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Development of a new multipoint calibration method and uncertainty of a high-performance spectrophotometer for ensuring accurate water turbidity measurements

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Abstract: Turbidity is a key indicator of water quality influencing the proliferation of protozoa. Accurate turbidity measurements are essential for optimal water resource management and river basin planning particularly in contexts where water quality is a primary concern. Turbidity of unknown samples is usually measured by turbidity meters or spectrophotometers under one point calibration at 860 nm in the UV region. This creates a measurement limitation since the turbidity of an unknown sample should be the same or quite near turbidity to the CRM. To overcome this limitation, this work describes a new multi-point calibration method for a high-performance Lambda Spectrophotometer equipped with Gallium-Indium-Arsenic (GaInAs) detector. The calibration was carried out using three turbidity standards of 100, 500 and 1000 Nephelometric Turbidity Unit (NTU) which were measured in the NIR region at 1070, 1372 and 1569 nm respectively. The absorbance of each standard was measured 10 times and the CRM turbidly values were plotted against the measured absorbance values. A very good linear relationship was obtained with R^2 of 1 and the linear calibration function can be used to obtain the turbidity of an unknown sample measured at each of the three used wavelengths. The type A and type B calibration uncertainty sources were quantified according to ISO GUM and the calibration results were found to be 100.14± 0.47, 498.03±1.60 and 997.81±3.54 NTU. The method has been applied for measuring turbidity of a CRM sample with a small error of approximately 1%. The developed calibration method will be useful for analytical laboratories serving the water quality in the environmental and industrial sectors.

Keywords: Spectrophotometer; GaInAs; turbidity; CRM; calibration; uncertainty.

1. Introduction

Turbidity measurement is crucial to various sectors, including water treatment facilities, water supply and drainage systems, river and lake management and the beverage industry [1-8]. Accurate turbidity assessment is vital, as it directly reflects the quality of drinking water, wastewater effluents, natural water bodies and beverage products [9]. Several techniques are employed to measure turbidity, each with distinct advantages and limitations. Nephelometry, for instance, is a highly sensitive method that quantifies the light scattered by particles in a water sample at a 90-degree angle to the incident beam

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[10]. The intensity of this scattered light correlates directly with turbidity levels, making nephelometers essential for precise measurements [11]. Spectrophotometry, on the other hand, assesses the amount of light absorbed by particles at specific wavelengths. In this method, a monochromatic light beam passes through the sample and the absorbed light is measured. The absorption pattern, unique to each substance due to its atomic structure, allows for the determination of substance concentration using the Beer-Lambert Law, which states that absorbance is directly proportional to concentration [12]. Ensuring the accuracy and precision of turbidity measurements can be better reached by establishing the linearity of the measurement method within a specific range. This can be achieved through multipoint calibration using at least three certified reference materials, offering an advantage over single-point calibration by accommodating a broader range of sample analyses. Calibration involves establishing a relationship between known quantity values, with associated uncertainties provided by measurement standards and corresponding instrument indications [13]. Certified reference materials serve as measurement standards, accompanied by documentation from authoritative bodies, providing specified property values with associated uncertainties and traceabilities [14]. This paper aims to establish a multipoint calibration method for the Lambda 1050 spectrophotometer, equipped with a Gallium-Indium-Arsenic (GaInAs) detector, using three turbidity standard solutions in the NIR region. The first solution, with a turbidity of 100 NTU, was measured at 1070 nm, the second of 500 NTU, was measured at 1372 nm and the third of 1000 NTU, was measured at 1569 nm. This multipoint calibration addresses the limitations of one-point calibration, typically conducted in the UV region at 860 nm, which is suitable only for determining unknown samples with turbidity values similar to the certified reference material. A calibration curve was generated by plotting the certified reference material turbidity values against absorbance and the calibration function was used to calculate the turbidity of unknown samples measured at the specified wavelengths. Type A and Type B calibration uncertainty components were identified, and the calibration uncertainty budget was estimated according to ISO GUM and the EURACHEM/CITAC guide [15,16]. The developed multipoint calibration method is anticipated to enhance the analysis of water turbidity samples, contributing to improved environmental and industrial turbidity measurements.

2. Experimental

2.1 Equipment

The spectrophotometer used in this study is a high-performance Lambda 1050 manufactured by PerkinElmer, Inc. USA and controlled by the UV WinLab Software. The absorbances were measured by GaInAs detector that works in the NIR range, 860-1800 nm. The three formazine standard solutions 100, 500 and 1000 NTU were purchased from Takween Chemicals Solutions Co., Jubail, Saudi Arabia. The ultrapure water used as a reference solution was obtained from Millipore Milli-Q RG, USA.

2.2. Spectrophotometric Measurements

The spectrophotometer was run for 20 minutes until stabilization. The spectral bandwidth was selected as 2 nm and a 100% baseline was set. The reference cuvette was filled with ultrapure water and the second cuvette with the shaked sample to be measured. The required wavelength, nm was set and the absorbance was selected. Then the two cuvettes were placed in the holder and the absorbance of each turbidity standard sample (100, 500, 1000 NTU) was measured 10 times. The same procedure was followed at each of the selected wavelengths (1070, 1372 and 1569 nm) and the measured absorbance values were saved.

2.3 Measurement of Absorbance at Different Temperatures

The absorbances of the three turbidity standards, 100, 500 and 1000 NTU were measured at 15, 20, 25 and 30 °C. The temperatures 15 and 20 °C were attained using an ice bath, while 25 and 30 °C were attained using a temperature-controlled water bath and the measurements were carried out by a calibrated thermometer.

3. Results and Discussion

3.1. Selection of the Three Wavelengths

To develop the multipoint calibration method, the absorbance of the three turbidity standards (100, 500 and 1000 NTU) was measured at various wavelengths in the range of 900 to 1700 nm in the NIR region. From the measurement results, it was found that the three turbidity values 100, 500 and 1000 NTU were in very good linear relationship with the measured absorbances at the wavelengths 1070 nm for the turbidity standard 100 NTU, 1372 nm for 500 NTU and 1569 nm for 1000 NTU. After wavelength selection, the absorbance of each turbidity standard was measured 10 times at the assigned wavelength and the results were recorded in Table 1. The calibration graph was obtained by plotting the CRM turbidity values against the means absorbance values obtained at each assigned wavelength as shown in Figure 1. The linear equation of the calibration line is: y = 0.0048x - 0.3217 and the R^2 value was almost 1 indicating a very good linearity of the method.

Table 1. The measured absorbances and the corresponding turbidity values at three wavelengths

Wavelength, nm	**1070**	**1372**	**1569**		**100**	**500**	**1000**
CRM (*NTU*)	**100**	**500**	**1000**				
Absorbance	0.1589	2.0689	4.4679	Corresponding turbidity, NTU	100.13	498.042	997.83
	0.1590	2.0685	4.4678		100.15	497.96	997.81
	0.1591	2.0689	4.4677		100.17	498.042	997.79
	0.1589	2.0689	4.4677		100.13	498.042	997.79
	0.1590	2.0687	4.4677		100.15	498.00	997.79
	0.1588	2.0688	4.4677		100.10	498.021	997.79
	0.1591	2.0689	4.4678		100.17	498.042	997.81
	0.1591	2.0688	4.4678		100.17	498.021	997.81
	0.1590	2.0689	4.4679		100.15	498.042	997.83
	0.1590	2.0689	4.4679		100.15	498.042	997.83
$\bar{x}$	0.16	2.069	4.47		100.14	498.025	997.81
SD	0.00010	0.00013	0.000088		0.021	0.027	0.018
RSD%	0.063	0.0064	0.0020		0.021	0.0055	0.0018
				Recovery%	100.14	99.61	99.78

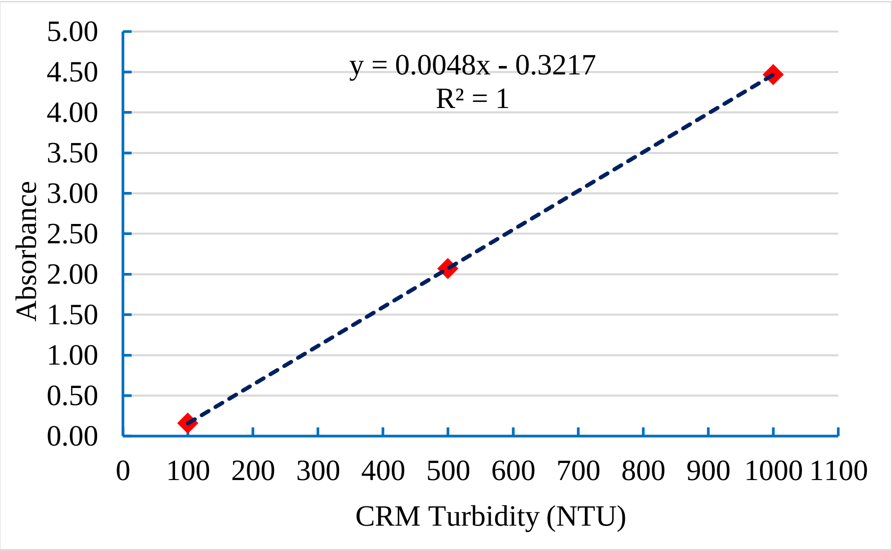

Figure 1. The calibration graph of spectrophotometer using three turbidity standards

3.2. Precision of the Method

A good level of precision is essential for reliable and accurate quantitative analysis. Precision is defined as closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions [13]. An assessment of precision can be made by considering the relative standard deviation, RSD which was calculated using equation 1, where SD is the standard deviation of the mean value. This provides a relative measure of precision indicating the variability of the data relative to the average value.

$$RSD\% = \frac{SD}{\bar{x}} \times 100 \qquad (1)$$

The RSD% values calculated from the turbidity values in Table1 were found 0.021%, 0.0055% and 0.0018%. These values are very low indicating that the measurements produced by the developed method are highly precise.

3.3. Recovery of the Method (accuracy)

Accuracy is a crucial performance characteristic of a measurement method, indicating the closeness of the average value to a reference value [13]. It can be inferred by calculating the percentage recovery. To perform this calculation, the turbidity of each CRM was calculated using the above-mentioned linear equation by substituting absorbance for the y-value and the obtained values were recorded in Table 1. The apparent recovery was then calculated by Equation 2, where x_{ref} represents the turbidity value of the CRM and the obtained values were recorded in Table 1[12]. It is clear that recovery values were 100.14%, 99.61%, and 99.78% for 100, 500 and 1000 NTU respectively indicating a very good accuracy of the developed method.

$$Recovery\% = \frac{\bar{x}}{x_{ref}} \times 100 \qquad (2)$$

3.4. The Method Bias

Bias is defined as: average of replicate indications minus a reference quantity value [12]. Thus, it was calculated by equation 3 in which $\bar{x}$ is the average turbidity and x_{ref} is the turbidity of the standard solution in NTU. The obtained bias% values were calculated by equation 4 and were found to be 0.14, 0.39 and 0.22 % indicating a very good accuracy of the method.

$$bias = \bar{x} - x_{ref} \qquad (3)$$

$$Bias\,(\%) = \frac{\bar{x} - x_{Ref}}{x_{Ref}} \times 100 \qquad (4)$$

3.5. The Uncertainty of Measurements

Establishing an uncertainty budget for turbidity measurements based on ISO GUM and EURACHEM guidelines is crucial, for assessing the quality of the measurement results [15,16]. In this study, a spectrophotometer equipped with a gallium-indium-arsenide (GaInAs) detector was calibrated using turbidity standards, 100, 500 and 1000 NTU. The mathematical model for this calibration is the linear equation 5, where y is the absorbance, x is the turbidity, a is the slope, and b is the intercept. From this equation, three explicit uncertainty sources can be identified: CRM turbidity (x), slope (a) and intercept (b).

$$y = ax + b \qquad (5)$$

However, a closer examination of the calibration procedure reveals implicit uncertainty sources derived from the manufacturer instructions. These include resolution, accuracy, reproducibility and the standard deviation of 10 measurements (all in nm) in addition to the photometric accuracy in absorbance unit. Furthermore, the effect of temperature on turbidity and the repeatability of measurements were considered. The all sources were represented by the fishbone structure in Figure 2 and the contribution of each source has been estimated as explained below.

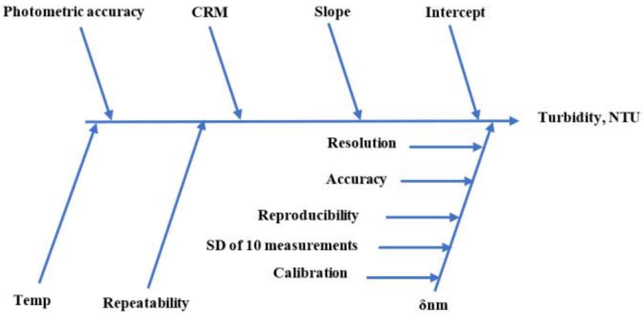

Figure 2. Fishbone structure of the uncertainty sources in turbidity measurements

3.5.1. Uncertainty of the CRM

The certificates of the three turbidity standards reported expanded uncertainties of 0.46, 1.60 and 3.54 NTU associated with reference values of 100, 500 and 1000 NTU respectively. These uncertainty values were divided by 2 using equation 6 to obtain the standard uncertainties, 0.23, 0.80 and 1.77, given that the calibration certificates indicated a coverage factor *k=2* at confidence level of approximately 95%.

$$u_{CRM} = \frac{U_{CRM}}{2} \qquad (6)$$

3.5.2. Uncertainty of the Slope

For estimation of the uncertainty of the slope of the calibration line, the standard deviation of the residuals, *S* was calculated by equation 7,

$$S = \sqrt{\frac{\sum_{i=1}^{N}(y_i - b - ax_i)^2}{N-2}} \qquad (7)$$

where,

N - number of measurements in the calibration process
y - response of the spectrophotometer
a - slope
b - intercept
x - turbidity of the CRM

The calculated *S* value was used in Equation 8 to calculate the uncertainty of the slope, *u(a)*

$$u(a) = \sqrt{\frac{S^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \qquad (8)$$

where,

S - standard deviation of regression

x_i - turbidity of the CRM
$\bar{x}$ - average turbidity of the CRMs
n - number of calibration points

The *S* value was also used for calculation of uncertainty of the intercept, *u(b)* by equation 9.

$$u(b) = \sqrt{\frac{S^2 \sum_{i=1}^{n} x_i^2}{n \sum_{i=1}^{n} (x_i - \bar{x})^2}} \qquad (9)$$

The uncertainties in the slope and intercept obtained from equations 8 and 9 were found to be 0.000013 NTU^{-1} and 0.0000016 Abs respectively. To determine the uncertainty of the intercept in turbidity units, the value 0.0000016 was added to 0.1641 (the absorbance value corresponding to a wavelength of 1074.80 nm) and the resulting absorbance was substituted for *y* in the aforementioned linear equation to calculate the corresponding turbidity. The difference in the calculated turbidity yielded an intercept uncertainty of 0.0013 NTU.

3.5.3. Uncertainty of the Photometric Parameters of the Spectrophotometer

The manufacturer instructions of the spectrophotometer identified the resolution, accuracy, reproducibility and the standard deviation of 10 measurements (in nm unit). Another uncertainty in nm unit is the calibration of the spectrophotometer (0.20 nm). The uncertainty value of each of the four sources was divided by √3 while the calibration uncertainty of the spectrophotometer was divided by 2 according to equation 6 to obtain the standard uncertainty as recorded in Table 2.

These five sources were combined using Equation 10 to yield an uncertainty, u_{nm} of 0.2098 nm, which was rounded to 0.21 nm.

$$u_{nm} = \sqrt{\left(C_1 . u_{Resol}\right)^2 + \left(C_2 . u_{Accu}\right)^2 + \left(C_3 . u_{Repro}\right)^2 + \left(C_4 . u_{SD}\right)^2 + \left(C_5 . u_{cal}\right)^2} \qquad (10)$$

Table 2. The uncertainty sources identified by the manufacturer and calibration of the spectrophotometer

Source of uncertainty	value	unit	divisor	$u(x_i)$	c_i	$c_i . u(x_i)$
Resolution	0.20	nm	√3	0.058	1	0.058
Accuracy	0.30	nm	√3	0.17	1	0.17
Reproducibility	0.040	nm	√3	0.023	1	0.023
SD of 10 measurements	0.020	nm	√3	0.012	1	0.012
Calb of spectrophotometer	0.20	nm	2	0.10	1	0.10
		u_{nm}		0.21	0.21	0.21
Photometric accuracy	0.00030	Abs	√3	0.036	0.036	0.036

To determine the uncertainty corresponding to 0.21 nm in turbidity unit (NTU), the 0.21 nm was added to 1074.60 nm to give a wavelength of 1074.81 nm. Then the absorbance of each standard turbidity, 100, 500 and 1000 NTU was measured at both wavelengths. The obtained absorbance values were then substituted for *y* in the linear equation: $y = 0.0048x - 0.3217$ to calculate the corresponding turbidity (*x*). The measured absorbances and the calculated turbidity values were recorded in Table 3. The difference in turbidity corresponding to 0.21 nm was found 0.0208 NTU, representing the uncertainty contribution of the above mentioned five sources.

Table 3. The turbidity values corresponding to the photometric uncertainty 0.21 nm.

CRM 100 NTU		**CRM 500 NTU**		**CRM 1000 NTU**	
nm	**Abs**	**nm**	**Abs**	**nm**	**Abs**
1074.81	0.1641	1074.81	0.3208	1074.81	0.5552
1074.60	0.1640	1074.60	0.3207	1074.60	0.5553
Turbidity, NTU	101.21 101.19	Turbidity, NTU	133.85 133.83	Turbidity, NTU	186.23 186.21
Difference	0.021 NTU		0.021 NTU		0.021 NTU

An additional source of uncertainty indicated by the manufacturer instructions is the photometric accuracy of 0.00030 Abs. To convert this absorbance uncertainty to turbidity units (NTU), it was added to the absorbance value 0.1641 measured at 1070 nm resulting in an absorbance of 0.1644. Substituting this value for *y* in the linear regression equation gave a turbidity of 0.0625 NTU, which was divided by √3 to obtain a standard uncertainty, u_{Paccu} of 0.036 NTU. This value was combined by equation 11 with the value of uncertainty, u_{nm} obtained above by Eq 10, resulting in an uncertainty value, u_{Phot} of 0.0417 NTU.

$$u_{Phot} = \sqrt{\left(C_1 . u_{nm}\right)^2 + \left(C_2 . u_{Paccu}\right)^2} \qquad (11)$$

3.5.4. Uncertainty due to the Effect of Temperature

To evaluate the uncertainty contribution of temperature on the measured turbidity values, a temperature range of 15-30°C was selected for this study. Measurements were taken at 15, 20, 25 and 30°C. At each temperature, the absorbance of the three standards, 100, 500 and 1000 NTU was measured 5 times at 1070, 1372 and 1569 nm respectively. The obtained absorbance results were recorded in Table 4 and converted to turbidity values by substitution as *y* in the linear equation mentioned above. The calculated turbidity values were also recorded in Table 4.

Table 4. The absorbance values of the three turbidity standards at different temperatures

Wavelength	**1070 nm**	**1372 nm**	**1569 nm**	**The corresponding turbidity, NTU**		
Temp (° C)	**Absorbance**			**100**	**500**	**1000**
15	0.1599	2.4677	4.5222	103.85	584.64	1012.66
20	0.1602	2.4680	4.5223	103.92	584.70	1012.68
25	0.1608	2.4682	4.5224	104.042	584.76	1012.71
30	0.1612	2.4683	4.5226	104.13	584.78	1012.75

The turbidity values in Table 4 were plotted against the temperature values as shown in Figure 3 (A, B, C) from which the slopes of 0.0192, 0.0092 and 0.0058 NTU/ºC respectively were taken as the sensitivity coefficients. They were multiplied by the calibration uncertainty (0.10 °C) of the thermometer used for temperature measurements to express the uncertainty contribution due to the temperature effect as $\delta Turb/\delta°C \ x \ u_{°C}$. The obtained uncertainties were found to be 0.0019, 0.00092 and 0.00058 NTU respectively.

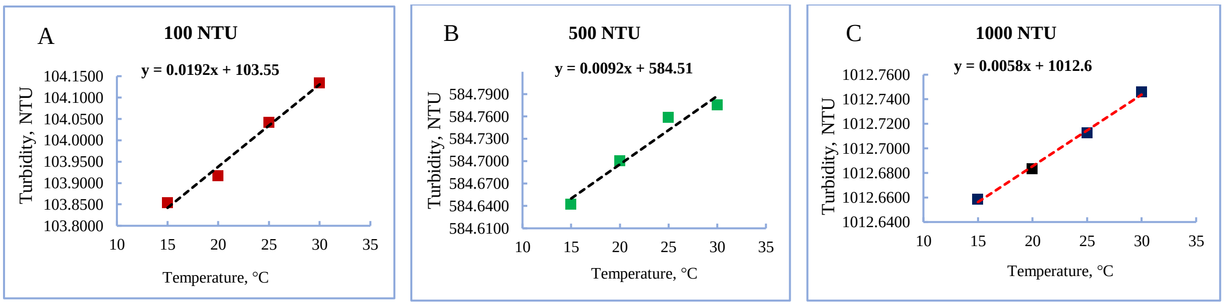

Figure 3. Temperature versus turbidity, **A** for 100NTU, **B** for 500 NTU and **C** for NTU.

3.5.5. Uncertainty of the Repeatability of Measurements

The uncertainty type A arising from the repeatability of the turbidity measurements of the three standard solutions was estimated using the turbidity values presented in Table 1. The standard deviation (*SD*) was calculated and divided by √10 according to equation 12 to obtain the repeatability uncertainty. The obtained values were then recorded in Table 5.

$$u_{rept} = \frac{SD}{\sqrt{n}} \qquad (12)$$

Table 5. The calculated turbidity values and the resulting uncertainty of the repeatability

100 NTU	$\bar{x}$	**SD**	**500 NTU**	$\bar{x}$	**SD**	**1000 NTU**	$\bar{x}$	**SD**
100.13	100.14	0.021	498.042	498.025	0.027	997.83	997.81	0.018
100.15			497.96			997.81		
100.17			498.042			997.79		
100.13			498.042			997.79		
100.15			498.00			997.79		
100.10			498.021			997.79		
100.17			498.042			997.81		
100.17			498.021			997.81		
100.15			498.042			997.83		
100.15			498.042			997.83		
		u_{rept} = 0.0066			u_{rept} = 0.0087			u_{rept} = 0.0058

To incorporate the implicit sources of uncertainty (u_{phot}, u_{Temp} and u_{rept}) into the mathematical model presented in equation 5, they were introduced by the term Δ*Tur*. The contribution of these sources was calculated by equation 13 resulting in a value of 0.042.

$$\Delta Tur = \sqrt{\left(C_1 . u_{Phot}\right)^2 + \left(C_2 . u_{Temp}\right)^2 + \left(C_3 . u_{Rept}\right)^2} \qquad (13)$$

The term u_{phot} in equation 13 represents the combined contribution of the five photometric sources outlined in the manufacturer instructions, while u_{temp} denotes the uncertainty contribution of temperature and u_{Rept} denotes the contribution of the repeatability of measurements. Consequently, the mathematical model was updated to equation 14 by adding the term Δ*Tur*.

$$Abs = a\,x + b + \Delta Turb \qquad (14)$$

3.5.6. The Combined Standard Uncertainty, u_c

The combined standard uncertainty, u_c was calculated using equation 15 which includes the CRM, slope and intercept as explicit sources of uncertainty, in addition to the implicit sources expressed by the term Δ_{Turb}. Since the four uncertainty terms are expressed in NTU, each of the sensitivity coefficients C_1, C_2, C_3 and C_4 was considered to be 1 [15]. The calculated u_c was found to be 0.234, 0.801and 1.770 associated with 100, 500 and 1000 NTU respectively.

$$u_c = \sqrt{\left(C_1 . u_{CRM}\right)^2 + \left(C_2 . u_a\right)^2 + \left(C_3 . u_b\right)^2 + \left(C_4 . u_{Turb}\right)^2} \qquad (15)$$

These standard uncertainties were multiplied by a coverage factor, $k = 2$ to provide the expanded uncertainties as 0.468, 1.602 and 3.541 NTU respectively according to equation 16.

$$U_{exp} = u_c \ x \ k \qquad (16)$$

3.5.7. Verification of the Calibration Results

To verify the validity of the calibration results produced by the developed method, this was done by examining whether the calibration results and their associated uncertainty fulfil the condition shown in Equation 17 [17,18],

$$\left| x_{obs} - x_{ref} \right| \leq 2\sqrt{(u_{x_{obs}})^2 + (u_{x_{ref}})^2} \qquad (17)$$

where

x_{obs} - measured turbidity
x_{ref} - standard turbidity
$u_{x\ obs}$ - standard uncertainty of the measured turbidity
$u_{x\ ref}$ - standard uncertainty of the standard turbidity solution

The absolute difference between measured turbidity results recorded in Table 1 (x_{obs}) and the reference turbidity values (x_{ref}) was calculated. Then the corresponding combined standard uncertainty multiplied by 2 was also calculated and all values were recorded in Table 6. From this table, it can be seen that the absolute difference in turbidity $/x_{obs}$-$x_{ref}/$ is smaller than double the combined standard uncertainty, thus fulfilling the criterion in equation 17. This means that a strong traceability link of the measured turbidity values to the CRM turbidity values was established.

Table 6. The verification of the measured turbidity by the reference turbidity values

x_{obs}	x_{ref}	$/x_{obs}$ - $x_{ref}/$	$u_{x\ obs}$	$u_{x\ ref}$	$2\sqrt{(u_{x_{obs}})^2 + (u_{x_{ref}})^2}$
100.14	100	0.14	0.23	0.23	0.65
498.03	500	1.97	0.80	0.80	2.26
997.81	1000	2.19	1.770	1.771	5.0077

3.5.8. Application of the Developed Method for Turbidity Analysis of a CRM Sample

To evaluate the performance of the developed method, the absorbance of a (CRM) sample with a nominal turbidity value of 550 NTU was measured at the three previously selected and used wavelengths in the calibration of the spectrophotometer: 1070 nm, 1372 nm and 1569 nm. The measured absorbance values are presented in Table 7. Then, these absorbance values (*y*) were substituted into the linear regression equation $y=0.0048x-0.3217$ to calculate the corresponding turbidity values (*x*) in NTU units. The calculated turbidity values at each wavelength along with their individual averages were also reported in Table 7. From these three averages, a grand mean turbidity value was determined yielding 555.58 NTU. Comparing this measured value with the value of the CRM reveals a deviation of 5.58 NTU, which corresponds to an error of approximately 1%. This minor deviation is considered highly acceptable, especially when accounting for external factors such as sample agitation, potential settling and other environmental influences that typically affect turbidity measurements. Overall, these results demonstrate that the developed spectrophotometric method provides reliable and accurate turbidity measurements and is therefore well-suited for its intended application.

Table 7. The absorbance values and the corresponding turbidity value of the CRM sample

1070 nm	**1372 nm**	**1569 nm**		**Corresponding turbidity (NTU)**		
	Absorbance					
0.3771	2.0732	4.5868		145.58	498.94	1022.60
0.3769	2.0735	4.5982		145.54	499.00	1024.98
0.3772	2.0731	4.5770		145.60	498.92	1020.56
0.377	2.0739	4.5874		145.56	499.08	1022.73
0.3771	2.0738	4.5904		145.58	499.06	1023.35
			$\bar{x}$	145.58	499.00	1022.85
			SD	0.024	0.074	1.59
			Grand Mean	555.58 NTU		

4. Conclusions

A method for multipoint calibration of a lambda 1050 spectrophotomer equipped with GaInAs detector by three turbidity standard solutions, 100, 500 and 1000 NTU was developed. The absorbance of the turbidity standards was measured at 1070 nm, 1372 nm and 1569 nm respectively. A very good linear calibration curve between the CRM turbidity and the absorbance values was obtained with R^2 almost 1. The method showed high precision expressed as very low RSD% values (0.021%, 0.0055%, and 0.0018%). It also demonstrated excellent accuracy with recovery values of 100.14%, 99.61% and 99.78% for 100, 500 and 1000 NTU respectively. In addition, the bias% values were very low (0.14%, 0.39% and 0.22%) further confirming the high accuracy of the developed method. The calibration expanded uncertainties were found to be 100±0.468, 500±1.602 and 1000±3.541 NTU, which are reasonable values. The method was examined by measuring the turbidity of a CRM of 550 NTU which yielded a turbidity value of 555.58 NTU with an acceptable error of approximately 1%, confirming the accuracy and reliability of the proposed method. The developed method will be useful for the environmental and industrial analytical laboratories measuring water turbidity.

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