Design of Low-cost Colorimeters (LCCs) for Water-based Pollutant Measurement in High School Environmental Education in Zambia

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Abstract

The need for a colorimeter with low capital and maintenance costs has been suggested for investigating water pollution in developing countries. This paper puts forward a design of such a device based on materials which can be purchased locally at very low cost (or salvaged electronic parts). It is shown that proper selection of the components will allow the cost objectives to be met and also provide acceptable precision and accuracy. The colorimeters in this study were designed to use inexpensive electronic components, such as light emitting diodes and photoresistors, which are readily available and hence render them affordable in many applications. The aim of this paper is to present a low-cost design of a colorimeter with regard to the maximum achievable accuracy and versatility in application. After testing the prototype instruments, it was found that Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma (ICP), Digital Water Analyser (DWA) using pack test and the Low-cost Colorimeters (LCCs) yielded identical results. It can be said that Manganese (Mn) in a mine effluent water sample was determined successfully using the LCC and hence can be applied to measure water related pollution parameters, on condition that a stable colour can be generated with an appropriate reagent, and hence a versatile tool for investigating the state of the environment.
Keywords: pack test, low-cost colorimeter, light-emitting diode, photoresistor, manganese

1. Introduction

Whether using simple, inexpensive field test kits, or more expensive and specialised instruments, students can gather data about water quality that will help them learn remarkably about rivers, streams, groundwater and other water bodies that they see everyday. Students can use monitoring equipment and apply scientific process skills as they gather data about many parameters of water quality. By assessing the water quality in a local water body, students will better understand how human activities affect this resource, and how we can protect its quality in future.

Social and technological changes require constant updating of the general population's knowledge and skills. Developments in science and technology are tangible realities affecting any member of society. Science education has become so important that many consider it necessary to strengthen considerably science teaching in all educational systems and to allow scientific literacy to develop. Provision of science equipment is so important such that in one study it was reported by teachers that adequate supply of materials made teaching more convenient and more effective, increased the amount of students work, and enabled teachers to broaden the science curriculum (Lazarowitz & Tamir, 1993).

The relevance of the low-cost equipment to the curriculum can be improved by showing its versatility and how accurate it can help in making students understand the quality of the water in their surrounding and how mass production of such equipment is

within the budget of even the most economically deprived school. This is also important in making schools to avoid buying, at a higher cost, from established manufacturers. Such easy to make low-cost equipment can induce a spirit of self-reliance and sense of ownership of the equipment and the process of gathering data. Relying on local resources as far as possible is crucial in moving the scientific literacy agenda forward (Jones et al., 1984).

At one point in the history of Zambia, there was the Overseas Development Administration (ODA)-funded Action to Improve English, Mathematics and Science (AIEMS) teacher training project which was initiated in 1994. The purpose of AIEMS was to strengthen the Ministry of Education in its provision of in-service training for trainers and teachers in primary and secondary English, Mathematics and Science (Miti & Herriot, 1997). Projects like AIEMS gradually went into oblivion (after the end of the project cycle) due to lack of a sense of ownership and reliance on the donated equipment which in some cases was irrelevant to the local circumstances. Nonetheless, AEIMS had good objectives as reflected in one of its workshop objectives of fostering repackaging of AIEMS materials to suit local needs and training strategies and to ensure that the 'source culture' does not clash with the 'recipient culture'. However, despite the good intentions and the heft funding which according to Miti and Herriot (1997) stood at £12.7 million for a period of seven years, all what remains of the project are only documents written about it. Long term sustainability (and lasting achievement) is not evident and was overtaken by other events (in-service programs) and the status quo, more or less, continues.

The low-cost equipment is appropriate in the light of economic deprivation and increasing water pollution not only in Zambia, but indeed in many other developing countries. Local development of equipment is supported in accordance with the curriculum and, where feasible, also local production of the equipment. Locally designed and produced equipment has a number of additional benefits, in that teachers and pupils can handle faults arising due to everyday usage. Investigation in the local environment is also useful in keeping up the objective of the Ministry of Education of providing safe water, by cooperating with the Ministry of Environment and Community Development (Ministry of Education, 1996). For the provision of safe water, it is vitally important to know the pollution parameters that are making it unsafe and the extent of the problem; and this is where the low-cost colorimeter (LCC) comes in handy. On the same issue, Musar (1993) argues that the supply of spare parts and repair services are ensured for a longer period.

Science is a subject with great practical importance and as much as possible equipment which encourages this objective to become a reality must be encouraged and sustained. Many students see science as abstract and irrelevant to their lives due to lack of engaging classroom laboratory equipment and activities. The importance of practical work in science is widely accepted and it is acknowledged that good quality practical work promotes the engagement and interest of students as well as developing a range of skills, science knowledge and conceptual understanding (SCORE, 2008).

There has been some efforts made in Zambia to address the problem of lack of teaching materials, and such efforts were addressed by the establishment of the National Science Centre (NSC) in Lusaka whose aim among other things, is to enable schools across Zambia to purchase laboratory supplies and apparatus affordably. Furthermore, local materials and labour are used, so expertise and capital are developed within the country. Despite this effort, the local curriculum does not require the pupils to determine the levels of pollutants in water; it is presumed that equipment for such a task is very costly to acquire by the local schools.

The NSC was established in 1991 with a core aim of upgrading of science and mathematics teaching and local production of science equipment. The NSC has two support centres referred to as satellite centres, one situated in the Northern Province (Mungwi) and the other in the Southern Province (Choma), and an outlet at the Ndola school of skills training. Both the head office in Lusaka and the satellite centres are production and delivery points. The NSC operational objectives include: the development of capacity for the local production of mathematics, science and technology teaching/learning equipment and materials. The NSC has designed a Science Kit and Mobile Laboratory meant for use in schools including those in the remotest areas (Malata, n.d.).

Using the LCC, teachers can demonstrate numerous scientific tests using water in their community derived from different sources. The students can learn the basic need for testing their water to avoid health complications and how microorganisms can grow in their water. Furthermore, pupils in collaboration with their teachers can compare the results of their own community drinking water to the guidelines of the Zambia Bureau of Standards (and Environmental Council of Zambia) drinking water quality, and to World Health Organisation (WHO) drinking water regulations.

Furthermore, teachers can guide their students to test for the most problematic water pollutants that are common in Zambia or in each region of the country since types of pollutants are largely dependent on human activities prevalent in a given location (e.g., mineral processing or agriculture). Some of the common parameters that may be of importance to pupils in Zambia include: Cu, Mn, NO_3^-, PO_4^{3-} and SO_4^{2-}. Students can compare their local water to three other samples of water, possibly from other regions (or towns) as well as to a control medium. The other water samples would include urban treated drinking water, rural treated drinking water and raw untreated water sources, and then to compare results from these waters to their own community drinking water.

Generally, four main categories of pollutants are of prime importance in Zambia.

These include:

1. Organic compounds that pollute water such as detergents, pesticides, fuels, and some types of industrial wastes (organic);

2. Inorganic compounds such as SO_4^{2-} from industries, PO_4^{3-} and NO_3^- from animals and fertilizers. By-products of most primary industrial activities fall in this category too;

3. Macroscopic pollutants that are usually large types of debris, for example, food waste, plastics and sediments from stormy water runoff. Sometimes trash dumped on the streets can end up in the rivers and that would be a form of macroscopic pollution. Basically, this is the pollution which is easily perceivable to the students and;

4. Thermal pollution mainly caused by industries. Usually the temperature is increased due to the reaction of some chemicals with the water. Chemicals like acid can release large amounts of heat when reacted with water.

This paper explored the qualitative method, such as used in the pack test, for analysis of Mn ions using an LCC. Some water samples collected from Zambia contain high concentration of Mn beyond what is locally and internationally accepted as revealed by several studies (Kabundihs, n.d.; Nachiyunde et al., 2012; Nwasco, 2010; Žaludková & Zeman, 2011). The analytical principle was based on allowing a beam of light to pass through a solution containing a coloured analyte initiated by the reaction of potassium periodate which is embedded inside the pack test tube; the Mn pack test is based on a reduction reaction by periodate ions. It allows measuring Mn ion concentrations in various samples like industrial waste water and environmental waters. Different concentrations and two LCCs were explored to determine the appropriate concentration by which the Beer's law is not violated. The response factors that affect the passage of current through a photoresistor are explored in the subsequent sections.

Over 40 different parameters have been successfully determined by colorimetric method and systematized for routine determination using the Digital Water Analyser (DWA) and pack test kit (Kyoritsu Chemical-check Lab., Corp, n.d.). These are the parameters which have been determined successfully using colorimetric techniques utilising a commercial colorimeter: aluminium, boron, calcium, chloride, residual chlorine, residual chlorine (free), total residual chlorine, chlorine dioxide, free cyanide, total cyanide, chemical oxygen demand with $KMnO_4$, colour, chromium hexavalent, total chromium, copper, anionic surfactants, dissolved oxygen, fluoride (free), iron, iron divalent, formaldehyde, hydrogen peroxide (high range), potassium, potassium permanganate consumption, manganese, ammonium, nickel, nitrite, nitrate, ozone, lead, phenol, phosphate, sulphide (hydrogen sulphide), silica, sulphate, total hardness, total nitrogen, total phosphorus, turbidity, zinc, and absorbance. Apart from these, many more parameters can be determined by colorimetric method as long as a stable product with a stable colour can be generated with an appropriate reagent and its colour intensity changes linearly (at an appropriate concentration) with increase or decrease in concentration. In this vein, a low-cost colorimeter can have limitless applications for investigating water pollution at high school level.

This study endeavoured to compare and verify the effectiveness of colorimetric methods by comparing the results of the same water samples but obtained by standard techniques of investigating heavy metal pollution in water, that is, by Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma (ICP). This study focused on the determination of Mn ions in an effluent water sample obtained from a copper mine in the Copperbelt Province of Zambia.

2. Low-cost Colorimeters (LCCs)

2.1 Materials

The materials used for the LCCs are: voltmeter, photoresistors, resistors, tri-colour light emitting diodes (LED) (rated 150mA, 3.0-3.5v), Darlington transistor, transformers (100v ac to 12v ac & 100v ac to 4.4v dc), multimeter (or voltmeter), batteries, two-way switch, 9v battery, cuvette, and improvised colorimeter boxes.

2.2 Circuit diagrams of the LCCs

A circuit diagram of the low-cost colorimeter 1 (LCC1) incorporating a 4 volt transformer and a separate 9 volt battery is shown in Figure 1. On the other hand, the low-cost colorimeter 2 (LCC2) incorporates a Darlington transistor as shown in Figure 2.
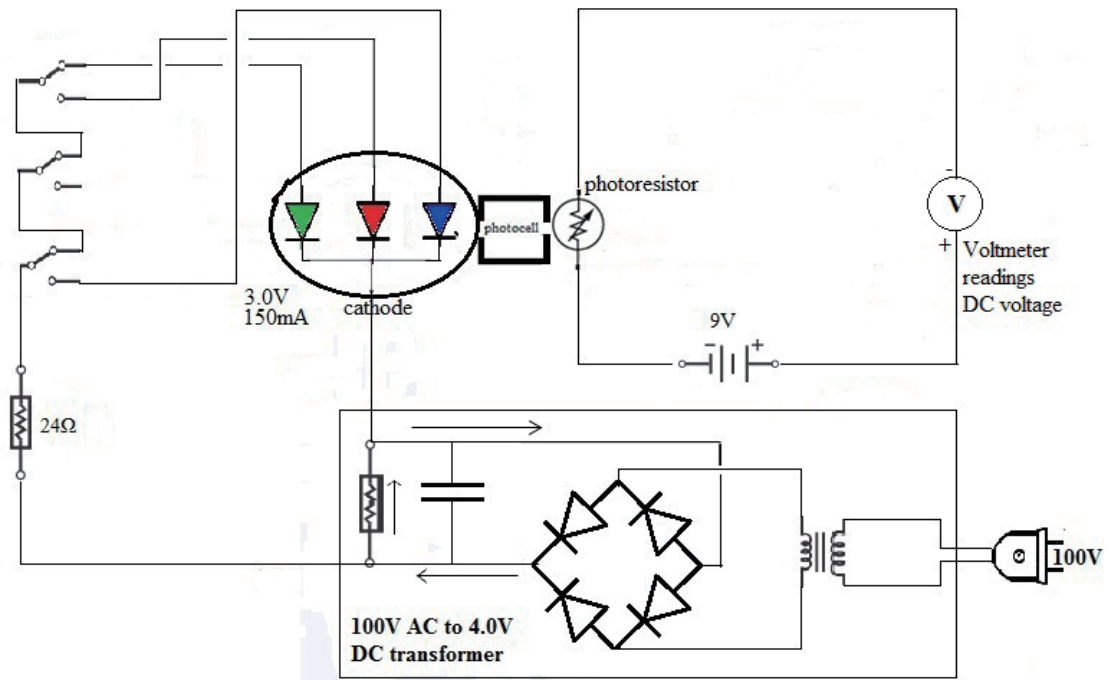
Figure 1. Circuit of the low-cost colorimeter 1 (LCC1) incorporating a 4 volt transformer and a separate 9 volt battery
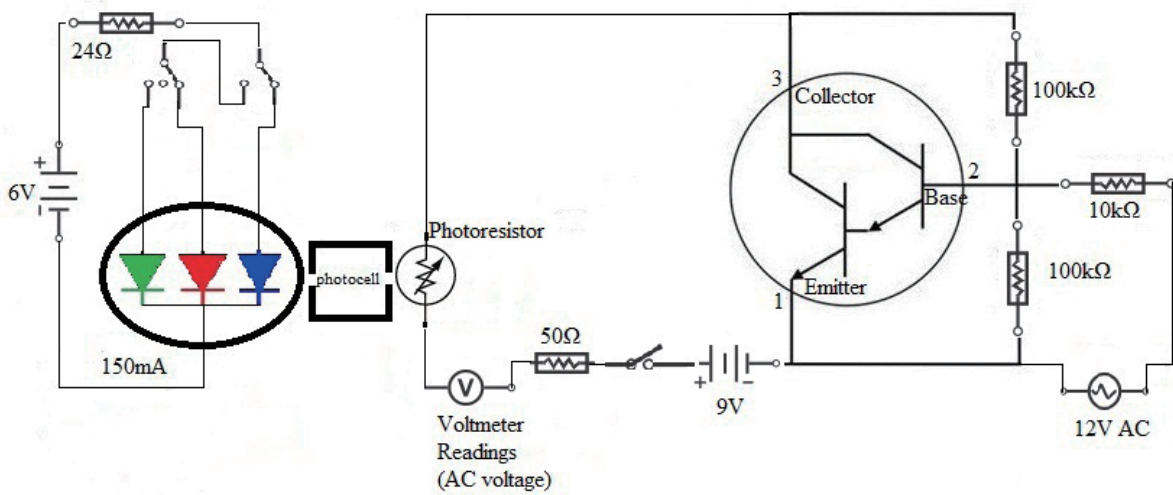

Figure 2. Circuit of the low-cost colorimeter 2 (LCC2) incorporating a Darlington transistor

An in-depth analysis of the performance of the LCC1 and LCC2 compared to the standard analytical instruments was performed and the results are reported in the subsequent sections.

2.3 Calculating the LED resistor value

An LED must have a resistor connected in series to limit the current through and hence avoid damaging it instantly. The LED resistor was worked out using the Ohm's law formula.

The resistor value, R was given by:

$$R = \frac{V_S - V_L}{I} \qquad (1)$$

Where: V_S = supply voltage; V_L = LED voltage (in this case $3.0V_{max}$); and I = LED current through resistor (in this case 150mA or 0.150A)

The supply voltage (to the LED) used in this experiment V_S = 6V, that is for LCC2, and the tri colour-LED rated forward voltage, V_L = 3.0V, and requiring a forward current I of 150mA (0.150A).

$$R = \frac{(6V - 3.0V)}{0.15A} = 20\Omega \qquad (2)$$

Because of the unavailability of the calculated resistor value (20Ω), the nearest standard resistor value which is greater was used (and should always be used), so that the current was a little less than the rated current. A greater resistor value was chosen to reduce the current and also to increase the battery life (but this can consequently make the LED less bright).

A 24Ω resistor connected in series (the nearest standard value which is greater than the calculated resistance) to the anode of the tri-colour LED was chosen. Alternatively, a variable resistor or rheostat can be used instead of a fixed value resistor. A similar resistor rated 24Ω was used in LCC1 because the voltage from the transformer was only 4V.

In LCC2, the output current passing through the photoresistor was amplified using a simple circuit incorporating a Darlington transistor.

2.4 Sample preparation and cost of the instruments

The next stage involved preparing solutions of known concentrations to be used in the colorimetric determination. A 320ppm standard solution of Mn^{2+} was prepared by adding 170.60 mg of 98% pure $Mn(NO_3)_2.6H_2O$ to a 100ml volumetric flask and adding distilled water up to the mark. From the standard solution, serial dilutions were done to prepare less concentrated samples (1ppm, 2ppm, 4ppm, 8ppm 16ppm and 32ppm) of Mn^{2+}. Using the potassium periodate method to generate a colour, the LCC1 and LCC2 were used to collect data which was used to prepare (linear) graphs. An effluent water sample (from tailings dump obtained from the mining town of Mufulira) known to be contaminated with Mn from stream (river) water was determined on the same colorimeters and the results recorded. Furthermore, two other samples were determined for Mn contamination on the DWA; Sample 1 was an upstream river water sample collected from Lusaka's Mutendere compound. Sample 2 was river water obtained from Lusaka's Chipata/Marapodi at Garden Park (stream) area.

An aliquot of the effluent water sample was determined by the DWA for comparison of its effectiveness to the LCC1 and LCC2. The DWA was set to measure Mn, and the following procedure was adhered to: a cell (cuvette) was filled with the sample up to the 1.5 mL line and inserted into the cell box and the instrument zeroed; the whole cell sample was drawn into the tube containing periodate ions and the instrument timer was started and the tube was shaken lightly 6 times and its content returned to the cell gently; the cell was inserted into the cell box and after 3 minutes passed, the measurement value was displayed automatically. The effectiveness of the DWA (using all three samples) was in turn counter-checked by comparing the results of the same samples obtained by a Perkin Elmer (PE) AAnalyst 100 Flame Atomic Absorption Spectrophotometer (AAS) and Varian 720-ES Inductively Coupled Plasma (ICP) optical emission spectrometer-model 720 ICPOES.

The PE AAnalyst system is used for flame operation and comes complete with air acetylene burner head, burner chamber, six lamp turret holder, background correction and safety drain bottle, and sold (reconditioned instrument) at a cost of ¥915,000 (£6,995) (Speck & Burke, n.d.). A similar instrument (a used STS Inductively Coupled Plasma High Density Plasma Etch System) as the Varian 720-ES Inductively Coupled Plasma (ICP) on ebay.com was priced at ¥6,283,161.2 ($79,999) ("STS Inductively Coupled Plasma High Density Plasma Etch System," n.d.). The total cost of the DWA is ¥315,000. The LCC1 used in this experiment cost ¥1,780 and the LCC2 cost ¥2,276 to assemble (see Table 1).

**Table 1.** Cost needed to assemble the Low-cost Colorimeters (LCC1 & LCC2)

No	Item	LCC1		LCC2	
		Source	Unit price (¥)	Source	Unit price (¥)
1	Power converter low voltage electronic transformer - 110v ac to 12v ac	na	na	eBay	316
2	Power converter low voltage electronic transformer - 110v ac to 4v dc	Junk	na		na
3	Five mm ultra-bright common cathode tri-colour RGB LED WL × 10pieces @ 393	eBay	40	eBay	40
4	Photo light dependent resistor photoresistor GL5549 × 5pieces @ 238	eBay	48	eBay	48
5	TIP142 transistor NPN Darlington 100v 10A	na	na	eBay	123
6	Improvised colorimeter box	Daiso	100	Daiso	100
7	Two way cable connector	Nafco	98	Nafco	98
8	Four way cable connector	Nafco	148	Nafco	148
9	Two way switch @ 200/unit	na	600		400
10	Resistors ×50 pieces @ 82	eBay	2	eBay	9
11	Four battery holder for 6v	na	na	eBay	250
12	One metre cable	Nafco	40	Nafco	40
13	Soldering wire	Nafco	100	Nafco	100
14	Circuit board		300		300
15	Battery - 9v	eBay	124	eBay	124
16	Voltmeter	eBay	180	eBay	180
	Total		1,780		2,276

na – not applicable

3.0 Measurement Theory

3.1 Radiation Absorbance

Colorimetry is a technique which applies to measurements made in the visible region of the electromagnetic spectrum, that is, between 380 nm and 780 nm. The extent to which light is absorbed by a sample is dependent upon many factors. The main general contributors are the wavelength of the incident light and the colour of the solution. Many compounds absorb ultraviolet or visible radiation. Figure 3 shows a beam of monochromatic radiation of radiant power P_0, directed at a sample solution. Absorption takes place and the beam of radiation leaving the sample has radiant power P.
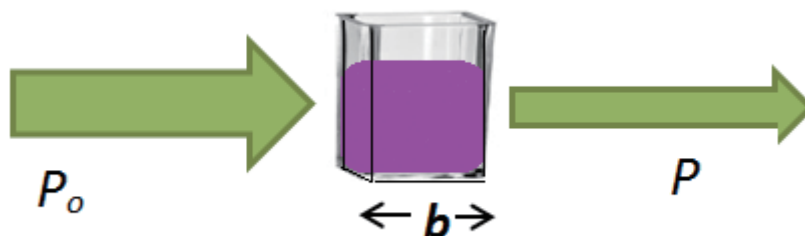
Figure 3. Monochromatic radiation passing through an absorbing species

The amount of radiation absorbed may be measured in a number of ways:

Transmittance, $T = P / P_0$ (3)

% Transmittance, $\%T = 100\ T$

Absorbance,

$A = \log_{10} P_0 / P$ (4)

$A = \log_{10} 1 / T$ (5)

Modern absorption instruments can usually display the data as transmittance, per cent transmittance, or absorbance. An unknown concentration of an analyte can be determined by measuring the amount of light that a sample absorbs and applying Beer's law. If the absorptivity coefficient is not known, the unknown concentration can be determined using a working curve of absorbance versus concentration derived from standards (as performed in this study).

In principle, if all the light passes through a solution without any absorption, then absorbance is zero, and per cent transmittance is 100%. If all the light is absorbed, then per cent transmittance is zero, and absorption is infinite.

3.2 The Beer-Lambert Law

The law describes the quantitative relationship between the absorbance of radiant energy, the concentration of the sample solution, and the length of the path through the sample.

$A=\varepsilon bc$ (6)

Where: A is absorbance (no units, since $A = \log_{10} P_0 / P$); ε is the molar absorptivity with units of L mol^{-1} cm^{-1}; b is the path length of the sample, that is, the path length of the cuvette in which the sample is contained, this measurement will be expressed in centimetres; c is the concentration of the compound in solution, expressed in mol L^{-1}.

Absorbance is directly proportional to the other parameters, as long as the law is obeyed.

From $A = \varepsilon bc$, it can be deduced that absorbance depends on the total quantity of the absorbing compound in the light path through the cuvette. If absorbance against concentration is plotted, a straight line passing through the origin (0, 0) is obtained as shown in Figure 4.
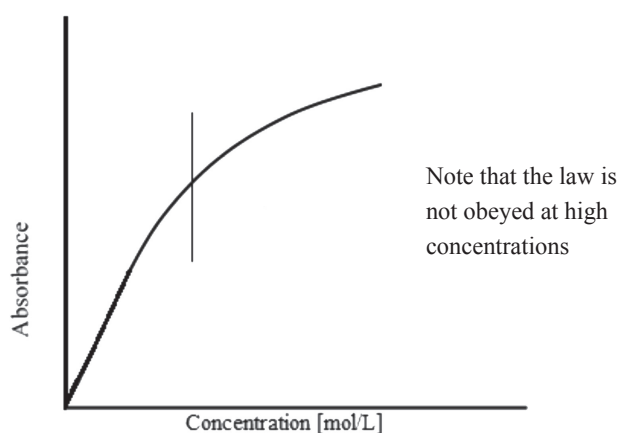

Note that the law is not obeyed at high concentrations

Figure 4. Absorbance vs. concentration

The linear relationship between concentration and absorbance is both simple and straightforward, and for this reason it was used to investigate the aspect of chemistry teaching involving determination of pollutants in aqueous medium.

3.3 Light source and colour of analyte

Colorimetry is just one of the types of photometric analysis techniques; it is a light measuring analytical procedure. It is vitally important to note the colour of the solution and correlate it with a light source of the appropriate wavelength. The LED or wavelength of the light source that will produce the maximum absorbance can be selected in two ways: taking readings throughout the spectrum on a typical standard solution of the substance under investigation and establish the peak wavelength (λ_{max}) and; method two (the method used in this study) involves choosing a light source of the complementary colour to the solution under investigation.

In colour theory, two colours are called complementary if, when mixed in the proper proportion, they produce a neutral colour (grey, white, or black). Complementary colours can also be visualized as pairs of colours that are opposite hues in a colour

model. If one references a colour wheel, a set of complementary colours would be the colours directly across from each other. These exact opposites help create contrast within a design and can help in choosing an appropriate monochromatic light source. In this study the reaction of Mn ions with periodate produced a purple solution and hence a green LED was used for the analysis as shown in Figure 3.

3.4 Reaction of Manganese ions with periodate

This study presents a novel way of LCC design which include among other things, signal amplification based on a 1 watt amplifier. These kinds of colorimeters can be applied to analyse various parameters similar to a conventional colorimeter. For Mn ion analysis involving periodate, the measurements were conducted at 520nm.

This study further shows a brief description of several experimental results using the LCCs in comparison to data obtained from standard equipment, and to verify its applicability to Mn determination.

Small quantities of Mn are readily determined colorimetrically by oxidation to the highly coloured permanganate ion. Potassium periodate is an effective oxidizing agent.

$$5IO_4^- + 2Mn^{2+} + 3H_2O \rightarrow 2MnO_4^- + 5IO_3^- + 6H^+$$
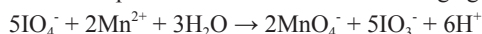
Permanganate solutions containing an excess of periodate are relatively stable.

There is little interference in this procedure. The presence of coloured ions can be compensated by employing a blank, that is, a sample that has not been oxidized by periodate. However, this method is not effective in the presence of appreciable quantities of chromium (III) ions, for it is oxidized to some extent by periodate, and its reaction products absorb in the spectral region commonly employed for permanganate (Bright & Larrabee, 1929).

3.5 Caution in using the periodate method with the Digital Water Analyser (DWA)

Only dissolved Mn ions (from divalent up to hexavalent) can be determined in this method.

For measurement of total Mn fraction including suspended particles, a pre-treatment was needed; in this study there was pre-treatment as the objective was to determine the total amount of dissolved Mn.

Another caution is in the measurement of heptavalent Mn ion; a lot of reducing agent has to be added into the sample in order to counteract red colour, and the blank measured.

The pH of the solution is known to affect the colour development, especially, if it is very acidic or alkaline. For this experiment pH was in the acceptable range of between pH 5 - 9, so there was no cause to adjust the pH with dilute sulphuric acid or sodium hydroxide solution. The temperature was kept within the acceptable range of 15 - 30°C.

Interference is expected because the built-in calibration curve is determined from standard solutions. However, coexisting ions can modify the reaction colour. Table 2 reports ion concentrations under which interferences are insignificant:

Table 2. Ion concentrations under which interferences are insignificant using the DWA

Concentration (ppm)	Species
	Miscellaneous ions
≤1000	B(II), Ca^{2+}, $C\ell^-$, F^-, K^+, Mg^{2+}, Na^+, NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-}, Anionic Surfactant, Residual Chlorine, Formaldehyde
≤50	NO_2^-
≤20	CN^-
≤5	I^-, Phenol
	Heavy metal ions
≤1000	Mo (VI)
≤500	Ni^{2+}
≤200	Al^{3+}, Ba^{2+}, Zn^{2+}
≤100	Cu^{2+}, Fe^{2+}, Fe^{3+}
≤50	Cr (VI)
≤20	Co^{2+}
≤5	Cr^{3+}

The method is considered to be equally suitable for seawater samples.

A lot of reductive substances can make negative error. For example, sodium hydrogen sulphite coexisting at higher than 10g/L is known to cause interference (Kyoritsu Chemical-Check Lab., Corp, n.d.).

4. Results and Discussion

The water samples suspected to be contaminated with Mn ions and whose results were used to test the colorimeter were obtained from Zambia. All the methods (AAS, ICP, DWA and LCCs) have been reported in the subsequent sections and the results compared to determine if they are similar despite their huge cost differences and amount of time needed for sample preparation before the actual analysis.

4.1 Comparison of LCC1 and LCC2

The different colorimeter designs or configurations were compared to establish under which conditions the Beer-Lambert law fails to maintain a linear relationship between absorbance and concentration of analyte. These deviations are classified into three categories namely: the real deviations, these are fundamental deviations due to the limitations of the law itself; the chemical deviations, these are deviations observed due to specific chemical species of the sample which is being analysed, and in this study it was the reaction of Mn with IO_4^-; and the lastly the instrument deviations. The instrument deviations occur due to how the absorbance measurements are taken, in this case two colorimeter designs were compared with some slight variations in the way measurements are taken. Figure 5 shows the results when values obtained using LCC1 were used to plot a graph of absorbance versus concentration, and Figure 6 shows the result when LCC2's experimental values were used to plot a graph of absorbance versus concentration.
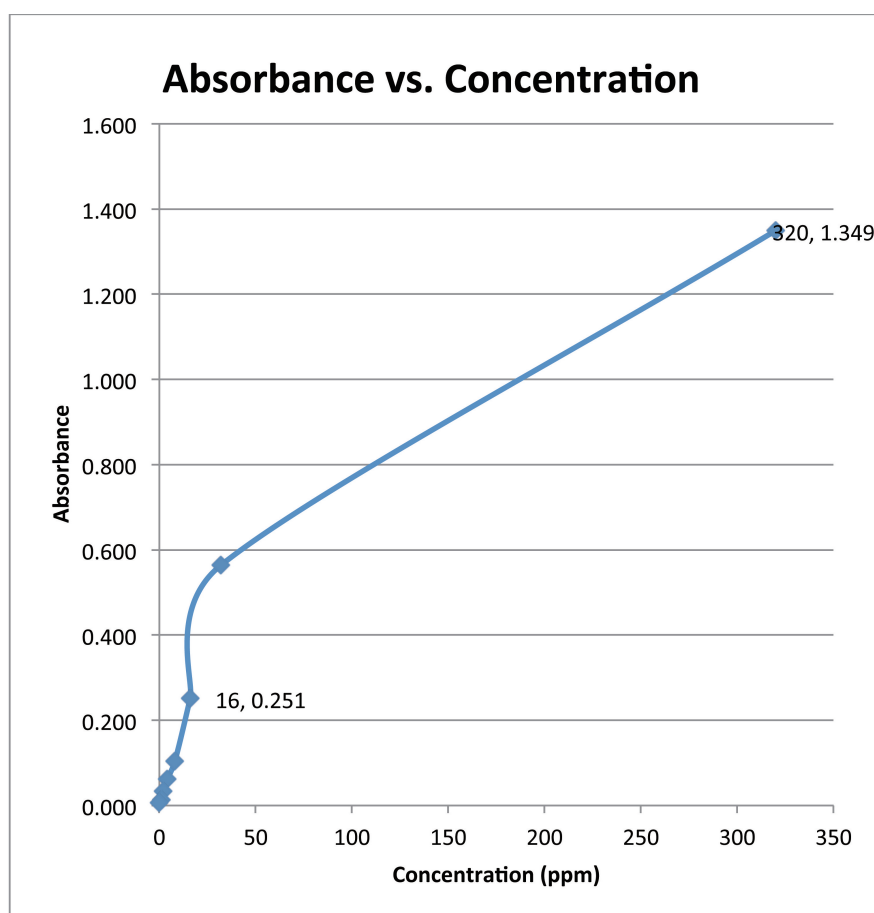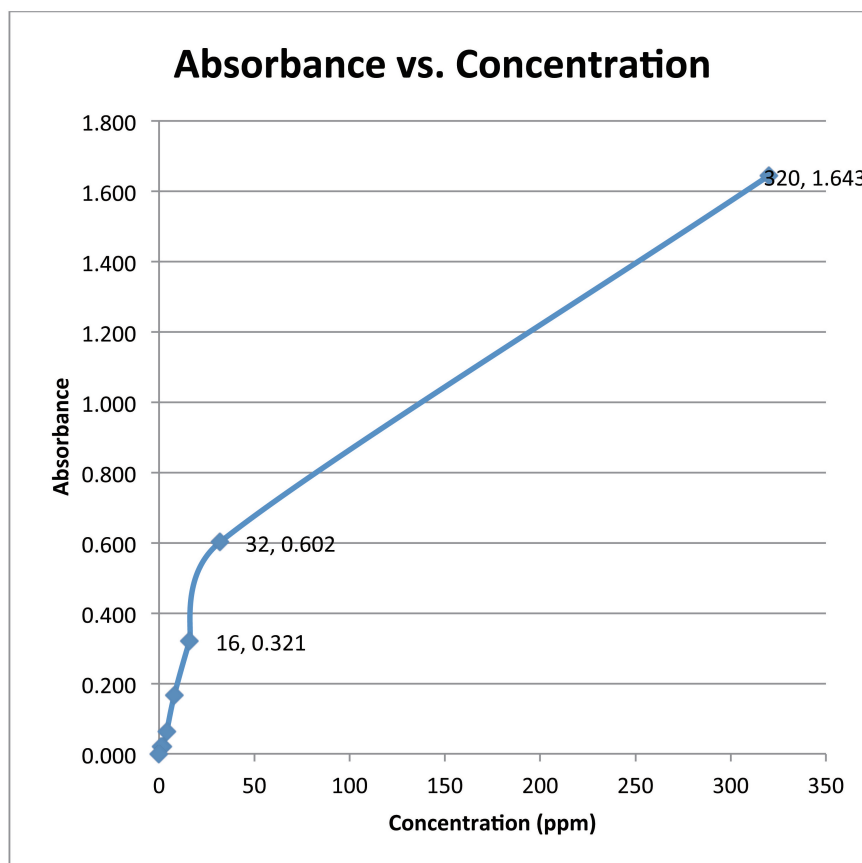

Figure 5. Plot of manganese concentration versus absorbance using the LCC1 (0ppm, 1ppm, 2ppm, 4ppm, 8ppm, 16ppm, 32ppm, 320ppm)

Figure 6. Plot of manganese ion absorbance using the LCC2 (0ppm, 1ppm, 2ppm, 4ppm, 8ppm, 16ppm, 32ppm, 320ppm)

Using both LCC1 and LCC2, it can be deduced that both instruments had the same range of linearity with reference to Mn reaction with periodate. The instruments show that for analytical purposes, it is appropriate to prepare standards not exceeding 16ppm. And using concentration values higher than 16ppm leads to a compromise on the obtained values as the Beer-lambert law is not obeyed as shown by both the figures representing LCC1 and LCC2. It is also important to note that these results apply only to the Mn/IO_4^- reaction and that the procedure should be repeated if the LCCs are to be used to analyse a different pollutant, for example Cu, or if the Mn is to be analysed using a different reagent to generate a colour; different reagents can be used to generate a colour for subsequent analysis. Some examples of the reagents that have been used before include the persulfate oxidation, formadoxime, and malachite green colorimetric methods as reported by Delfino and Lee (1969).

Table 3. Concentration of Sample 1 as generated by different methods

Method/ Instrument	Measurement 1 (ppm)	Measurement 2 (ppm)	*Average (ppm)*
DWA	0.60	0.90	*0.75*
ICP	0.52	0.52	*0.52*
AAS	0.56	-	*0.56*

Average (ICP&AAS) = 0.54ppm

4.2 Values obtained by DWA, ICP and AAS

Table 3 shows the experimental values obtained when the concentration of sample 1 was determined by three methods

namely, DWA, ICP, and AAS.

The average of the ICP and AAS was taken as the acceptable value and the per cent deviation of DWA was found to be 39%

Table 4. Concentration of Sample 2 as generated by different methods

Method/ Instrument	Measurement 1 (ppm)	Measurement 2 (ppm)	*Average (ppm)*
DWA	0.70	0.80	*0.75*
ICP	0.80	0.81	*0.81*
AAS	1.12	-	*1.12*

Average (ICP&AAS)= 0.97ppm taken as the acceptable value

The effectiveness of the DWA compared to the results obtained by ICP and AAS on sample 2 was compared as shown in Table 4 and the per cent deviation was found to be 23%.

Table 5. Concentration of Sample 3 (effluent water) as generated by different methods

Method/ Instrument	Measurement 1 (ppm)	Measurement 2 (ppm)	*Average (ppm)*
DWA	6.40	6.30	*6.35*
ICP	-	-	-
AAS	9.50	-	*9.50*

The value obtained by AAS is taken as the acceptable one

The same procedure, as shown in Table 5, was performed on sample 3 (mine effluent water) to determine the effectiveness of the DWA compared to the results obtained by AAS and the per cent deviation was found to be 33%. When three samples were determined by the three standard methods, it was proved that the result obtained by the colorimetric method (the DWA) was always lower in comparison to the results by ICP and AAS. The deviations ranged from 39% to 33%. Furthermore, the results show that determining lower concentrations of Mn ($\leq$ 1ppm) was less accurate as can be perceived by the relatively higher per cent deviation of sample 1. The DWA is taken as the standard colorimetric instrument from which the LCCs were developed and so it was imperative to ascertain its accuracy relative to the systematic instruments: ICP and AAS.

4.3 Results obtained by LCC1 and LCC2 with comparison to results by AAS, ICP and DWA

From the sample of unknown concentration (effluent water) and seven standard samples of known concentration, from a maximum of 320ppm to 1ppm (and a blank solution) of Mn as shown in Table 6, absorbance values were obtained using both LCC1 and LCC2. The absorbance values versus concentration were plotted on graphs for comparison of the effectiveness of the two instruments. From the graphs obtained by a combination of known concentrations (Figure 7 to Figure 10), the unknown concentration of the effluent water was determined.

Table 6. Absorbance values of the standard samples and the Cu mine effluent sample obtained from Zambia using the low-cost colorimeters (LCC1 and LCC2)

Concentration	LCC1			LCC2		
	$P_o(V)$	$P(V)$	Absorbance (Log P_o/P)	$P_o(V)$	$P(V)$	Absorbance (Log P_o/P)
320ppm	6.70	0.30	1.3490	4.40	0.10	1.6435
32ppm	6.60	1.80	0.5643	4.40	1.10	0.6021
16ppm	6.60	3.70	0.2513	4.40	2.10	0.3212
8ppm	6.60	5.20	0.1035	4.40	3.00	0.1663
4ppm	6.80	5.90	0.0617	4.40	3.80	0.0637
2ppm	6.70	6.20	0.0337	4.20	4.00	0.0212
1ppm	6.70	6.50	0.0132	4.40	4.20	0.0202
Blank solution	6.70	6.60	0.0065	4.40	4.40	0.0000
Effluent Water	6.60	5.40	0.0872	4.40	3.40	0.1120

A graph of absorbance against concentration was plotted and the results show that the LCC1 and LCC2 produced reasonably linear graphs. The Mn concentration (9.50ppm) obtained by AAS was taken as the accepted value for the mine effluent water from which the subsequent per cent deviations were computed.
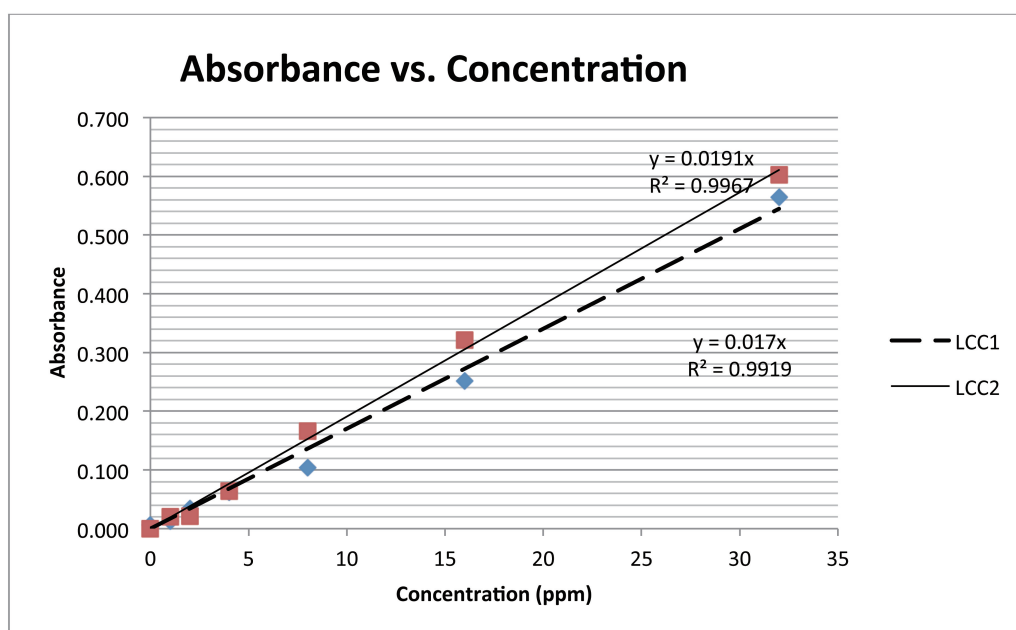
Figure 7. Plot of absorbance vs. concentration (0ppm, 1ppm, 2ppm, 4ppm, 8ppm, 16ppm, 32ppm)

Using the linear equation *y = 0.017x* obtained by LCC1 and generated by plotting the standard concentration values from 0ppm to 32ppm (Figure 7), it was found that the effluent water had a Mn concentrations of 5.13ppm and a per cent deviation from the systematic instrument of 46%. Using LCC2, the Mn levels in the same effluent water was determined as 4.57ppm (with a deviation of 52%).

A second graph (Figure 8) was plotted where the 32ppm value was eliminated and the standard concentrations from 0ppm to 16ppm were plotted in order to check the effect of the higher value(s) on the unknown concentration of the sample.
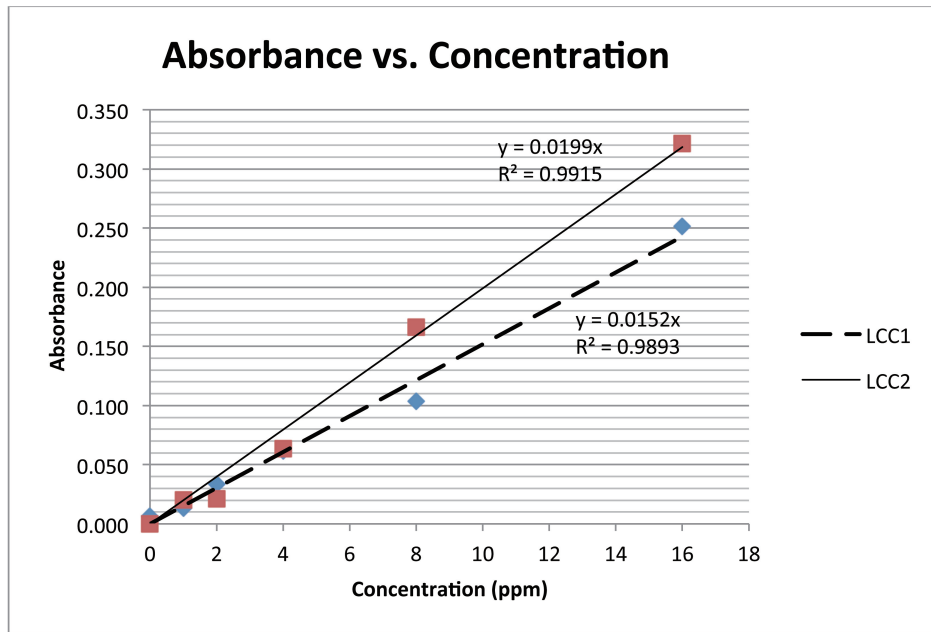
Figure 8. Plot of absorbance vs. concentration (0ppm, 1ppm, 2ppm, 4ppm, 8ppm, 16ppm)

Once more, using the linear equation, *y = 0.0152x* as generated by LCC1, it was found that the effluent water yielded a concentration of 5.7ppm (with deviation of 39.6%). On the other hand, using LCC2, the effluent water's Mn level was determined to be 4.38ppm with a deviation of 53.9%. It can be deduced from the results that when the higher value (32ppm) is not included in plotting the linear graph, LCC1 gave a more accurate value; however, the LCC2 value was less accurate and a further deviation from the value obtained by AAS. In this particular case, it can be deduced that including the 32ppm sample affected the accuracy of the determined value of the effluent water differently. It was more accurate for LCC1 and less accurate for LCC2.
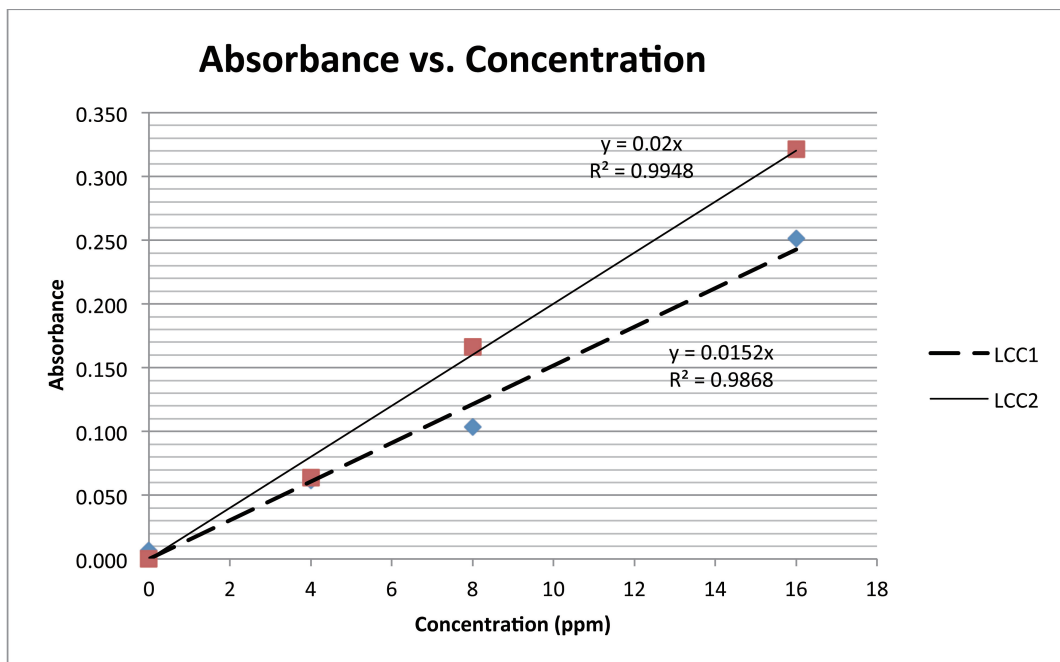

Figure 9. Plot of absorbance vs. concentration (0ppm, 4ppm, 8ppm, 16ppm)

The third graph (Figure 9) was plotted in which case the calibration curve was derived by considering only four standard concentration values (0ppm, 4ppm, 8ppm & 16ppm) obtained using the LCCs. The LCC1 resultant graph is shown in Figure 9.

Using the linear equation, $y = 0.0152x$, the effluent water's Mn levels was determined as 5.73ppm with a deviation of 39.6%. The analysis was repeated by using LCC2 and the effluent water was determined to have a Mn concentration of 4.36ppm with a deviation of 54.1%.
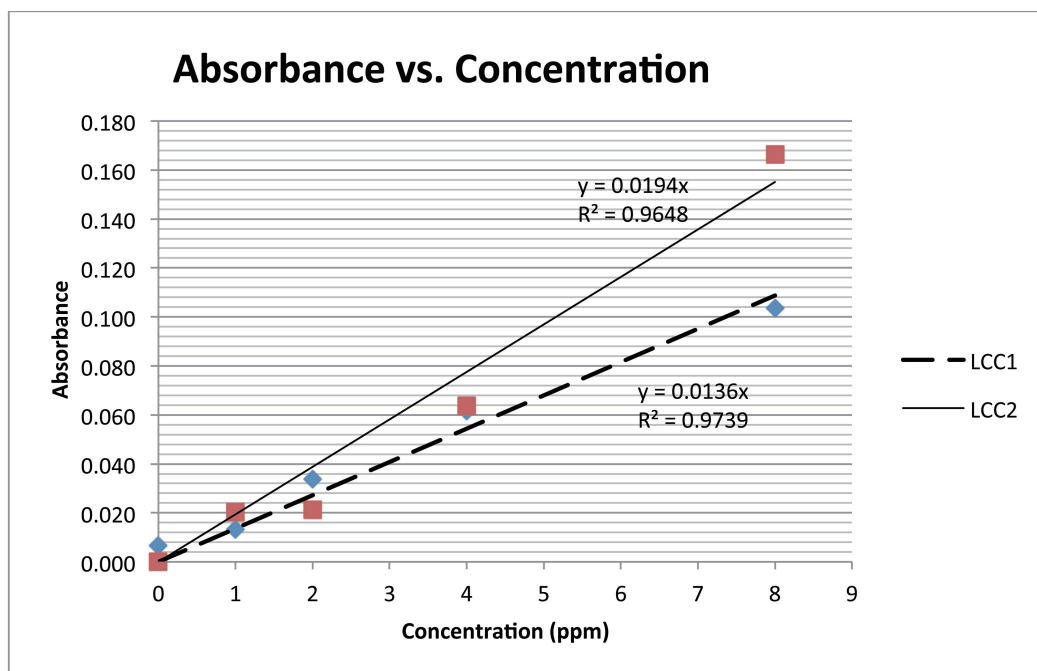

Absorbance vs. Concentration

$y = 0.0194x$
$R^2 = 0.9648$

$y = 0.0136x$
$R^2 = 0.9739$

Figure 10. Plot of absorbance vs. concentration (0ppm, 1ppm, 2ppm, 4ppm, 8ppm)

  The fourth graph (Figure 10) was plotted in which case only the lower concentration values (0ppm, 1ppm, 2ppm, 4ppm, 8ppm) were used to prepare the calibration graph. The same effluent water sample, using LCC1, was determined as 6.4ppm and per cent deviations of 33%; using LCC2 the same sample was determined as 4.49ppm and corresponding to a per cent deviation of 53%.

  The fourth scenario gave the closest values and per cent deviations like those obtained by comparing DWA to ICP and AAS. The sample 3 (the effluent water) was determined using the DWA and compared with ICP and AAS, it yielded a deviation of 33%. However, the deviations when LCC1 and LCC2 were used to analyse the same effluent water sample, were 33% and 53% respectively. The DWA's accuracy is comparable in accuracy to the LCC1. On the other hand, the LCC2 gave results that are less accurate than the DWA. LCC1 gave results that were very close to the results obtained by the more expensive and systematic instruments. LCC1 proved, beyond reasonable doubt that it was more reliable, accurate and hence a feasible approach for investigating the state of the waste and environmental waters.

5. Conclusion

  In this study, the relationship between the concentration of a light-absorbing species and the intensity of the transmitted light was investigated, under the conditions of a constant path-length and fixed wavelength (520nm). The experiment demonstrated that the LCC is appropriate, reasonable and a feasible option for use at high school level for investigating the condition of the water in the environment. The results show that using the LCC, it was possible to generate similar results like those generated by the DWA and also similar to the high cost instruments, namely ICP and AAS. It is appropriate that this simple application is considered for adoption in Zambia and other low income countries overwhelmed by lack of resources for effective teaching of science and especially in the investigation of water based pollutants in the environment. This type of colorimeter can simplify measurement procedures, and is able to work in any environment. Thus, it introduces two types of benefits: a decrease of equipment and procedure costs and, an uncovering what's hidden in the water found in the environment where the students reside. The findings suggest that using concentrations 0ppm, 2ppm, 4ppm and 8ppm for calibration of the graph is the most acceptable scenario because the values obtained produced the most favourable calibration curve which yielded concentration values close to the values obtained by more accurate/precise instruments (DWA, ICP and AAS). Despite the huge cost disparity, the results obtained using the LCC1

was comparable to the ones generated by ICP, AAS and the DWA. It was further proved that LCC1 was the favourable colorimeter configuration for producing the best fit linear graph for pollutant determination (and hence strongly recommended for high school use). LCC2 was not as favourable as LCC1 because the concentration of the effluent water obtained using the former produced a large deviation from the accepted values or values obtained by more systematic analytical instruments. Apart from accuracy superiority, LCC1 is less costly to assemble and hence an added advantage over LCC2.

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