nominal volume (1 mL) ranged from -0.85% to +1.5%. These values could be considered satisfactory and consistent with comparing the theoretical and calculated volumes (Table 4). It could be concluded that none of the syringes presented means that they were significantly different from the nominal values (at a 5% confidence level). The three types of syringes presented good relative standard deviations (%RSD or coefficient of variation) for the intended use, with values lower than 1%. The accuracy values were also satisfactory, with errors between -1.7 and 2.8%. For teaching purposes, precision is more important than accuracy since coherence among the results is easier for the student to understand, while accuracy (or lack of it) is a more abstract parameter. Figure 5 shows the results for evaluating the propagation of error for the syringes used in TC and TD formats, as proposed in this work. Figure 5A shows the spectra obtained for different dilutions of the gentian violet solution. Figure 5B shows the relationship between the volume of gentian violet solution added and the absorbance at a wavelength of 582 nm.



A



B

Figure 5. Dilution of the gentian violet solution using the syringe system. (A) Spectra for dilutions of 200, 300, 400, 500, and 600 µL of 0.980 mmol/L gentian violet solution in 50 mL(in crescent order: green, pink, blue, orange and black lines): . (B) Analytical curve at 582 nm as a function of the volume of gentian violet solution (red: syringe; black: micropipette). The insert shows a plot of the residuals.

The regression model obtained for dilution using the syringes is shown in Equation 1. The model obtained for the micropipettes and volumetric flask is shown in Equation 2.

$$\hat{A} = (1.510 \pm 0.019)V_{syringe}, \quad R^2 = 0.9993, \quad sd = 0.019 \qquad (1)$$

$$\hat{A} = (1.500 \pm 0.017)V_{micropipette}, \quad R^2 = 0.9992, \quad sd = 0.021 \qquad (2)$$

Where, *sd* is the estimated standard deviation of the residuals.

The analytical resolution (*AnR*), corresponding to the smallest volume required to obtain an absorbance, calculated using Equation 3 (Andrade, Oliveira, Neves, & Queiroz, 2016) was 43 µL for the 1 mL syringe used as a TD glassware substitute and the 60 mL syringe used as a TC glassware substitute, while a value of 36 µL was obtained for the micropipette and volumetric flask. It should be noted that the resolution of the 1 mL syringe (most minor division) was 10 µL.

$$AnR = \frac{3 \cdot sd}{S} \qquad (3)$$

Where, *S* is the slope of Equation 1 and 2.

This analytical resolution could be explained by the propagation of errors (considering the syringe and the absorbance reading). Applying of the two-tailed Student's t-test showed no significant difference between the slopes (95% confidence level). The slope was a consequence of factors including the molar absorptivity of the dye, the optical path length, and the solution concentration, with its numerical value not being important in this case.

4. CONCLUSIONS

The quality of the data, as shown by comparison with the micropipettes and flask, as well as the analytical resolution, indicated that syringes can be used as both TC and TD devices. Therefore, in high school education, their use can assist in the development of methods for data collection, supporting theoretical descriptions of the behavior of processes and improving the ability of students to use graphs and other tools. Considering the reagents required, many are commercially available and are easily obtained at outlets such as supermarkets, pharmacies, pool cleaning product stores, and agricultural product stores.

The findings showed that disposable plastic syringes with 1, 5, and 10 mL volumes presented good precision and accuracy, with relative standard deviations lower than 1% and error percentages smaller than 3.5%. The data obtained in this work demonstrated that the use of plastic syringes is an attractive option for developing low-cost and safer experiments for high school students, involving precise volume measurements.

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Appendix 1

Grubbs' test

The Grubbs' test involves calculation of the G_{calc} statistic (Equation 1), considering all N points of the sample, where an extreme point, x_i, is suspected of being an outlier. Since this statistic (Equation 2) is a function of the Student's t-distribution, the suspected value is accepted as belonging to the sample if the calculated p-value of t is greater than the 95% confidence level (significance level, α, equal to 0.05).

$$G_{calc} = \frac{\max|x_i - \bar{x}|}{s} \qquad (1)$$

Where, $\bar{x}$ is the simple mean and s is the estimated standard deviation.

$$G_{(\alpha/2N,N-2)} = \frac{N-1}{\sqrt{N}} \sqrt{\frac{t^2_{(\alpha/2\mathrm{N},\mathrm{N}-2)}}{(N-2)+t^2_{(\alpha/2\mathrm{N},\mathrm{N}-2)}}} \qquad (2)$$

The p-value of this statistic is obtained considering the Student's t-value calculated according to Equation (3).

$$t_{calc} = \sqrt{\frac{NG^2_{calc}(N-2)}{(N-1)^2 - NG^2_{calc}}} \qquad (3)$$