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Development of a low-cost portable turbidimeter for chemical processes

Desarrollo de un turbidímetro portátil de bajo coste para procesos químicos

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Abstract

Turbidity is a physical property related to the scattering of light by particles that are suspended in a liquid. Measuring turbidity of potable water, fluids from industries, or effluents is a quality control practice. Commercial turbidimeters are priced in the range of hundreds to thousands of dollars. The calibration technique required by standards is also expensive, and difficult to perform. Considering this scenario, it is proposed in this work the development of a low-cost portable turbidimeter for monitoring turbidity in chemical processes. An infrared LED was used as light emitter and an infrared phototransistor as light receiver. The signal processing control unit was developed with the Arduino Uno platform. It was also investigated alternative ways to calibrate the device, by using a random fluid and comparing the results with a calibrated turbidimeter. The calibration of the turbidimeter was done by means of a comparative test in triplicate, using as reference the commercial turbidimeter 2100P, HACH®. The proposed device was able to perform analysis in the range of 100 to 1000 NTU, and within a good price range, costing US$ 46.30.
Keywords: low-cost technology, nephelometry, open-source technology, turbidimeter.

Resumen

La turbidez es una propiedad física relacionada con la dispersión de luz por partículas que están suspendidas en un líquido. La medición de la turbidez del agua potable, fluidos de industrias o efluentes es una práctica de control de calidad. Los turbidímetros comerciales tienen un precio que oscila entre cientos y miles de dólares. La técnica de calibración requerida por los estándares también es cara y difícil de realizar. Considerando este escenario, se propone en este trabajo el desarrollo de un turbidímetro portátil de bajo coste para el monitoreo de turbidez en procesos químicos. Se utilizó un LED infrarrojo como emisor de luz y un fototransistor infrarrojo como receptor de luz. La unidad de control de procesamiento de señales fue desarrollada con la plataforma Arduino Uno. También se investigaron formas alternativas de calibrar el dispositivo, utilizando un fluido aleatorio y comparando los resultados con un turbidímetro calibrado. La calibración del turbidímetro se realizó mediante un ensayo comparativo por triplicado, utilizando como referencia el turbidímetro comercial 2100P, HACH®. El dispositivo diseñado fue capaz de realizar análisis en el rango de 100 a 1000 NTU, y dentro de un buen rango de precio, con un costo de US$ 46,30.
Palabras clave: tecnología de bajo coste, nefelometría, tecnología de código abierto, turbidímetro.

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1 Introduction

Turbidity monitoring is an important method of quality control, widely used in many food, chemical, pharmaceutical, and processing industries (Metzger *et al*., 2018). The analyzes of this property can be applied in the quality monitoring of a variety of fluids, ranging from the raw materials to the resulting processed goods. An example is an application in the production of crystal sugar, where the turbidity of the sugarcane juice is constantly monitored to guarantee the conditions of clarity of the juice (Rodrigues *et al*., 2018). It can also be used for monitoring effluents, by the industry itself or by governing agencies inspecting fluid discharges into open waters.

Turbidity is a physical property related to the presence of suspended particles, leading to the loss of clarity of the liquid. In physical concepts, it is related to the intensity of light that is scattered as it propagates in the liquid when interacting with the suspended particles and therefore being deflected in different directions. The higher the number of suspended particles, the greater the turbidity of the liquid. The most commonly used turbidity unit is the nephelometric turbidity unit (Sampedro & Salgueiro, 2015).

Modern turbidimeters are based on the transmission and scattering of light from a source, such as a light-emitting diode (LED). Typically, photodiodes or phototransistors are used as light receptors. These radiation emitters and receptors can be implemented in various geometrical arrangements. There can be also several extra receptors, in different positions related to the path of light, to improve the accuracy of measurements in both extremes of suspended particles concentrations. Either low or high concentrations are difficult to accurately measure turbidity.

The single-beam turbidimeter is the simplest modern model available. It consists of one light emitter and one light detector and can be designed based on two measurement techniques: turbidimetry and nephelometry. In turbidimetry, the detector and the emitter are positioned with their optical axes on the same line, i.e., facing each other. In this way, the reduction of light intensity through the liquid to be measured is detected (Fetisov & Melnichuk, 2009). The turbidity technique works better for the measurement of samples with a high concentration of suspended particles.

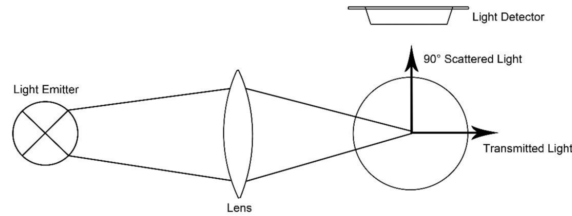


Fig. 1. Single beam model using the nephelometry technique (detection of light scattered at 90º).

In nephelometry, the detector is positioned at an angle of 90° to the light emitter to capture the light that has been scattered. The greater the intensity of the scattered light detected, the greater the turbidity of the liquid (Khairi *et al*., 2015). The light scattered can have a linear relationship with the turbidity of the sample, especially in the range of 0 to 40 NTU (Sadar, 2003). The operating principle of a turbidimeter using the nephelometry technique is illustrated in Fig. 1.

Many commercial turbidimeters are based on the nephelometry principle, with prices ranging from a few hundred to several thousand US dollars. In developing and third-world countries, these devices may not be affordable. In this scenario, the development of a low-cost device made up of simple and cheap electronic parts, that is able to measure turbidity becomes a subject of interest. Previous works relied upon open-source technologies to achieve the low-cost feature (Kelley *et al*., 2014; Román-Herrera *et al*., 2016; Metzger *et al*., 2018)

Advances in both open-source software (FOSS: Free and Open-Source Software) and hardware (OSH: Open-Source Hardware) occurred in the last decades. FOSS rise dates back to the 1990s (Heikkinen *et al*., 2020). Open-source hardware is a more contemporary philosophy and is related to breakthroughs in microchip manufacturing and technology (Pearce, 2017). It can be highlighted the enormous success of the Arduino and the Raspberry Pi platforms, given their large communities of developers and widespread commercialization. The development of turbidimeters under the FOSS and OSH frameworks is a well-established idea (Kelley *et al*., 2014; Román-Herrera *et al*., 2016; Wiranto *et al*., 2016; Metzger *et al*., 2018; Nguyen & Rittmann, 2018; Kovačić & Ašperger, 2019).

Kelley *et al*. (2014) was the first work to combine open-source methods, very low-cost design, and simple manufacturing procedures to turbidimeters that facilitate large-scale production. Their design integrated a near-infrared LED, a light-to-frequency sensor, and some very inexpensive options, namely a simple analog display and a microprocessor instead of the whole Arduino board. What is remarkable about their work is the reliable measurement of samples with low turbidity, except at the 0 - 1 NTU range. This feature allows potable water analyzes in countries where the potable water regulation is not so stringent, which was their original goal and, thus, scientific contribution.

Subsequently, authors came up with different designs of open-source turbidimeters. Kirkey *et al*. (2018) designed a low-cost submersible turbidimeter and incorporated additional features, such as the ambient light rejection through an electronic high-pass filter. Nguyen & Rittmann (2018) reported an Arduino-based turbidimeter with a washing machine turbidity sensor, model TSD-10, based on the turbidity technique (emitter and sensor facing each other). Metzger *et al*. (2018) developed a turbidimeter based on Gradient-Index lenses that was rigorously calibrated using formazin and against a commercial turbidimeter, with improved precision and reproducibility of the results for low turbidity samples. Gillett & Marchiori (2019) contributed to this series of developments by combining the low-cost open-source turbidimeter framework with a continuous inline design that communicates results via a WiFi module.

Román-Herrera *et al*. (2016) also developed an open-source turbidimeter, using two white light LEDs as emitters and two light-dependent resistors (LDR) as receivers. Wiranto *et al*. (2016) developed a single beam turbidimeter with a probe, using laser as a beam of light and a light-to-voltage sensor. Kovačić & Ašperger (2019) developed a device for research but also for undergraduate experiments, where students would explore how the device works, from the electronic components to the software that integrates all functionalities. Zang *et al*. (2020) developed a low-cost turbidimeter, with a custom microprocessor board, for in-situ measurement in traditional Chinese medicine extraction processes.

Other relevant works in the development of turbidimeters, that did not explore completely open-source methods, are discussed next. Aisopou *et al*. (2012) developed a multiparameter sensor, which contains a single beam turbidimeter and applies scattered light detection, to be installed directly in a water distribution line. Hamidi *et al*. (2017) used an image-processing technique and a smartphone camera as the sensor for the turbidimeter. Shenoy (2014) applied optical fibers in probes for submersion measurement.

Optical fibers, applied to the design of turbidimeter, offer the advantage of separating sensors and electronic circuits from the liquid samples. The use of optical fiber is being studied since the 2000s (García *et al*., 2007; Omar & MatJafri, 2009). Most recently, several papers successfully applied optical fiber to turbidimeters (Omar & Matjafri, 2012; Arifin *et al*., 2017; Bayram *et al*., 2018; Koydemir *et al*., 2019). Omar & Matjafri (2012) made relevant comparisons with different low-cost configurations using near-infrared sensors, optical fibers, and high sensitivity sensors. Bayram *et al*. (2018) and Koydemir *et al*. (2019) combined optical fibers with a smartphone-based design.

There is also a number of papers that describe the development of turbidimeters by making use of flash-light source, the camera, and the computational resources of a smartphone (Hussain *et al*., 2016; Hussain *et al*., 2017; Bayram *et al*., 2018; Koydemir *et al*., 2019). All of these devices exhibit low cost and can be seen as practical implementations for turbidity measurements within the reported range. One problem that can arise is the dependence of the calibration method upon the model of the smartphone.

One of the steps required for the development of a turbidimeter is the calibration one, in which electric signals are converted to the actual values in turbidity units. A formazin suspension is required - for mainly, but not exclusively, drinking water quality control - by the standards from the Environmental Protection Agency (EPA, 1993), and the International Standards Organization (ISO, 2016). Formazin is also recommended by the World Health Organization for calibration purposes.

Formazin is expensive to purchase and is produced through a polymerization reaction using hydrazine sulfate, a carcinogenic chemical substance. The final solution can still have traces of hydrazine. Furthermore, formazin has to be handled with caution as it may cause skin allergies and respiratory diseases if inhaled. Several issues need to be taken into account when applying formazin suspensions for turbidimeter calibration - for instance, the stability of the suspension, and the temperature of the solution during calibration (Münzberg *et al*., 2017).

Given these facts, alternatives may be sought. One is to use stabilized formazin, which is based on a polymer matrix and is stable (homogeneous), considerably safer, although still expensive. The use of styrene-divinylbenzene is a recommended alternative documented in the EPA 180.1 method. The last alternative is to use a random suspension with known turbidity and compare the measurements of the device being calibrated with an already calibrated turbidimeter. This approach is the cheapest, the easiest to perform, and can provide acceptable outcomes.

Gillett & Marchiori (2019) suggested the use of apple juice for calibration, for reducing the absorbance phenomena. Shenoy (2014) used dairy milk, red ink from a fountain pen, and an alkaline suspension. Even though Kelley *et al*. (2014) performed a test (validation) with formazin, they effectively calibrated their device with a hydrophilic oil suspension and by Commercial Turbidimeter Comparison (CTC). Kirkey *et al*. (2018) also performed a CTC calibration with an oil suspension. Kovačić & Ašperger (2019) calibrated the device with a formazin solution and validated it with a sulfate suspension. Hussain *et al*. (2017) calibrated using fluoride suspensions, even though their device was conceptualized, exclusively, for measuring this kind of solution. It is, therefore, a common practice in the field the use of random suspensions and a commercial turbidimeter for faster, cheaper, and reliable calibration (Lambrou *et al*., 2014; Román-Herrera *et al*., 2016; Metzger *et al*., 2018).

To summarize, it is evident the necessity of further development of low-cost turbidimeters for potable water analyzes not only for third-world countries but also for poor communities from wealthy and developing countries. Kelley *et al*. (2014) were the first to address this problem, although their design was inaccurate at the range 0 - 1 NTU. Metzger *et al*. (2018), through rigorous calibration and validation, achieved a lower limit of measurement of 0.1 NTU. Furthermore, researchers did not explore the design of a low-cost, portable, sample-based turbidimeter for median to small-scale industries and other institutions. For this purpose, the turbidimeter needs to be reliable - meaning, to a large extent, precise and accurate - for strict quality control practices.

Calibration is a challenge and, oftentimes, when performing calibration by CTC, the commercial turbidimeter chosen may limit the measurement range of the design being studied, or the manufacturer parameters are not consistent with the actual measuring range being observed. The CTC approach may be safer, less expensive, and may produce valid outcomes. Studies providing a rigorous foundation for the application of this technique are still scarce. Metzger *et al*. (2018) used a combination of both techniques, calibrating with formazin and by comparison of measured values from the devices. This practice should be studied further and should be recommended as a precise and robust calibration technique.

In view of the above, the objective of this paper was to develop a low-cost portable turbidimeter (with the possibility of conversion to an inline, in situ, and online turbidimeter), applying nephelometry technique and open-source technologies. The employed calibration technique was intended to be less expensive than that using formazin, but still reliable. The measurement range should be appropriate for use by chemical industries, universities, and environmental agencies from developing and third-world countries.

The rest of the paper is organized in the following manner: in section 2 we describe the low-cost, portable turbidimeter design, the sensing technique, and the modular hardware we used to develop the prototype. In section 3 we present the results, namely the experimental data collected and the calibration outcome. In section 4 we discuss our results and compare them to other devices reported in the literature. At last, we make concluding remarks about our work and propose new directions for future research in section 5.

2 Materials and methods

In order to meet the defined objectives, a low-cost portable turbidimeter for liquid analysis was developed with great applicability in food processing industries, but also in process plants in general where it may be of interest to analyze turbidity of a liquid stream. The operating principle of the developed turbidimeter is the emission of an infrared light beam in the direction of the sample and the detection of the light intensity that is scattered at 90º of the incident light beam (nephelometry). For the development of the turbidimeter, different items needed to be developed and/or implemented: measurement chamber, infrared emitter driver circuit, infrared receiver reading circuit, control and processing unit, peripheral components.

Because it is a low-cost turbidimeter, designing and manufacturing a cuvette has proved completely impractical. Using cuvette of a turbidimeter already existing in the market would be more viable, but still financially out of the proposal. Then, a search for an alternative sample container was performed, which was easy to acquire and inexpensive. We decided to use a blood sample cylindrical cuvette, a cheaper

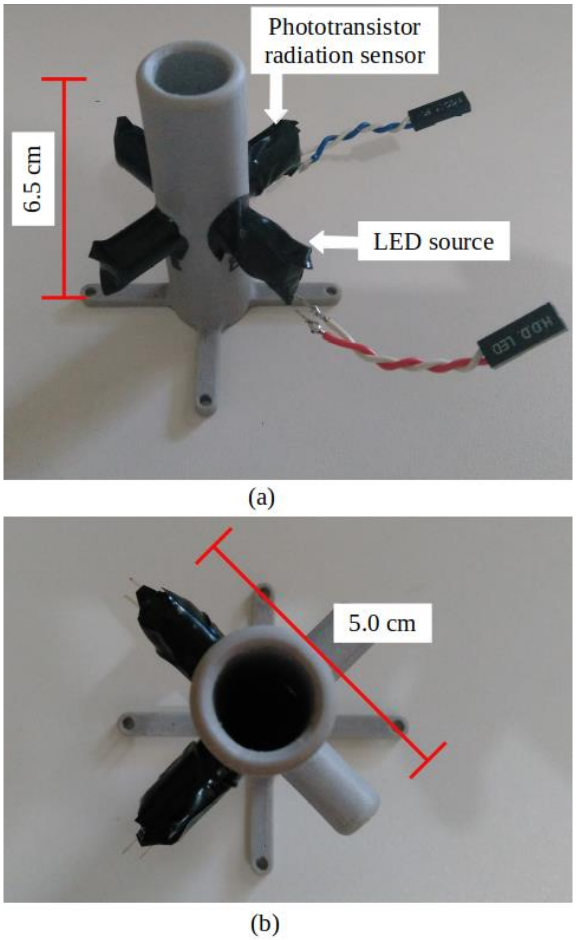


Fig. 2. Measurement chamber developed in a 3D printer. Frontal view, displaying the NIR-LED source and radiation sensor (a), upper view of the chamber (b).

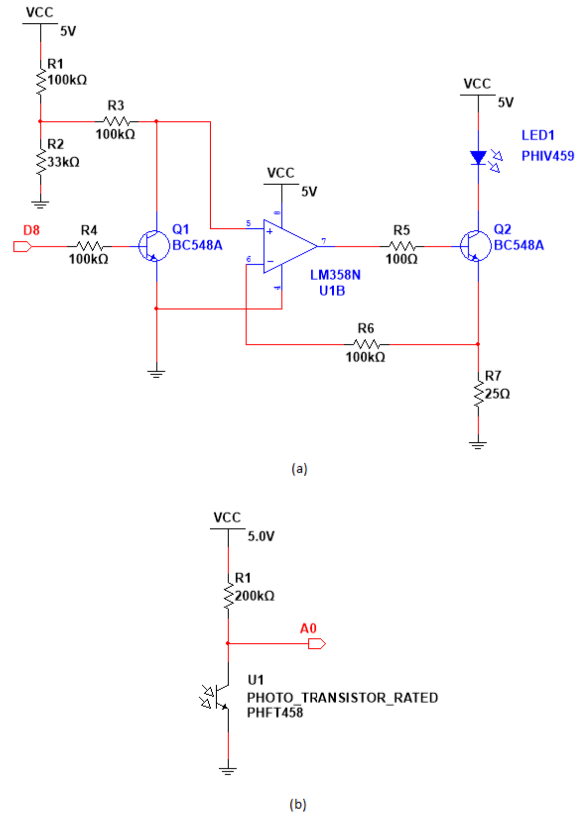


Fig. 3. LED driver circuit (a) and phototransistor measurement circuit (b).

alternative that was also adopted in previous works (Kelley *et al*., 2014; Román-Herrera *et al*., 2016; Kovačić & Ašperger, 2019).

The measurement chamber was manufactured in a 3D printer, a technique widely used today in design and prototyping, especially for OSH. Acrylonitrile butadiene styrene (ABS) was used as raw material. The measurement chamber is a tube with one open end and the other closed, with the inner diameter slightly larger than the outer diameter of the sample container, so that it can be inserted into the chamber. It has four holes, a design that allows further research with the developed prototype using two emitters and two sensors as following the modulated four-beam technique, documented in a paper by Postolache *et al*. (2007). In the prototype and the results generated for this paper, it was inserted in the measurement chamber the emitter and receiver, positioned at the same height and around the tube, equally separated from their adjacent ones by 90° as required by the nephelometry technique. The measurement chamber is shown in Fig. 2.

To act as a light source in the turbidimeter, the PHIV459 LED was chosen. It emits infrared light with an emission angle of 30º and nominal wavelength of 940 nm when operating with electric current of 100 mA and voltage of 1.7 V. After defining the LED to be used as an infrared emitter, its driver circuit was developed. This circuit must be able to receive the digital signal to drive the emitter from the D8 digital port of the control and processing unit and supply it with a constant current of 50 mA. For this type of power, a current source known as the current drain was chosen. The diagram of the LED driver circuit is shown in Fig. 3 (a).

As to the light receiver, as suggested by the manufacturers, it is typically used the pair of the employed emitter. In this case, it is the phototransistor

PHFT458. This phototransistor has an angle of incidence of 25° and a peak wavelength of 880 nm. The encapsulation and dimensions are the same as the LED PHIV459.

To perform the measurement, the phototransistor was used in a circuit known as the common emitter amplifier, operating in the active region. In this configuration, the measurement is performed at the collector and the emitter is grounded, with the result that the electrical voltage on the collector is inversely proportional to the infrared light intensity incident on the phototransistor. This voltage value should be between 0 and 5 V, being read by the A0 analog port of the control and processing unit and converted to a dimensionless value between 0 and 1023. The diagram of the phototransistor reading circuit is shown in Fig. 3 (b).

Regarding the control and processing unit of the turbidimeter, the microcontrolled platform Arduino Uno was used. It is an open-source and low-cost electronic prototyping platform, capable of receiving and processing inputs from sensors or other devices and then generating outputs for actuators or other devices, according to the programming developed by the user.

To power the entire system, a 9 V battery connected to the P4 connector of the Arduino was employed, which is suitable for external power (power without using the USB port). To turn the entire system on and off, a small on/off switch was used between the positive pole of the battery and the positive pole of the P4 connector, so that the switch could interrupt this connection when it was turned off, thus turning off the entire system.

As for the peripherals, a liquid crystal display of 16 × 2 characters and a push-button were used. The screen has the function of instructing the operator when turning on the turbidimeter and then informing the measured turbidity value of the sample. When the button is pressed, connected to the D9 digital port of the control and processing unit, the sample turbidity measurement is started.

With the development of each part of the turbidimeter completed, the next step was to assemble the device. Firstly, the electronic board was built by integrating the LED driver circuit and the phototransistor reading circuit. To facilitate and organize the connections, the connectors for power the liquid crystal display and the start button were integrated into the board. The resulting electronic board is shown in Fig. 4.

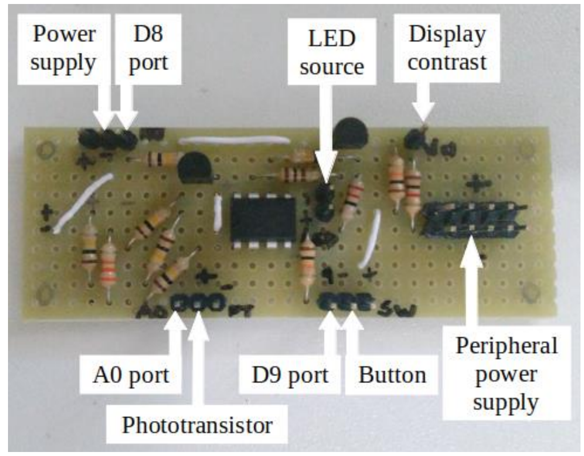
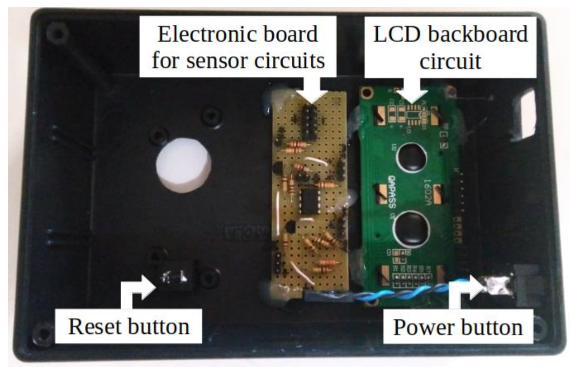
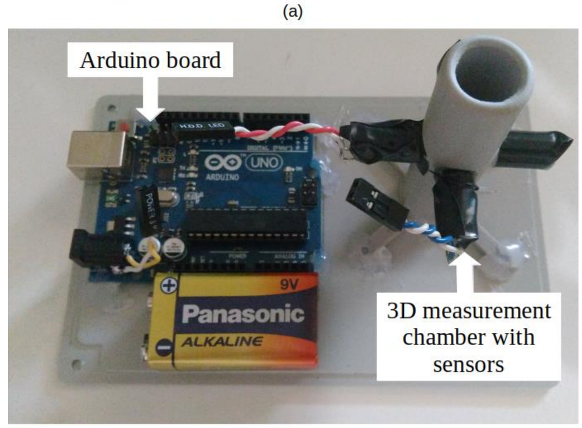


Fig. 4. Electronic board for LED driver and phototransistor measurement.



(a)



(b)

Fig. 5. Upper frame (a) and bottom frame (b) structures for assembly of the turbidimeter prototype.

Subsequently, all components were fixed to the turbidimeter structure, as shown in Fig. 5. A plastic box with dimensions of 15 × 10 × 5.5 (cm) was used as structure. Once the turbidimeter assembly was completed, the complete system programming was

Fig. 6. Turbidimeter developed (left) and 2100P turbidimeter (right).

developed. This programming is done on a computer, using Arduino Integrated Development Environment (IDE), and transferred to the Arduino Uno through the USB connection.

The device works as follows. The user turns on the turbidimeter with the on/off switch and waits until the message "INSERT SAMPLE AND PRESS THE BUTTON" appears on the screen. Then the sample container with the liquid to be analyzed should be placed in the measurement chamber and the button should be pressed to start the analysis. At the end of the measurement and processing steps, the dimensionless reading value and calculated turbidity value in NTU are displayed on the screen. If the turbidimeter is connected to a computer through the USB port, then the calculated turbidity value will also be sent through serial communication. After five seconds, the system returns to the beginning, being able to analyze a new sample.

For reasons already discussed, we investigated the possibility of calibrating the developed device by comparison with a commercial turbidimeter, using passion fruit juice as turbid fluid. The yellow-colored juice may not be rigorously appropriate, but it may be argued that near-infrared (NIR) wavelengths tend to be less susceptible to absorbance. The turbidimeter chosen was the Hach® model 2100P. The 2100P turbidimeter operates in the range of 0 to 1000 NTU, with accuracy of ±2% of reading. Thus, the developed portable turbidimeter could only be evaluated in this measuring range. Fig. 6 shows the developed turbidimeter and 2100P turbidimeter side by side to compare the physical dimensions.

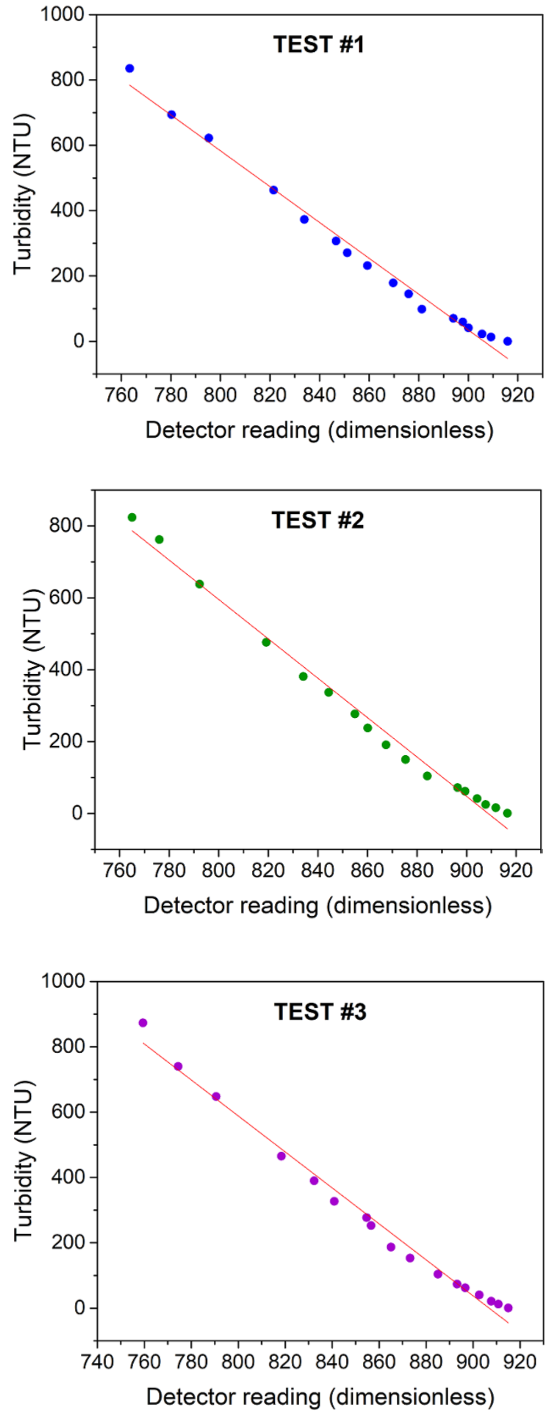


Fig. 7. All experimental data of the calibration procedure (calibration data of Table 1) and the corresponding regressed linear model.

We prepared solutions (samples) by diluting, in different proportions, a commercial brand of concentrated passion fruit juice with deionized water

- obtained in a reverse osmose water purifier system. The calibration method consisted in performing in each sample the turbidity measurement with the 2100P turbidimeter and the dimensionless reading in the developed turbidimeter, recording these two pieces of information together with the proportion of juice and water used to produce each sample. Three test sequences were performed in order to perform the study in triplicate. The calibration equation was obtained through regression, using the least squares method to determine the parameters.

3 Results

Data collected in the three test sequences are presented in Table 1, and their respective scatter plots and regressions are shown in Fig. 7.

By analyzing more carefully the behavior of the data in the graphs of the three tests (Fig. 7), it is possible to verify that in the samples with turbidity less than 100 NTU, the relation between the reading of the receiver and the value of the turbidity ceases to behave in a linear way. Therefore, it is not appropriate to represent this range through the linear equation resulting from the regression procedure.

In addition, it can be seen that this non-linear tendency of the data of samples with turbidity less than 100 NTU ends up displacing the equation resulting from the regression, damaging the correct representation of the collected data that presents linear behavior, which is the desired behavior in the turbidity measurement.

This behavior may be the result of an unsatisfactory resolution of the developed turbidimeter for the 0 to 100 NTU range. The device, though, is applicable in industrial processes where high turbidity liquids are commonly needed to be monitored. Then it was decided to exclude the data for the range of 0 to 100 NTU of the analysis and to determine the calibration equation for the range of 100 to 1000 NTU. The corrected scatter plots and the new regressions are shown in Fig. 8.

Analyzing the graphs in the new working range, shown in Fig. 8, it is evident that the data collected in the three tests, for the working range of 100 to 1000 NTU, showed the desired purely linear behavior. This is corroborated by the values of the respective adjusted coefficients of determination R^2, which were between 0.99 and 1.00. Thus, there is excellent representativeness of the data through the respective calibration equations. In addition, the calibration equations resulting from the regression of the data of each test have parameters values very close to each other, characterizing good repeatability of measurements by the developed turbidimeter.

Table 1. Data for calibration using the commercial turbidimeter 2100P and the low-cost portable turbidimeter.

	Test #1		Test #2		Test #3	
Sample (ratio juice:water)	2100P [NTU]	Prototype [dimensionless]	2100P [NTU]	Prototype [dimensionless]	2100P [NTU]	Prototype [dimensionless]
5:70	835	763.4	824	765.1	873	759.5
5:80	694	780.3	762	776.1	740	774.4
5:90	622	795.3	638	792.3	648	790.6
5:115	463	821.5	476	819.2	465	818.4
5:135	373	833.9	381	834.1	390	832.4
5:155	307	846.7	337	844.4	327	840.9
5:175	271	851.2	277	855	277	854.7
5:195	232	859.3	238	860.1	253	856.6
5:235	179	869.7	191	867.5	187	865.1
5:275	145	876	150	875.4	153	873.2
5:355	98.2	881.3	104	884.2	104	885.1
5:475	70.3	894	72.1	896.4	73.6	893.2
5:555	59.5	897.8	61.5	899.4	62.2	896.7
5:795	41	900.1	41.6	904.3	40.3	902.7
5:1115	22.8	905.6	24.9	907.7	21.3	907.8
5:1915	13.1	909.2	16.1	911.8	12.5	910.8
PURE WATER	0.13	915.9	0.45	916.5	0.6	915

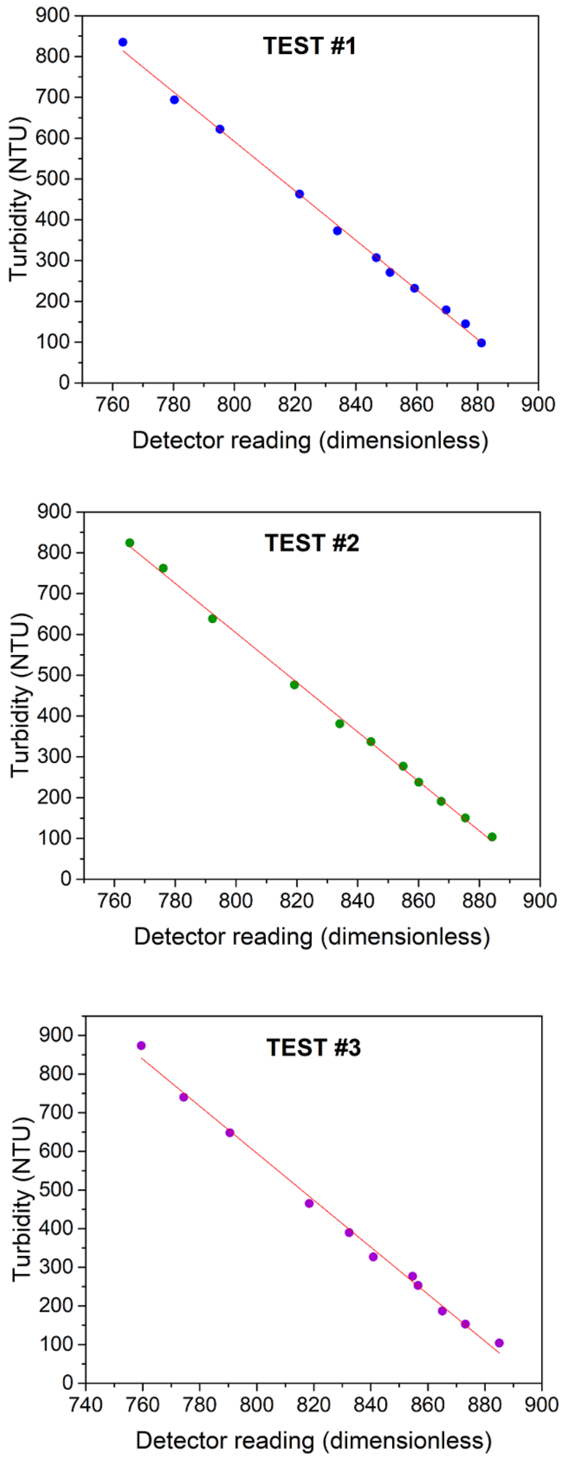


Fig. 8. Experimental data of the calibration procedure with data of turbidity greater than 100 NTU and the regressed linear model.

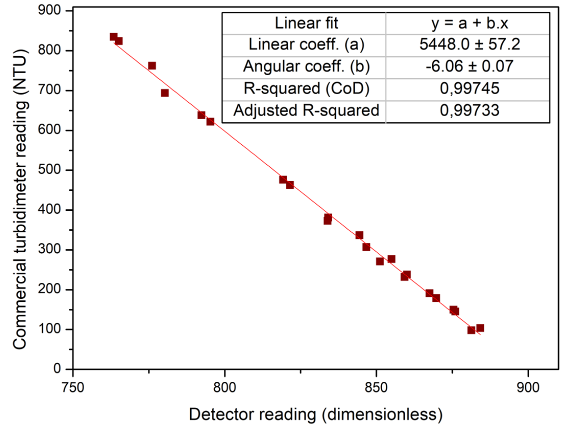


Fig. 9. Experimental data of sets #1 and #2 (Table 1) with turbidity greater than 100 NTU and the corresponding regression model.

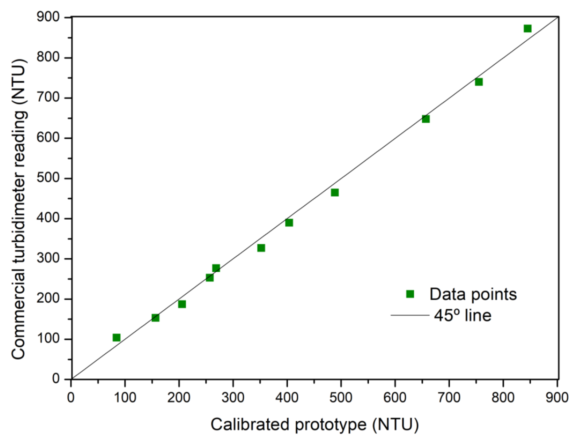


Fig. 10. Validation of the turbidimeter calibration, using dataset #3.

As evidenced by analyzing the data, only one calibration equation is required, and it was chosen to generate an equation by applying linear regression to datasets #1 and #2. The third dataset, which was the one with the relatively worst R^2 parameter, was used for validation of the turbidimeter calibration procedure. This new analysis is presented in Figs. 9 and 10.

Again, the data presented the purely linear behavior desired, resulting in an excellent quality regression with an adjusted coefficient of determination R^2 of 0.9973. The errors of the linear and angular coefficients of this regression were ± 57.2 and ± 0.07, respectively. The resulting calibration equation is expressed in Equation 1, where x is the value of reading detector, dimensionless, and y is the predicted value of turbidity, in NTU. Fig. 10 shows the validation of the generated equation, using dataset #3.

$$y = -6.06x + 5448.0 \quad (1)$$

4 Discussion

The calibration parameters indicate that the turbidimeter is precise and accurate in its range of operation. The CoD and adjusted R-squared demonstrate the appropriateness of the linear fit we performed and the standard deviation of the angular and linear coefficients are relatively small. In addition, the turbidimeter is reliable, as previously defined, for process industries quality control of its materials. The validation step supports this, as can be observed in the graph of Fig. 10 because the data points are very close to the identity line.

A relevant discussion of this research involves comparing performance parameters of previous works that developed portable hardware for measuring turbidity from a sample. The turbidimeter presented in Román-Herrera *et al*. (2016) has a large number of similarities, such as using the Arduino platform, a 3D-printed measurement chamber, and a blood test tube for holding samples. This work also compares the results with commercial turbidimeter model HACH® 2100P for calibration of the device. The differences come from the fact that the sensors (emitters and receivers) were different, the circuits for electrical integration of the sensors with the processing unit were as well not the same. Also, in the calibration phase, the work presented here used more data points. Most importantly, the results obtained in this work displayed less error deviation, and our design has a wider turbidity reading range (100 to 1000 NTU versus 50 to 650 NTU) and was significantly cheaper (US$ 46.30 versus US$ 150).

In Kelley *et al*. (2014), the authors report that it is achieved a turbidity measuring range of 0 to 1000 NTU, with the lower limit of calibration being analyzed at ~1 NTU, and low standard deviation, indicating that their design is suitable for drinking water quality assessment in developing and third world countries. They calibrated their device with five regression curves for the whole measurement range. It is reported, for the nephelometric technique, that there should be two linear ranges, one for low and the other for high turbidity of samples (García *et al*., 2007). Concerning the calibration method, we, in our work, hypothesized that the NIR LED would not be absorbed by the particles in the suspension, and it was confirmed by experiment as we successfully calibrated by CTC, and as the parameters of the regression curve showed an almost perfect linear fit to the experimental data.

Another point to be evaluated is the cost of the prototype, given the objective was the development of a low-cost portable turbidimeter. Concerning the materials used, acquired in the Brazilian market, the device documented in this paper costs less than US$ 50. Commercial portable turbidimeters, with similar features, which operate with samples up to 1000 NTU, have prices in the Brazilian market starting at approximately US$ 530. We state that - even if the associated costs of production are estimated, including other factors such as profit margins, capital cost, and labor cost - the final turbidimeter price would be significantly lower compared with prices of commercial turbidimeters available on the market.

Analyzing designs, with similar objectives, found in papers reported in the literature, it is clear that the proposed turbidimeter design achieved a reasonable price range. The cheapest device reported is the one by Kelley *et al*. (2014). They achieved a total cost per prototype of US$ 35. Additionally, it was stated by the authors that scale-up could decrease the cost per unit to around US$ 25. This approach and cost reduction could also be achieved by our design, in the scale-up phase. Using cheaper technologies, such as an analog display and a microcontroller, we estimate we could match the cost reported by Kelley *et al*. (2014). Other configurations, from different papers, are presented in Table 2.

Our prototype design, in addition to being a low-cost turbidimeter, is also distinguished as portable and allows serial communication with a computer via a USB port. The prototype was calibrated using juice and a commercial turbidimeter - a less expensive technique - and achieved remarkable accuracy in the linear fit. Also, the range of turbidity reading is adequate for use by small to medium-scale industries, universities, and regulatory agencies, guaranteeing that, with no need for major technical development, the turbidimeter has applicability and can be commercially explored. Moreover, the features in the device developed are hardly found in any commercial device available in the Brazilian market, especially at low cost.

Table 2. Comparison of different turbidimeters reported on scientific papers. Papers were chosen by relevance for comparison with the turbidimeter developed and described in this paper.

Reference	Turbidity Range	Prototype Cost	Calibration Method	Type of Radiation Source & Sensor	Technique of Turbidity Sensoring
This work	100 - 1000 NTU	US$ 46.30	CTC with passion fruit juice	NIR-LED (940 nm) & phototransistor	Nephelometry
Kelley *et al*. (2014)	1 - 1000 NTU	US$ 35.00	CTC with hydrophilic oil suspension	NIR-LED (860 nm) & light-to-frequency sensor	Nephelometry
Román-Herrera *et al*. (2016)	50 - 650 NTU	US$ 150	CTC	White LED & light-dependent resistor	Nephelometry
Zang *et al*. (2020)	40 - 300 NTU	US$ 46	Formazin	NIR LED (860 nm) & photodiode	Turbidimetry and Nephelometry
Metzger *et al*. (2018)	0.1 - 1000 NTU	Not revealed	Formazin	SMD-LED (860 nm) & light-to-frequency sensor	Nephelometry (GRINephy)
Kovačić & Ašperger (2019)	5.4 - 40 NTU	Less than US$ 100	Formazin and sulfate suspension	Blue LED (470 nm) & light-dependent resistor	Nephelometry
Kirkey *et al*. (2018)*	< 20 NTU & 0** - 815 NTU	US$ ~70	Formazin	RGB-LED & photodiode sensor	Optical Backscatter (120º)
Gillett & Marchiori (2019)*	0** (~1 NTU) - 100 NTU	US$ ~64	CTC with oil suspension and formazin	White-LED (4000K) & ambient light sensor	Nephelometry

* The reference turbidimeter is not sample-based nor portable.
** Inferior limit not rigorously determined in the original paper.
CTC = Commercial Turbidimeter Comparison (calibration technique).

Finally, we presented here a turbidimeter design that is portable and sample-based (offline measurements). The framework used the Arduino platform, inexpensive and modular electronic parts, and open-source software. This framework allows further developments and adaptations. For instance, the turbidimeter can be installed in a chemical process stream-line and we can develop a user interface for reading the measurements instantaneously. The turbidimeter, then, would be inline, in situ, and online.

Conclusions

As proposed, this work dealt with the development of a low-cost portable turbidimeter. The turbidimeter was able to work with turbidity samples in the range of 100 to 1000 NTU, presenting good accuracy and repeatability of the readings within this range. Above 1000 NTU it was not possible to evaluate the effectiveness of the developed turbidimeter, given that the commercial turbidimeter used in the calibration of the developed device is not able to read samples with turbidity greater than that value. Below 100 NTU turbidity readings are not reliable, given that the linear model cannot represent the data in this range satisfactorily.

The developed turbidimeter prototype had materials cost below US$ 50.00. Faced with the prices of commercial turbidimeters, which are found on the market starting around US$ 530.00, it is reasonable to consider the prototype a low-cost portable turbidimeter. The device is still innovative, whereas it has the features of being portable, making use of a battery as a power source, and offers to the user the communication with a computer through a USB port, features difficult to find on the commercial turbidimeters available on the market. Additionally, the device was calibrated with passion juice fruit by CTC, instead of using formazin solution, which is expensive and hazardous.

As suggestions for future developments, improving the range below the 100 NTU mark would dramatically expand the commercialization possibilities of the device. It is reported by Omar & MatJafri (2009), that the nephelometric technique may require two calibration curves, one for low turbidity (< 100 NTU), and another for higher turbidity suspensions, so this possibility should be explored. Another possible improvement is adding light sources and sensors for a four-beam technique, developing further on the work of García *et al*. (2007).

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